DEPARTMENT OF FORESTRY AND FIRE PROTECTION
P.O. Box 944246
SACRAMENTO, CA 94244-2460
Website: www.fire.ca.gov
(916) 653-7772

R13

February 11, 2004

Art Bagget, Chair
State Water Resource Control Board
P. O. Box 100
Sacramento, California 95812-0100

Dear Chairman Bagget:

Subject: DRAFT Water Quality Control Policy for Developing California's Clean Water Act Section 303(d) List

The California Department of Forestry and Fire Protection (CDF) supports the efforts of the State Water Resource Control (SWRCB) to make the process of listing and delisting impaired waterbodies more consistent and more transparent. CDF believes that the timely adoption of the Draft Water Quality Control Policy for Developing California's Clean Water Act Section 303(d) List will lead to much better documentation upon which listing and delisting decisions can be made by the Regional Water Quality Control Boards (RWQCBs).

CDF strongly supports timely adoption of the proposed policy in order to promote the rapid recovery of impaired water bodies by focusing resources effectively on where they are needed. Following are some specific areas where CDF suggests the SWRCB provide guidance on the use of the new policy and/or amend the draft proposed policy. It is hoped that these can be considered without delaying adoption of the new policy.

1. Section 3.1.10. Trends in Water Quality: Item 1 states that at least three years of data will be used. Based on work conducted by several researchers, including Benda (USFS 2002, Benda 2003), it is clear that in many environments, including landslide prone terrain, background conditions and trends in water quality cannot be determined in such a short time. The typical recurrence interval for very large storms and wildfires are in the hundreds of years. Therefore, it is impossible to define background sediment yields over a few years at the site scale, without accounting for the effects of infrequent natural catastrophic events. CDF suggest adding the following language (underlined) to the last sentence of this section: "Waters shall be

placed on the section 303(d) list if the declining trend in water quality is substantiated (steps 1 through 4 above) and impacts are observed (step 5) <u>that are not the result of natural catastrophic events in the watershed</u>."

2. Section 3.3. Enforceable Program Category Factors: The document currently states that waters shall be placed in the ***enforceable program category*** if water quality standards are not met and there is an existing program being implemented to address the identified problem. This category is used when programs **other than Total Maximum Daily Loads (TMDLs)** are in place that can reasonably be expected to result in attainment of water quality standards. The document also states that "Documentation that Best Management Practices (BMPs) will lead to attainment of water quality standards shall be based on site-specific study, case studies from similar locations, or research results from applicable situations."

   This section clearly applies to forestry operations on non-federal lands in California where the Forest Practice Rules (FPRs) are an "enforceable program", directed in large part to protect water quality, that could be used to reduce TMDL assignments in the future. It is not clear, however, what is meant by "site-specific study, case studies from similar locations, or research results from applicable situations." We have monitoring results that suggest that riparian leave requirements, particularly under the Threatened and Impaired Watersheds Rule Package, are adequate to prevent water temperature effects related to forestry operations, with post-harvest canopy exceeding FPR requirements. Sediment is more problematic, since monitoring in Caspar Creek (Lewis et al. 2001), as well as Hillslope Monitoring on a statewide basis (Cafferata and Munn 2002), has shown some increases in hillslope erosion and suspended sediment yields related to forestry operations. This is usually related to erosion from landslides, roads, and watercourse crossings. We can state that monitoring has shown: 1) individual practices required by the FPRs are generally effective in preventing hillslope erosion features when properly implemented (Cafferata and Munn 2002), 2) implementation of the modern FPRs (post-1973) substantially reduced water quality impacts related to sediment (Lewis et al. 2001), and 3) roads and watercourse crossings require better implementation of the Rules related to design, construction, and maintenance.

   The SWRCB could greatly increase regulatory effectiveness and efficiency by acknowledging that California Forest Practice Act and FPRs are an enforceable program for purposes related to this category, while at the same time providing guidance on what additional studies or monitoring programs are needed for documentation under the proposed policy.

3. Section 6.2.3.1. Evaluation Guideline Selection Process—Sediment Quality Guidelines for Marine, Estuarine, and Freshwater Sediments. The document states that the RWQCBs may select sediment quality guidelines that have been published in the peer-reviewed literature or by state and federal agencies. This approach has led to problems in the past and will continue to cause problems in the future, since sediment values (suspended sediment concentrations, bedload, channel parameters such as V-star, percent fine sediment <0.85 mm, etc.) vary widely depending on the location of the watershed. For example, extrapolating fine sediment values from one area to areas with different geology, slope or other characteristics can lead to recommended values that are not obtainable, even in the absence of management activities. Bedrossian and Custis (2002) concluded that natural/background rates of sedimentation for North Coast watersheds range from 300 to 3000 tons/square mile/year in Franciscan terrain. This wide range in sediment generation makes it very difficult to take absolute values from peer-reviewed papers in one area and extrapolate them to another area. In adopting the proposed policy, the SWRCB should state that it is not intent of the Board that inappropriate extrapolations or inappropriate methods be used in formulating sediment quality guidelines.

4. Section 6.2.5.4. Data Quality Assessment Process—Temporal Representation. The document states: "In general, samples should be available from two or more seasons or from two or more events when effects or water quality objectives exceedances would be expected to be clearly manifested. " As stated above under comment No. 1 for Section 3.1.10, it is clear that in many environments, particularly those in landslide prone terrain, sediment trends in water quality and background conditions cannot be determined in such a short time. Watershed processes, are dynamic in both time and space, with typical recurrence interval for very large storms and wildfires in the hundreds of years. Therefore, it is not possible to define background sediment yields over a few years at the site scale (Benda 2003). The policy should acknowledge this recent finding and reference this research in the Functional Equivalent Document (FED).

5. Section 6.2.5.5. Data Quality Assessment Process—Minimum Number of Samples. The document states: "Generally for assessment of numeric water quality standards or evaluation guidelines, a minimum of 10 or 20 temporally independent samples is needed from each water body segment for placement on the planning list or the section 303(d) list, respectively. " While this may work well for chemical pollutants, parameters with high variability like sediment, require many more samples. The proposed policy should state that highly variable parameters like suspended sediment and turbidity require larger sample sizes, and that sample size should be appropriate to the variability of parameter being monitored.

Thank you for the opportunity to comment on the proposed policy. Again, CDF strongly supports timely adoption of the proposed policy to promote the rapid recovery of impaired water quality by focusing resources effectively on waterbodies where they are needed. Please contact Clay Brandow or Pete Cafferata of my staff at (916) 653-0719 and (916) 653-9455, respectively, if you have specific questions concerning our recommendations.

Sincerely,

for William E. Snyder
Deputy Director,
Resource Management

References

(1) Bedrossian, T.L. and K. Custis. 2002. Review of July 2002 EPA analysis of impacts of timberland management on water quality. Memorandum dated November 27, 2002, sent to Mr. Ross Johnson, Deputy Director for Resource Management, Calif. Dept. of Forestry and Fire Prot., Sacramento, CA. California Geological Survey, Sacramento, CA. 23 p.

(2) Benda, L. 2003. The Dynamic World of Mountain Drainage Basins. Abstract. Water Quality Monitoring Workshop, Redding, CA, Dec. 1-2, 2003. University of California Center for Forestry.
http://ucce.ucdavis.edu/files/filelibrary/5098/12537.pdf

(3) Cafferata, P.H., and J.R. Munn. 2002. Hillslope monitoring program: monitoring results from 1996 through 2001. Monitoring Study Group Final Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, CA. 114 p.
http://www.bof.fire.ca.gov/pdfs/ComboDocument_8_.pdf

(4) Lewis, J., S.R. Mori, E.T. Keppeler, and R.R. Ziemer. 2001. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. In: M.S. Wigmosta and S.J. Burges (eds.) Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. Water Science and Application Volume 2, American Geophysical Union, Washington, D.C.; 85-125.
http://www.fs.fed.us/psw/rsl/projects/water/CWEweb.pdf

(5) USDA Forest Service (USFS). 2002. Landscape dynamics and forest management. Gen. Tech. Rep. RMRS-GTR-101-CD. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. CD-ROM.

State of California

Reference ___

THE RESOURCES AGENCY OF CALIFORNIA

Memorandum

To : Ross Johnson, Deputy Director for Resource Management
California Department of Forestry and Fire Protection

Date: November 27, 2002

From : Trinda L. Bedrossian, Supervising Geologist, and Kit Custis, Senior Engineering Geologist
Department of Conservation—California Geological Survey

Subject: Review of July 2002 EPA Analysis of Impacts of Timberland Management on Water Quality

At the request of the California Department of Forestry and Fire Protection (CDF), the California Geological Survey (CGS) has reviewed the U.S. Environmental Protection Agency's (EPA) "Analysis of the Impacts of Timberland Management on Water Quality based on North Coast TMDLs from 1998 through 2001". The EPA analysis was provided in a July 11, 2002, letter from EPA Water Division Director Alexis Strauss to State Water Resources Control Board Chair Arthur G. Baggett in conjunction with the review of silviculture waivers. Comments on the EPA analysis were provided by CGS licensed geologists Trinda Bedrossian, Kit Custis, Gerald Marshall, Bill Short and Tom Spittler.

CGS's review of the July 2002 EPA analysis included: (1) review of data provided in the EPA analysis and work sheets; (2) review of published and unpublished geologic reports, including articles on tectonic uplift and erosion rates on the North Coast, that apparently were not considered in the development of the Total Maximum Daily Loads (TMDLs) analyzed by EPA, and (3) review of CGS field reports and mapping on the North Coast. Based on our review of these documents, CGS conclusions are different from those of EPA. CGS believes some of the TMDLs used in the EPA analysis underestimate natural/background rates of sedimentation. In addition, while timber harvesting undoubtedly contributes to management-related sediment delivery to streams in these watersheds, our review of the literature indicates it is not the sole source.

Background

It is our understanding that the EPA based their analysis on the review of selected data from portions of seven (TMDL) studies on North Coast watersheds that met their screening criteria: (1) sources active since the mid to late 1970's; and (2) watersheds dominated by timberland. The seven watersheds selected for the EPA analysis included: Van Duzen (lower basin only); South Fork Eel (Sproul Creek and Hollow Creek intensive areas only), Noyo, Ten Mile, Albion, Big and Gualala (Buckeye, North Fork, and Rockpile subwatersheds only). Summaries of the sediment source analyses for the seven watersheds divide sources of sediment into three categories related to: (1) timberland management, (2) other management related sources, and (3) natural/background. However, the assumption was made that all human-caused sediment is attributable to timber management in a given area if that area is predominantly managed for timber. The EPA concludes that (1) on the average, 43% of the sediment delivered to streams was from natural or background sources; 1% was from specific sources other than silviculture; and the remaining 56% was associated with recent timberland management; and (2) based on data from TMDL development, current timberland management practices are resulting in roughly a doubling of the amount of sediment being delivered to streams as compared with natural background loads.

The EPA analysis of the seven watersheds shows the following estimates of natural/background:

Van Duzen (Lower Basin):		183,600 cu yds (115 tons/sq mi/yr*)
South Fork Eel:	Sproul Creek =	133 tons/sq km /yr (379 tons/sq mi/yr**);
	Hollow Tree Creek =	298 tons/sq km/yr (849 tons/sq mi/yr)
Noyo:		374 tons/sq mi/yr
Ten Mile:		311 tons/sq mi/yr
Albion:		231.5 tons/sq mi/yr
Big:		261 tons/sq mi/yr
Gualala:	Buckeye =	360 tons/sq mi/yr
	N. Fork =	370 ton/sq mi/yr
	Rockpile =	390 tons/sq mi/yr

* Assumes density of 120 lbs/cu ft per Table 5 of PWA (1999) over 20 year period 1980-1999 per Table 10 (PWA, 1999); Lower Basin = 129 sq mi (USEPA, 1999). ** 1 Metric ton/square kilometer/year = 2.85 US tons/square mile/year.

Summary of CGS Findings

Recent studies by CGS indicate that natural/background estimates of sediment delivery to streams are strongly influenced by the type of bedrock material and the percentage of lands underlain by historically active deep-seated landslides, especially earthflows. Based on CGS geologic mapping in the Gualala River watershed (Fuller and others, 2002) and review of available geologic and sediment yield literature, an estimate of the annual rate of natural/background annual sediment delivery was found to be approximately 1000 to 3000 tons/sq mi/yr, which is much greater than the Gualala River subbasins listed in the EPA analysis. This higher estimate of sediment delivery rate is due to a larger area of deep-seated landslides identified than is assumed in the studies utilized in the EPA analysis. This rate of natural sediment delivery is consistent with past regional suspended sediment studies done at stream gages on other California North Coast rivers and offshore sedimentation studies in watersheds of similar geologic setting. In addition, regional tectonic and landform analysis supports this estimated range of long-term erosion for other watersheds near the Cape Mendocino Triple Junction/San Andreas Fault system. The underestimation of large landslide areas as a source of natural sediment has also occurred in several other watersheds listed in the EPA analysis.

CGS concludes that natural/background rates are underestimated in some of the TMDLs used in the July 2002 EPA analysis for the following reasons:

1. Erosion and sedimentation from large deep-seated landslides are significantly underestimated. This is particularly true for watersheds underlain by Central Belt Franciscan mélange, where the rate of movement in deep-seated landslides, i.e., earthflows, typically fluctuates seasonally and heavy, long duration precipitation results in localized shallow failures, gully erosion and erosion of the in-channel toes of these large unstable features.

2. Tectonic uplift and erosion rates are not considered. Although uplift and erosion from uplift are episodic events, evaluation of the known geologic units, topography and geomorphic responses to tectonic uplift within a given watershed can be used to cross-check estimated erosion rates generated by other methods. Measured sediment loads in North Coast streams are generally consistent with those predicted in tectonically uplifted areas.

3. Previous regional-scale sediment yield studies have not been sufficiently considered. These studies show that coastal rivers that drain active continental margins are more susceptible to periodic floods and, because of their steeper gradients and proximity to source materials, have large contributions of bedload material, which is seldom included in the sediment load values reported in the literature.

4. Legacy effects of past land use and their effects on in-channel sediment transport and storage are under-represented. These impacts have been widely recognized as causing dramatic increases in past soil erosion on hillslopes and on-going sedimentation in coastal rivers where sediment trapped in long-term storage is transported downstream during high-discharge events, thereby increasing the overall suspended sediment load. Many on-going impacts from legacy practices on forested lands, both in-channel and on hillslopes, are being mitigated through implementation of current Forest Practice Rules (FPRs) and other specified restoration measures identified during timber harvest planning.

5. Screening criteria used in the July 2002 EPA analysis may eliminate areas of significant natural/background sediment generation and transport, especially from the headwaters areas of watersheds with highly erodible and landslide-prone slopes. Recent studies of sediment generation in these watersheds attribute differences in basin wide sediment yield largely to climatic variability and in-channel geomorphic changes triggered by periodic flooding over time.

6. The assumption in the July 2002 EPA analysis that all human-caused sediment is attributed to timber management in a given area if that area is predominantly managed for timber may result in the underestimation of sedimentation from other land uses. For example, significant sources of sediment have been observed on and adjacent to forested lands as a result of improper drainage, maintenance, and storm-proofing of multiple-use roads; county road discharge; grazing activities; instream mining; erosion from wildfires; and installation of fish traps that collect sediment.

Each of these topics is discussed in more detail below.

Given the above considerations and lack of documentation in the July 2002 EPA analysis, it is unclear as to how EPA reached the conclusion that current timberland management practices are resulting in roughly a doubling of the amount of sediment being delivered to streams as compared to natural background loads. As reported by numerous authors and in monitoring studies reviewed in this memorandum, implementation of the Forest Practices Act (FPA) of 1973 and associated FPRs appears to have resulted in substantial sediment reduction from management-related activities, especially from hillslopes. Naturally high rates of sediment production continue from erosion of both active and dormant landslides; erosion of weakly consolidated soils and bedrock resulting from recent tectonic uplift; and in-channel erosion and transport of sediment from both (1) natural stream channel slopes that may be adjusting to geomorphic changes from past flooding events, and (2) legacy forest management practices. While studies of changes since implementation of the FPA and FPRs indicate that timberland roads and associated crossings still have the greatest potential to deliver sediment to watercourses, most researchers recognize that current harvesting activities are not the only cause of management-related sediment on timberlands. If the data presented in the July 2002 EPA analysis is to be used for public decision-making, CGS believes additional documentation

Deep-Seated Landslides

Numerous studies of natural landslide movement and sediment production conducted on the California North Coast indicate that deep-seated landslides, both active and dormant, and gullying are major sources of natural sediment (Harden and others, 1978; Kelsey 1977, 1978, 1980, 1987; Madej, 1999; Nolan and Janda, 1995; Swanston and others, 1995). Recent CGS mapping in the Gualala River watershed (Fuller and others, 2002) indicates approximately 33.6% of the 298 square-mile watershed is underlain by deep-seated landslides, e.g., earthflows or rock slides (see Table 1). In addition, GIS analysis based on the number of smaller landslides indicated that 58% of the smaller landslides mapped by CGS occur within larger deep-seated landslides or geomorphic terrains created by landsliding, i.e., debris slide slopes or disrupted ground. This strong spatial correlation between the smaller landslides and larger underlying deep-seated landslides and landslide-related geomorphic terrain suggests additional study is needed before assigning actual cause of small-scale landsliding to either natural or anthropogenic activities or some combination of both. In addition, these areas should be given additional consideration during land use planning. While the rate of movement in deep-seated landslides typically fluctuates seasonally and during periods of long duration heavy rainfall, heavy precipitation can result in localized shallow failures and gully development and enlargement within these deep-seated landslides. In fact, much of the sediment shed from deep-seated landslides, i.e., earthflows, is derived from shallow failures and concurrent surface erosion within these large unstable terrains (Kelsey, 1977, 1978).

Table 1
Gualala River Watershed
Estimated Natural Sediment Source Budget from
Deep-Seated Landslides and Soil Creep

Lower Estimate	Percent Area	Annual Delivered Sediment, m^3	Annual Unit Sediment* Load, Mg/km^2	Annual Unit Sediment* Load, tons/mi^2
Historic Active Earthflows	8.3	134,500	306	874
Historic Active Rock Slides	0.5	1,700	4	11
Dormant Earthflows	8.0	7,000	16	45
Dormant Rock Slides	16.8	7,000	16	45
Other Terrains	66.4	2,900	7	19
Total area = 298 mi^2 Sum	**100**	**153,100**	**349**	**994**
Higher Estimate				
Historic Active Earthflows	8.3	408,000	928	2,651
Historic Active Rock Slides	0.5	6,400	15	41
Dormant Earthflows	8.0	23,000	53	152
Dormant Rock Slides	16.8	24,000	54	154
Other Terrains	66.4	3,300	8	21
Total area = 298 mi^2 Sum	**100**	**464,700**	**1,060**	**3,019**

* Assumes density of 1.48 tons/cu yd per NCRWQCB (2001)

Natural sediment loads in the Gualala River watershed were estimated by CGS based on landslide type, landslide area, stream density, stream length, and stream order developed as part of geologic and geomorphic mapping under the North Coast Watershed Assessment Program (Fuller and others, 2002). Assuming that the average annual sediment delivery to watercourses is approximately proportional to the average annual rate of slope movement, both a low and high estimate of natural sediment load were developed in order to evaluate the importance of variations in rates of landslide movement by landslide type. Although research on natural annual displacement rates in redwood and mixed conifer forests is limited, work in the Redwood Creek watershed (Harden and others, 1978; Kelsey, 1977, 1978, 1987; Nolan and Janda, 1995; Swanston and others, 1995) provided information for CGS to assign reasonable estimates of lower and upper limits for natural slope displacements. Because published displacement rates were used to give general order-of-magnitude of sediment delivery, they are rounded to either one or two significant figures. The lower estimate of natural sediment delivery is based on a downslope displacement rate of 130 mm/yr for historically active earthflows (Harden and others,1978), a 25 mm/yr displacement rate for historically active rockslides (Swanston and others,1995) and a 10 mm/yr displacement rate for dormant earthflows (Swanston and others,1995). Using rates of movement from Kelsey (1977, 1978, 1987), the upper limit of natural sediment delivery is estimated to result from a 300 mm/yr displacement rate for historically active earthflows, a 50 mm/yr displacement rate for historically active rockslides, and a 20 mm/yr displacement rate for dormant earthflows. A soil creep rate of 1.6 mm/yr was used for areas not associated with landslides, which is consistent with the range in soil creep of 1.0 to 2.5 mm/yr reported for schists in the Redwood Creek watershed (Swanston and others, 1995). A soil density of 1.48 tons/cu yd was retained from the NCRWQCB (2001) sediment budget for the Gualala River. The results of these estimates are shown in Table 1.

Based on these natural sediment source calculations, CGS studies in the Gualala River watershed indicate a watershed-wide annual average background sediment load of approximately 1000 to 3000 tons/sq mi/year from large deep-seated landslides, both earthflows and rockslides, combined with slower soil creep on more stable terrain. This is approximately three to fifteen times higher than the 200 tons/sq mi/year reported for earthflows in the Technical Support Document (TDS) for the Gualala TMDL (NCRWQCB, 2001) and the overall 360-390 tons/sq mi/year values in the July 2002 EPA analysis. As illustrated in Table 1, 88-90% of the estimated volume of sediment delivered from large deep-seated landslides was derived from those mapped as historically active, 94% of which were historically active earthflows. The remaining 10-15% of background sediment was delivered primarily from dormant deep-seated landslides where creep rates may be higher than adjacent slopes.

Another study, conducted by Ritter and Brown (1971) prior to implementation of the 1973 FPA and FPRs, evaluated turbidity and suspended sediment transport in the Russian River basin, which included the Dry Creek watershed located directly east of the Gualala River. The Dry Creek watershed is similar to the Gualala River watershed in that it is underlain by Franciscan terrain, has similar uses of timber and agriculture, and a climate similar to the eastern portion of the Gualala River watershed. At the time of this sediment study, land uses in the Dry Creek basin included ranch lands, some vineyards, and timber harvesting. Thus, the sediment yields come from both natural and anthropogenic sources. For the years 1965 to 1968, Ritter and Brown found an average suspended sediment load of 5700 tons/sq mi/yr, with a range from approximately 1150 to 14,000 ton/sq mi/yr, the highest being in the very wet 1965 water year. Sediment studies conducted by the U.S.

association with construction of the Warm Springs Dam. Prior to construction of the dam, suspended sediment discharge measured from USGS gage station 11465200, with a drainage area of approximately 162 square miles, shows suspended sediment yields typically ranged from 200,000 to 600,000 metric tons per year (1350 to 4000 US tons/sq mi/yr). Using this data, Brown and Jackson (1974) calculated the average annual basin-wide elevation loss at 1.15 mm/yr (7500 tons/sq mi/yr), which is consistent with other studies of direct landslide movement on the coast.

For example, Nolan and Janda (1995) reported on two landslides in Redwood Creek that had movement rates as high as 15,300 mm/yr and annual sediment yields that ranged from 730 Mg/sq km (2000 US tons/sq mi/yr) to 25,100 Mg/sq km (71,500 US tons/sq mi/yr). They note that sediment yield for a specific slide can be highly variable (i.e., 1.6 to 18.3 times the basin wide average) and that a range of one and a half orders of magnitude is not unexpected. Nolan and Janda also reported gully erosion was approximately 10% of the sediment load from the two earthflows in the Redwood Creek watershed and that fluvial processes in the gullies on earthflows delivered up to 80% of the sediment during years of low colluvial discharge. Similarly, Kelsey (1977,1978, 1980) reported an annual sediment yield from earthflows in the Van Duzen watershed of 24,900 metric tons/sq km/yr (71,000 US tons/sq mi/yr). Kelsey also reported that gully erosion from earthflows produced 26,300 metric tons/sq km/yr (75,000 US tons/sq mi/yr), approximately equal to the load discharged by landslide mass movement.

A more recent study in the Van Duzen River watershed by Pacific Watershed Associates (PWA, 1999) found significant differences from Kelsey (1977) in both the absolute quantities and relative percentages of sediment delivered from three landslide prone terrains (potentially unstable sandstone, older slump-earthflow melange, and active earthflow) that generate 91% of the upland sediment. The hillslope sediment yield estimated by Kelsey for lands above the Bridgeville stream gage (Upper Basin/upper half of Middle Basin) are approximately 33 percent higher than sediment yields estimated by PWA for the entire watershed (6500 tons/sq mi/yr versus 4300 tons/sq mi/yr). Kelsey also estimated an average hillslope sediment yield of approximately 5500 tons/sq mi/yr when the sediment from the 1964 storm event is excluded. Table 10 of the PWA study shows that pre-1980 sediment yields were much greater across the three Van Duzen River subbasins than post-1980 (see Table 2 below). PWA concludes that: "The data suggests considerably less natural and management related sediment is being produced in the VDR basin in the post-1980 period. This probably most strongly reflects the differences in the frequency and magnitude of storms which trigger widespread watershed response, but could be partially attributed to improvements in land management practices brought on by the FPRs or voluntarily by landowner actions." PWA also suggested that the differences with Kelsey's study may be due to differences in estimation methodology including Kelsey's reliance on stream gage data and the unusually wet period of Kelsey's study.

The high natural variability of sediment rates demonstrated in the PWA (1999) study results from differences in geology, landslide processes, hydrology, land use, sampling methods, and duration and frequency of sampling. For example, PWA (1999) found that the 95% confidence interval for earthflow sediment sources they studied to be "much poorer" than those on other terrains with a watershed average of +/- 147%. PWA noted that this wide confidence interval is not unexpected for earthflows, but that "The wide confidence interval serves to illustrate the difficulty of estimating long term sediment delivery from earthflows. Fortunately, most earthflows in the VDR are natural

Table 2
Van Duzen River watershed sediment deliver volumes
(from PWA, 1999*)

Table 10. Total sample plot and aerial photograph determined sediment delivery by time frames and potential controllability.

Sub-watershed		Total Yield by Time Period for Management Sediment Yield (yds³ & %)	Total Yield by Time Period for Non-Management Sediment Yield (yds³ & %)
Upper Basin	Pre-1980	394,400 (22%)	1,054,400 (59%)
	Post-1980	176,900 (10%)	167,700 (9%)
	Subtotals	574,300 (32%)	1,222,100 (68%)
Middle Basin	Pre-1980	796,300 (21%)	1,862,500 (50%)
	Post-1980	303,600 (8%)	775,700 (21%)
	Subtotals	1,099,900 (29%)	2,638,200 (71%)
Lower Basin	Pre-1980	1,049,600 (56%)	494,200 (27%)
	Post-1980	136,100 (7%)	183,600 (10%)
	Subtotals	1,185,700 (63%)	677,800 (37%)
	Totals for whole basin	2,859,900 (39%)	4,538,100 (61%)

*Same as Table 4.4 of Van Duzen TMDL (USEPA, 1999)

Elsewhere in the PWA (1999) *report, estimates of unit* sediment yield (cu yds/sq mi/yr) were provided by terrain type that generally agree with CGS's estimates made for the Gualala River Basin for similar geology and landslide types. An overall watershed sediment yield for the entire Van Duzen River watershed of approximately 2600 tons/sq mi/yr is presented (conversion from cu yards assuming density of 120 lbs/cu ft). The PWA report also notes that approximately 72 percent of the watershed's sediment yield *comes from the upper and middle basins and that 80 to 84* percent of the sediment yield in the upper and middle Van Duzen River watershed has no land use association. In these two domains, 94 to 100 percent of the sediment is derived from earthflow terrains that had no associated land uses.

In addition to the Gualala River and Van Duzen River TMDL studies, other TMDLs *appear to* underestimate or ignore erosion and sedimentation from large deep-seated landslides in the *development of sediment budgets. For example,* even though deep-seated landslides were mapped in conjunction with development of the Noyo River TMDL, deep-seated landslides were assumed to contribute little sediment except that derived from sheetwash or gullying processes (Matthews, 1999). According to Matthews (1999), virtually all large, inactive landslides were eliminated during the sediment source analysis screening process, including many deep-seated rotational/translational slides mapped throughout the *watershed, and a number of slow-moving earthflows in the eastern*

Albion and Big River sediment source analyses (Graham Matthews & Associates, 2001a and 2001b). Differences in natural/background sediment rates reported in the TMDL sediment budgets, compared with other assessments mentioned above, therefore appear, in part, to be the result of the proportion or the area of large landslides mapped and the nature of the underlying geologic units.

Tectonic Uplift and Erosion Rates

Because northwestern California is seismically active, studies of natural sediment production on the California North Coast need to consider tectonic uplift and resulting erosion over time. Evaluation of the known geologic units, topography, and geomorphic responses to tectonic uplift within a given watershed can be used to cross-check estimated erosion rates generated by other methods. For example, geologic investigations near the south end of the Cascadian Subduction Zone near Cape Mendocino indicate a rate of 3.6 mm/yr for tectonic uplift along the coast, with at least nine emergent terraces and beach ridges formed during the past 5000 years, presumably in episodic rather than gradual events (Lajoie and others, 1983). Similarly, Kelsey (1987) notes that uplift rates on the North Coast range from 1.9 to 4.0 m per 1000 years (m/ka) with regional averages on the order of 0.5 to 1.5 m/ka. Uplift of about 1 m (3 ft) produced during the 1992 Magnitude 7 Petrolia earthquake over a 10 km (6 mi) segment of the coast (Mattole watershed) is significant in this regard (Toppozada and others,1995). Merrits and Vincent (1989) studied geomorphic responses to uplift in the Cape Mendocino triple junction region and reported uplift rates of approximately 0.3 mm/yr at Fort Bragg and about 4 mm/yr at King Mountain in the Mattole watershed. Richardson (2000) reported that the marine terraces along the coast west of the Gualala River watershed have uplift rates that increase northward from Fort Ross to Sea Ranch of 0.24 to 0.58 m/ka, respectively. If it is assumed that during periods of tectonic uplift the regional erosion rates are about half the tectonic uplift rates, then the long-term rate of natural erosion can be estimated from the long-term regional erosion rate. Again using the Gualala River watershed as an example, the regional erosion rate would range from approximately 700 to 1450 tons/sq mi/year, or an average of approximately 1075 tons/sq mi/yr (1.0 m/ka uplift = 1 mm/yr = 1000 cu m/sq km = about 5000 US tons/sq mi/yr erosion).

The assumption of 50% tectonic uplift eroding is consistent with the 0.376 value for the hypsometric integral (Ohmori, 1993) calculated for the Gualala River using River Tools software along with an assumption that the Pliocene age (2 million years old) Ohlson Ranch Formation was deposited at near sea level elevations until uplift began approximately 1.5 million years ago (Sims, 1988). The hypsometric curve is a normalized area versus normalized elevation curve of the topography and its integral is the normalized volume of land underlying the topographic surface. Today the highest elevation in the Gualala River watershed is Gube Mountain, approximately 810 m, and the top of the Ohlson Ranch Formation is at an elevation of approximately 400 m. For the normalized hypsometric integral, this represents a maximum normalized volume of 0.75 rather than 1.0. Thus a hypsometric integral value of 0.376 represents approximately half of the maximum volume (0.376/0.750 = 0.501). For comparison, 75% of the watershed maximum 810 m elevation is approximately 607 m and 50% of that results in approximately 304 m of vertical erosion. If this vertical section of bedrock was eroded over the 1.5 million years since deposition of the Ohlson Ranch Formation, an average erosion rate of approximately 0.20 mm/yr is calculated. Assuming the material eroded was bedrock at a density of approximately 2.65 Mg/cu m (Selby, 1982), the long term average erosion rate in the Gualala River watershed would be approximately 530 Mg/sq km/yr or 1500 US tons/sq mi/yr (0.20

Regional-Scale Studies

In a study of world-wide rivers, Milliman and Meade (1983) conservatively estimated the yields for mountainous coastal rivers to be 1000 tons/sq km/yr (2850 tons/sq mi/yr). New data presented in Milliman and Syvitski (1992) suggested that yields could be as high as 3000 tons/sq km/yr (8550 tons/sq mi/yr). Milliman and Syvitski indicate that, while the role of sediment erodibility (mainly a function of geology, vegetation cover and human activities) clearly cannot be discounted, the correlation between topography and sediment yield is strongly influenced by tectonism. They state that "It is probably the entire tectonic milieu of fractured and brecciated rocks, oversteepened slopes, seismic and volcanic activity, rather than simple elevation/relief, that promotes large sediment yields from active orogenic belts."

According to Milliman and Syvitski, rivers that drain active edges of continental margins (e.g., western North America) are generally much smaller than more passive margin rivers, but they may transport similar amounts of sediment. In addition, smaller rivers often have no estuaries, are more susceptible to periodic floods and (because of their steeper gradients and proximity to source materials) have large contributions from bedload material, which is seldom included in the sediment load values reported in the literature. In addition, earthquakes and volcanic eruptions along active margins can result in mudslides and floods that can increase the sediment loads in adjacent rivers. Smaller mountainous rivers are therefore more likely to discharge larger percentages of their sediment loads directly to the sea where, along active margins, much is subducted back into orogenic zones. Suspended sediment yields for several North Coast rivers listed in Milliam and Syvitski show the following values: Redwood Creek, 1700 tons/sq km/yr (4800 tons/sq mi/yr) based on Nolan and others (1987); Mad River, 2000 tons/sq km/yr (5700 tons/sq mi/yr) based on Janda and Nolan (1979); and Eel River, 1700 tons/sq km/yr (4800 tons/sq mi/yr) based on Milliman and Meade (1983). These suspended sediment yields include both natural and anthropogenic sources.

Other regional-scale studies of suspended sediment done for many of the major rivers on the California North Coast suggest natural sediment yields range from approximately 300 to greater than 7000 tons/sq mi/yr (de la Fuente and Haessig, 1993; Hawley and Jones, 1969; Janda and Nolan,1979; Griggs and Hein, 1980). As mentioned previously, this wide range is largely due to the regional variations in percentage of geologic materials making up each watershed, the strength of these geologic materials, the hydrology (rainfall, infiltration, depth of soil), the topographic relief and slope aspect, the vegetation density and type, and the rates of regional tectonic uplift. Table 3 shows suspended sediment yields taken from the above literature for six of the seven watersheds included in the July 2002 EPA analysis. Note that these suspended sediment yields include both natural and anthropogenic sources. However, even applying the average natural sediment yield ratio of 43% used in the EPA analysis, natural rates based on the suspended yield rates listed in Table 3 are approximately double those used in the July 2002 EPA analysis. These values do not include bedload which studies of north coast California rivers have found to range from 4 to 30 percent of suspended sediment loads (Hawley and Jones, 1969; Janda and Nolan, 1979). In addition, Figure 1 shows a comparison of estimates of average erosion rates for a number of other California North Coast watersheds based on off-shore sedimentation studies (Griggs and Hein, 1980). Note an average erosion rate of 1 mm/yr is approximately equal to 5000 tons/sq mi/yr of sediment, depending

Table 3
Suspended Sediment Yield Rates
(tons/sq mi/yr)

River	Griggs & Hein, 1980	Janda & Nolan, 1979	Hawley and Jones, 1969
Van Duzen near Bridgeville	8500	8500; 6470; 6045	
South Fork Eel Miranda		4980; 3306	3400
Branscomb		2470; 1476	1800
Noyo	1510		
Ten Mile	1425		
Big	940		
Gualala	1995		

Figure 1. Average erosion rates for selected northern coastal California Rivers (from Griggs and Hein, 1980)

FINE-GRAINED SEDIMENT 549

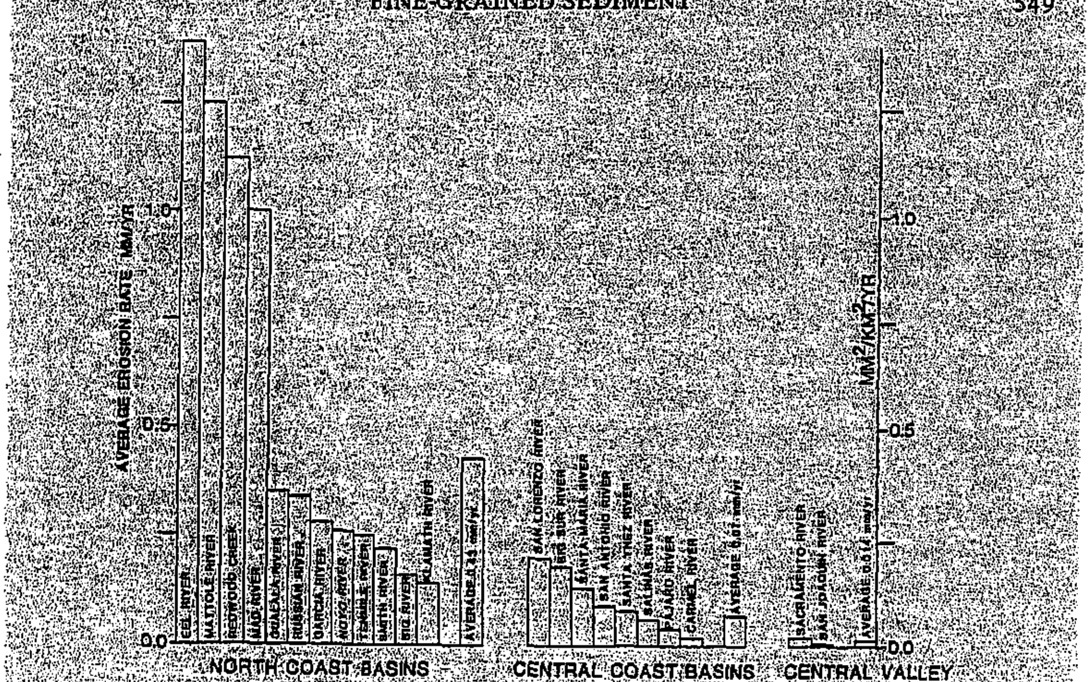

Fig. 3. – Average erosion rates for individual river basins based on suspended-sediment discharge. Regional averages were determined by weighting each basin according to its drainage-basin area.

Note: 1 mm/y = about 5000 tons/sq mi/yr, depending on density

Legacy Effects and In-Channel Sediment Transport

Legacy forest practices prior to implementation of the 1973 FPA, such as the use of stream channels for skidding, steam donkey yarding, construction of corduroys and rail lines, etc., severely impacted watersheds on the North Coast. The impacts are widely recognized as causing dramatic increases in past soil erosion on hillslopes and on-going sedimentation of coastal rivers (Cafferata and Spittler, 1998; Hagans and Weaver, 1987; Maas and Barber, 2001). It is likely that present channel conditions are largely controlled by legacy era disturbances, especially in highly and moderately disturbed channels (Knopp,1993). Research recently conducted in the South Fork Noyo River watershed includes a history of early logging, as well as a second phase of intense logging and road construction on steep slopes and adjacent to stream channels (Koehler and others, 2001). Koehler and others also showed that sediment trapped in long-term storage along the South Fork Noyo River channel is transported downstream during high-discharge events, thereby increasing the overall suspended sediment load.

Through field studies and the analysis of historic aerial photographs dating back to the 1940s, CGS staff have also recognized and documented effects of previous practices, including the erosion and slow movement of large sediment slugs within various North Coast channels, (e.g., Marshall, 2002). Widespread removal of large woody debris in the early 1980's also resulted in a loss of complexity in the upper reaches of many watersheds and deposition of sediment into lower reaches where recovery time is longer (Chorley and others, 1984; Sloan and others, 2001; Wolman and Gerson, 1978). Many of these on-going impacts from legacy practices on forested lands, both in-channel and on hillslopes, are now being mitigated through implementation of current FPRs and other specified restoration measures identified during timber harvest planning.

The July 2002 EPA analysis uses sources of sediment active since the mid- to late 1970's as a basis for one of the screening criteria used in the study and assumes that all human-caused sediment is attributable to timber management in a given area if the area is predominantly managed for timber. If human-caused sedimentation is to be attributed solely to timber harvesting since implementation of the FPA in 1973, there must be a clear effort to isolate current practices from natural sediment sources and from on-going background sedimentation resulting from legacy practices. This requires a clear linkage and understanding of how hillslope operations affect in-channel conditions.

Although sediment transport corridors largely related to failed crossings and road-related diversions have been identified in some watersheds, to date, upslope disturbances caused by timber harvest activities have not been traced, or linked directly, to habitat in the channel (Maahs and Barber, 2001). Furthermore, published sediment source analyses cannot distinguish whether post-FPA road-related sediment delivery originated from older roads or roads constructed under the FPA (Kramer and others, 2001). The current Hillslope Monitoring Program, implemented by the Board of Forestry and Fire Protection to evaluate the effectiveness of current FPRs, traces timber harvest disturbances downhill to the receiving waterways, but does not determine downstream channel and habitat conditions. The 1999 Interim Report (Board of Forestry and Fire Protection, 1999), in fact, concludes "Recent timber operations cannot be linked to current instream channel conditions based on results of the Hillslope Monitoring Program because the project evaluated FPR effectiveness on hillslopes, not in the stream channels."

Future sediment transport studies designed to assess sediment contributions from upslope activities should, therefore, include an assessment of in-channel storage and transport. A clear understanding of the volume and timing of sediment stored in the channel is necessary to properly evaluate sediment generated by upslope management practices (Koehler and others, 2001) and to encourage continued mitigation of the most egregious sites during future land use planning. As stated in Robben and Dent (2002): "Instream measurements are an integration of everything upslope. Instream measurements can be a diluted or exaggerated version of what is occurring higher in the channel network or on adjacent slopes. It is usually easier to accurately identify a drainage-related sediment source and quantify the volume of sediment it produces than it is to measure sediment in the stream and work backwards to the source".

The ability to work backwards from the stream to the source is complicated by the effects of dispersion, grain size breakdown and mixing of sediment over time making identification of the actual source of channel sediment difficult. As time progresses, channel recovery will reduce the characteristics that make source identification possible. The ability of a channel system to recover from a formative event, one that shapes the landscape, is based on both the effectiveness of the event to affect the shape or form of the landscape, i.e. storm magnitude, and the recurrence interval of these extreme events (Wolman and Gerson, 1978). Thus, the "...magnitude of an event and its effectiveness must be related to the mean conditions of climate and process in a given region."

The significance of an extreme event in changing the landscape need not be the same across watersheds. In fact, the effects will differ depending on the watershed characteristics, i.e. geology vegetation, land use, and the location within the watershed and the time interval between extreme events (Wolman and Gerson, 1978). Studies in Redwood Creek (Madej, 1995; Pitlick, 1995), Van Duzen River (Kelsey, 1977), and Eel River (Sloan and others, 2001) suggest that the recovery time in the steeper tributaries are on the order of tens of years, while the lower gradient main channels may take 50 to several hundred years. This linkage between recovery time and recurrence time of extreme events controls the length of time that legacy impacts will continue. There is no practical way to assess this linkage since it depends on the magnitude and frequency of future extreme precipitation events. Nevertheless, the persistence of legacy impacts is a critical issue in the determination of TMDL load allocations since the loads are in part dependant on recovery from legacy impacts.

Other Factors Associated with Natural/Background Sediment Generation

As recognized by Kramer and others (2001), sediment source analyses from nine recently completed TMDLs in northern California, including four of the seven evaluated in the July 2002 EPA analysis (Noyo River, South Fork Eel, Ten Mile River and Van Duzen River), are based on different time frames and source categories. According to Kramer and others, the sediment analyses progress from estimates of actual potential loading from hillslopes and banks to receiving waters, estimates of instream storage and transport of sediment, to estimates of the net sediment discharge (or yield) from drainage basins. Kramer and others state: "Although the degree of uncertainty depends upon the methodology used, the range of uncertainty in sediment source analyses is generally on the order of 40-50% (Raines and Kelsey, 1991; Stillwater Sciences, 1999b). Methodological constraints (e.g., estimates of landslide frequency, areal extent, depth, age, bulk density, estimates of landslide uncertainty may be too high to reliably detect differences between land uses or recent changes in land use practices such as those introduced in 1973 under the Z'Berg-Nejedley Forest Practices Act (FPA) of 1973 (CCR 14 Chapters 4 and 4.5)."

Although CGS believes natural/background levels in some of the North Coast TMDLs have been greatly underestimated, as discussed above and below, a comparison of TMDL data from Kramer and others (2001) with the July 2002 EPA analysis shows the following percentages of natural/background sources for the four rivers evaluated in both studies: Noyo River = 56% background in both studies; South Fork Eel = 54% in Kramer and others, 34% in the EPA study; Ten Mile River = 36% in Kramer and others, 39% in the EPA study; Van Duzen River = 72% in Kramer and others, 57% in the EPA study. Because there is little supporting data provided as to how conclusions were reached in the July 2002 EPA analysis, it is difficult to determine why the discrepancies in the percentage of background sources exist in the South Fork Eel, Ten Mile and Van Duzen watersheds when similar information from the TMDLs was presumably used.

It appears that screening criteria used in the July 2002 EPA analysis may eliminate areas of significant natural/background sediment generation and transport, especially from the headwaters areas of watersheds with highly erodible and landslide-prone slopes (e.g., Van Duzen River, Gualala River, and Eel River). In addition, impacts from erosion-producing storms do not appear to have been taken into consideration. For example, in a recent study of an increase in the frequency of major floods throughout the western United States during the past half century, Sommerfield and others (2002) compared river discharge and sedimentary records for the Eel River and ocean shelf to examine links between hydroclimatology, coastal sediment delivery, and marine sedimentation. This research recognizes that "Streamflow in California's North Coast is dominated by intense, short-duration (3-6 days) rainstorms in winter, with peak flows that rank among the highest on record for the western United States...Factors including steep, mountainous and geologically unstable terrain and limited flood plain storage engender enormous suspended-sediment discharges to the coastal ocean during floods..." Sommerfield and others further note that, regionally, the Eel River has the largest mean annual sediment load at 15-24x10^6 ton/yr (4800 to 7700 tons/sq mi/yr) and is the largest point source of terrigenous sediment to the conterminous U.S. Pacific Coast (Meade and others, 1990).

Based on investigations of ocean dispersal and flood response studies of major events in 1995 and 1997 (Sommerfiled and Nittrouer, 1999; Sommerfield and others,1999; Wheatcroft and Borgeld, 2000), oceanic flood deposits are known to be packaged into distinctive sediment beds on the shelf that are unique to flood-producing rainstorms and that have potential to document paleohydrologic phenomena in the Eel River watershed. Through core samples collected on the Eel River shelf and magnitude and frequency analysis of U.S. Geological Survey discharge data for the Eel River at Scotia (1911-1999), Sommerfield and others (2002) determined that the past half century in northern California has been particularly flood prone, with direct implications to coastal sediment delivery. The shelf record revealed a sudden, three-fold increase in sedimentation rate around 1954 and an increase in the frequency of preserved flood beds that document sedimentation from major floods in 1955, 1964, 1974, 1986 and 1995.

Sommerfield and others (2002) attribute the recent increase in sediment accumulation offshore of the Eel River to two principal factors: (1) mulitdecadal changes in flood hydroclimatology; and (2) intrabasinal geomorphic changes triggered by the 1955 and 1964 floods. They point out that the Eel River peak flow record since 1950 mirrors the upward trend in extreme rainfall events throughout the western United States, which have been attributed to variations in the strength and position of Pacific pressure cells and trajectories of westerly rainstorm tracks over the western United States. They also recognize evidence that land-use practices (timber harvesting and cattle grazing) in the watershed may have elevated suspended sediment loads. They conclude, however, that: (1) the anthropogenic increase in watershed production is a probable secondary factor; (2) anthropogenic sediment production in the Eel River basin may account for a maximum of about 33% of the total sediment load reaching the coast; (3) although the 33% is not trivial, it is clearly too small to account for the three-fold increase in sedimentation rate measured on the shelf; and (4) because the climatic and anthropogenic influences on river discharge are coeval and the gage record is biased by an extreme event, it is not possible to elucidate an anthropogenic impact on the shelf record. Sommerfield and others (2002) further conclude that: "Although historical increases in sedimentation rate are often attributable to land use activities..., climate variability may be a contributing, if not the chief, factor in some cases. Increasing use of geologic observations to deduce rapid climate change...demands that these issues be addressed for the full range of sedimentary issues."

<u>Sedimentation from Other Land Uses</u>

Given the above considerations and lack of documentation in the July 2002 EPA analysis, it is unclear as to how EPA reached the conclusion that current timberland management practices are resulting in roughly a doubling of the amount of sediment being delivered to streams as compared to natural background loads. In addition to Kramer and others (2001), who noted a substantial decrease in sediment yields since implementation of the 1973 FPA, there have been numerous other studies that indicate improved forest practices after 1974 have significantly reduced sediment yields.

For example, Lewis and others (2001) showed that logging conducted in South Fork Caspar Creek prior to implementation of present-day FPRs produced 2.4 to 3.7 times more suspended sediment compared to more recent logging in the North Fork. The shallow landsliding component of hillslope erosion was approximately 50% lower in the 1978 to 1996 period than in the 1958 to 1978 period due to a large reduction in road related failures (Stillwater Sciences, 1999a). Cafferata and Spittler (1998) also concluded from the Casper Creek watershed study that impacts from logging operations conducted under the FRPs in the 1980's and 1990's were considerably less than those conducted in the early 1970's (pre-FPA). Maas and Barber (2001) stated that present-day FPRs have greatly improved on-the-ground methods used to access and harvest timber. Koehler and others (2001) also noted that the passage of the Z-Berg-Nejedley FPA of 1973 dramatically changed timber management practices in California and that new guidelines for buffer zones to protect watercourses and inner gorge areas, as well as higher standards for road construction and harvesting techniques, have contributed to a decrease in the rate of sediment delivery to channels in the South Fork Noyo River. Similarly, Rice (1999), in a study of road-related erosion in Redwood Creek, reported that changes in forest practices since 1976 resulted in a reduction in road-related erosion by an order of magnitude, primarily as a result of better culvert sizing and placement and less reliance on culverts to handle runoff from logging roads. Custis and Spittler (2002) also found that channel conditions in

Independent of the above studies, hillslope monitoring conducted on a statewide basis over the past six years under the Board of Forestry and Fire Protection's Hillslope Monitoring Program has shown that individual practices required by the FPRs are generally effective in preventing hillslope erosion and erosion problems from randomly selected road and skid trail segments, as well as from landings and watercourse crossings, when properly implemented (Board of Forestry and Fire Protection, 1999). These conclusions are consistent with previous assessments of the FPRs in the 1980's by the State Water Resources Control Board (1987). CGS staff have also noted a general improvement in sediment reduction activities during the past 25 years including fewer failures from landings, less gully erosion along roads due to increased outsloping, fewer culvert failures as a result of use of temporary rocked crossings, more skyline and helicopter yarding, and greater use of hydraulic excavators resulting in less sidecast and perched fill.

In spite of these improvements, data collected under the Hillslope Monitoring Program continue to show that roads and associated crossings still have the greatest potential to deliver sediment to watercourses. These findings are consistent with results of instream monitoring conducted by Maas and Barber (2001) in the Garcia River, where watercourse crossings, ditch relief culverts and inadequate waterbars were found to be the most common sources of sediment caused by timberland management. In both studies, however, the timberlands where these features are documented are owned and managed by a variety of landowners and are used to access industrial timberlands, privately owned timberlands, hunting lands and ranchlands. The majority (approximately 80%) of the problems (design, construction, maintenance) identified under the Hillslope Monitoring Program were associated with watercourse crossing structures that were in place prior to development of the Timber Harvesting Plan evaluated (Cafferata, CDF, personal communication; Ice and others, 2002). Similarly, many of the roads observed in the Garcia River study were constructed prior to the FPA of 1973 (Maas and Barber, 2001). According to Maas and Barber, timber harvesting activities were not the only cause of management related sediment, e.g., some streambank failures appeared to be caused by grazing.

The assumption in the July 2002 EPA analysis that all human-caused sediment is attributed to timber management in a given area if that area is predominantly managed for timber could result in the underestimation sedimentation from other land uses. Studies of variations in fine bed material in pools of natural gravel channels by Lisle and Hilton (1999) illustrate potential sources of sediment that may or may not be anticipated in timberland areas. For example, unexpected increases in sediment were experienced from illegal mining operations in Bear Creek and from a severe fire in Pilot Creek. In French Creek, large chronic inputs of sediment were reduced by an erosion control program implemented by the U.S. Forest Service from 1991 to 1994 that mainly targeted roads. According to Lisle and Hilton, fine volumes decreased during this period by more than one half, however, a large rain-generated flood in 1997 caused fine volumes to nearly double again.

Other chronic sources of sediment have been observed by CGS staff along county roads that are within or adjacent to individual Timber Harvesting Plans (Haydon, 2000; Sowma, 1989 and 1990; Spittler, 1995); along unpaved roads where Off-Highway-Vehicle use has destroyed waterbars and other erosion control measures implemented as part of timberland management; and along unpaved roads where road storm-proofing projects have been improperly implemented (e.g., Armstrong

Redwoods State Park, personal observations). Unless these sites are mitigated in conjunction with timber harvesting, they may be erroneously attributed to current harvesting activities. Significant sources of sediment also have been observed in-channel as the result of the installation of fish traps that collect sediment from erosion of in-channel streambanks during low flows and subsequent discharge during peak flows (e.g., Cloney Gulch/South Fork Freshwater Creek, Smelser, 2002). Examination of stream channels located upstream of the fish traps and downslope from several recently active Timber Harvesting Plans revealed no evidence of hillslope discharge from timberland management activities. Another land use prevalent on timberlands in the urban/rural interface, and in mixed ownerships where agriculture and ranching are common, is the diversion of water for drinking and irrigation purposes. Such diversions, especially those in the upslope headwaters reaches of a watershed, can reduce in-channel flows downstream thereby reducing the capacity to carry sediment in the lower reaches. As an example, this condition has been observed and appears to have impacted fish habitat in the Mattole River watershed (North Coast Watershed Assessment Program, 2002).

CGS believes that additional improvement is still needed to reduce timberland management-related sediment production, particularly for activities associated with road construction and reconstruction (i.e., drainage structure design, construction and maintenance); the design, construction and maintenance of watercourse crossings; and mitigation of legacy effects from past harvesting operations. However, assumptions made regarding various land uses and anthropogenic sources of sediment, as well as other pollutants identified in TMDLs, need to be more carefully validated and the basis for the assumptions clearly documented if the results are to be used appropriately in public decision-making.

Conclusions

CGS believes natural/background rates of sedimentation are underestimated in some cases by at least an order of magnitude in both the TMDLs and the July 2002 EPA analysis of the TMDLs. Reasons for this apparent underestimation include: (1) erosion and sedimentation from large deep-seated landslides are either underestimated or ignored, particularly in areas underlain by Central Belt Franciscan terrain; (2) tectonic uplift and erosion rates are not considered; (3) results of past regional sediment source studies are not adequately addressed; (4) legacy effects of past land use and their effects on in-channel sediment transport and storage are under-represented; (5) screening criteria used in the July 2002 EPA analysis may eliminate areas of significant natural/background sediment generation and transport, especially in watersheds with highly erodible and landslide prone slopes; and (6) the assumption made in the July 2002 EPA analysis that all human-caused sediment is attributed to timber management in a given area if that area is predominantly managed for timber may result in the underestimation of sediment impacts from other land uses.

From a review of the literature and analysis of recent studies conducted by CGS mentioned in this memorandum, CGS concludes that natural/background estimates of 300 to 3000 tons/sq mi/yr are more realistic for most North Coast watersheds underlain by Franciscan terrain. Watersheds underlain by Central Belt Franciscan melange are more likely to have natural/background sediment loads of approximately 1000 tons/sq mi/yr or greater. These ranges are consistent with other studies of natural/background sediment production conducted by Griggs and Hein (1980); Hawley and Jones and Syvitski (1992), Nolan and Janda (1995), PWA, 1999; Ritter and Brown (1971), Sommerfield and others (2002), and USGS (http://co.water.usgs.gov/sediment).

Based on these studies and the lack of documentation in the July 2002 EPA analysis, it is unclear as to how EPA reached the conclusion that current timberland management practices are resulting in roughly a doubling of the amount of sediment being delivered to streams as compared to natural background loads. As observed and reported by numerous authors and in various monitoring studies reviewed in this memorandum, implementation of the FPA of 1973 and associated FPRs appears to have resulted in substantial sediment reduction from management-related activities, especially from hillslopes. Naturally high rates of sediment production continue from erosion of both active and dormant landslides; erosion of weakly consolidated soils and bedrock resulting from recent tectonic uplift; and in-channel erosion and transport of sediment from both (1) natural stream channel slopes that may be adjusting to geomorphic changes from past flooding events, and (2) legacy forest management practices. While the studies of changes since implementation of the 1973 FPA and FPRs indicate that timberland roads and associated crossing still have the greatest potential to deliver sediment to watercourses, most researchers recognize that current harvesting activities are not the only cause of management-related sediment on timberlands. Unless legacy effects of past harvesting practices and other chronic sources of sedimentation from other land uses are mitigated in conjunction with timber harvesting, they may be erroneously attributed to current harvesting activities.

If the data presented in the July 2002 EPA analysis is to be used for public decision-making, CGS believes additional documentation is warranted to validate the assumptions and findings made in the analysis. Due to California's complex geologic and geomorphologic setting, watershed-wide assessments of sediment sources on the California North Coast should clearly identify and take into consideration: (1) the nature of the underlying geologic units and the geologic structure; (2) potential failure and erosion of large, active and dormant deep-seated landslides as well as shallow-seated failures; (3) earthquake history and rates of tectonic uplift, which influence erosion rates, topography and physical properties of the underlying geologic units; (4) impacts of historic large storm and flooding events; (5) in-channel erosion and transport; and (6) impacts from past land uses. Recognition of the variability in sediment source yields, both spatial and temporal, appears to be missing from the TMDL sediment load allocation process. If resulting land use regulations do not take natural variability in watershed geologic and hydrologic characteristics into account, then expected targets may not be obtainable.

Trinda L. Bedrossian

Trinda L. Bedrossian, CEG #1064
Supervising Geologist

Kit Custis

Kit Custis, CEG #1219, CHG #254
Senior Engineering Geologist

CC: Darryl Young
Debbie Sareeram

References

Board of Forestry and Fire Protection, 1999, Hillslope Monitoring Program: Monitoring Results from 1996 through 1998: Interim Report prepared by the Monitoring Study Group, Sacramento, CA, 70 p.

Brown, W. M., and Jackson, L.E., Jr., 1974, Sediment Source and Deposition Sites and Erosional and Depositional Provinces, Marin and Sonoma Counties, California: U. S. Geological Survey Miscellaneous Filed Studies map, MF-625, 31 p.

Cafferata, P.H., and Spittler, T.E., 1998, Logging Impacts of the 1970's vs. the 1990's in the Caspar Creek Watershed: in Ziemer, R.R., Technical Coordinator, Proceedings from the Conference on Coastal Watersheds: the Caspar Creek Story, May 6, 1998, Ukiah, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, General Technical Report PSW GTR-168, Albany, CA, p.103-115.

Chorley, R.J., Schumm, S.A., and Sugden, D.E., 1984, *Geomorphology*: Methuen & Co. Ltd, London, p. 1-16.

Custis K. H., and Spittler, T. E., 2002, Evaluation of Watershed recovery, Rockpile Creek, Sonoma County, California: California Geological Survey Memorandum to William Snyder, July 31, 10p.

de la Fuente, J., and Haessig, P.A., 1993, Salmon Sub-Basin Sediment Analysis: Final Report for Interagency Agreement #14-16-001-91522, Project No. 91-HP-9 1133-1331-1046, USDA - Forest Service, Klamath National Forest, Yreka, California.

Fuller, M.S., Haydon, W.D., Purcell, M.G., and Custis, K., 2002, Draft Version of Geologic and Geomorphic Features Related to Landslides, Gualala River Watershed, Sonoma and Mendocino Counties, California: California Geological Survey, Watershed Mapping Series, Map Set 5, Plate 1, 1:24,000; see http://www.consrv.ca.gov/cgs/ncwap/maps.html.

Graham Matthews & Associates, 2001a, Sediment Source Analysis and Preliminary Sediment Budget for the Albion River Watershed, Mendocino County, CA: Prepared for Tera Tech, Inc., Contract 68-C99-249, Work Assignment #0-34, June 2001, 67 p.

Graham Matthews & Associates, 2001b, Sediment Source Analysis and Preliminary Sediment Budget for the Big River Watershed, Mendocino County, CA: Prepared for Tera Tech, Inc., Contract 68-C99-249, Work Assignment #0-34, July 2001, 69 p.

Griggs, G.B., and Hein, J.R., 1980, *Source, Dispersal, and Clay Mineral Composition of Fine-Grained Sediment Off Central and Northern California*: Journal of Geology, v. 88, pgs. 541-566.

Hagans, D. K., and Weaver, W.E., 1987, Magnitude, Cause and Basin Response to Fluvial Erosion, Redwood Creek Basin, Northern California: In Beschta, R.L., Blinn, Grant, G.E., Swanson, F.J., and Ice, G.G., eds., Erosion and Sedimentation in the Pacific Rim: Proceedings of a Symposium held at

Harden, D.R., Colman, S.M., and Nolan, K. M., 1995, Mass Movement in the Redwood Creek Basin, Northwestern California: U. S. Geological Survey Professional Paper 1454-G, p. G1-G11.

Harden, D. R., Janda, R.J., and Nolan, K.M., 1978, Mass Movement and Storms in the Drainage Basin of Redwood Creek, Humboldt County, California-A Progress Report: U. S. Geological Survey Open-File Report 78-486, 161 p.

Hawley, N.L., and Jones, B.L., 1969, Sediment Yield of Coastal Basins in Northern California, 1954-1964: U.S. Geological Survey Open-file Report 69-124, June 11, 19 p.

Haydon, W. D., 2000, Engineering Geologic Review of Nonindustrial Timber Management Plan 1-00NTMP-006 SCR: Division of Mines and Geology Memorandum to Ross Johnson, California Department of Forestry and Fire Protection, April 4, 14 p.

Ice, G., Dent, L., Robben, J., Cafferata, P. Light, J.; Sugeden, B., and Cundy, T., 2002, Programs Assessing Implementation and Effectiveness of State Forest Practice Rules and BMPs in the West: Paper presented for the Forestry Best Management Practice Research Symposium, April 15-17, 2002, Atlanta GA.

Janda, R.J., and Nolan, K. M., 1979, Stream Sediment Discharge in Northwestern California: in *Guidebook for a Field Trip to Observe Natural and Management-Related Erosion in Franciscan Terrane of Northern California*: Geological Society of America, Cordilleran Section, p. IV-1-27.

Kelsey, H. M., 1977, Landsliding, Channel Changes, Sediment Yield and Land Use in the Van Duzen River Basin, North Coastal, California: Ph.D. Dissertation, Published in Earth Resources Monograph 3, U. S. Forest Service Region 5, 370 p.

Kelsey, H. M., 1978, Earthflows in Franciscan Melange, Van Duzen River Basin, California: Geology, v. 6, p. 361-364.

Kelsey, H. M., 1980, A Sediment Budget and an Analysis of Geomorphic Processes in the Van Duzen River Basin, North Coast California, 1941-1975: Geological Society of America Bulletin, v. 91, n. 4, Part II, p. 1119-1216.

Kelsey, H. M., 1987, Geomorphic Processes in the Recently Uplifted Coast Ranges of Northern California: in Graf, W. L., editor, Geomorphic Systems of North America, The Geological Society of America, Centennial Special Volume 2, p. 550-560.

Knopp, C., 1993, Testing Indices of Cold Water Fish Habitat: Unpublished Final Report submitted to the North Coast Regional Water Quality Control Board and the California Department of Forestry under Interagency Agreement No. 8CA16983, Sacramento, CA, 56 p.

Koehler, R.D., Kelson, K.I., and Matthews, G., 2001, Sediment Storage and Transport in the South fork Noyo River Watershed, Jackson Demonstration State Forest: Report prepared for and published

Kramer, S.H., Trso, M., and Hume, N., 2001, Timber Harvest and Sediment Loads in Nine Northern California Watersheds Based on Recent Total Maximum Daily Load (TMDL) Studies: Watershed Management Council Networker, Summer 2001, v. 10, no. 1, p. 1,17-24.

Lajoie, J.R., Kennedy, G.L., Mathieson, S.A., Sarna-Wojcicki, A.M., Morrison, S.A., and Tobish, M.K., 1983, Emergent Holocene Marine Terraces at Cape Mendocino and Ventura, California, U.S.A.: Proceedings of International Symposium on Development of Holocene Shorelines, Tokyo, Japan.

Lewis, J.; Mori, S.R., Keppler, E.T.; Ziemer, R.R., 2001, Impacts on Logging on Storm Peak Flows, Flow Volumes and Suspended Sediment Loads in Caspar Creek, California: in Wigmosta, M.S., and Burgess, S.J. (eds.), Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas: Water Science and Application, v. 2, American Geophysical Union, Washington, D.C., p. 85-125.

Lisle, T.E., and Hilton, S, 1999, Fine Bed Material in Pools of Natural Gravel Bed Channels: Water Resources Research, v. 35, no. 4, p.1291-1304, April.

Maas, M, and Barber, T.J., 2001, The Garcia River Instream Monitoring Project: Final Report to the California Department of Forestry and Fire Protection, 98 p.

Madej, M.A., 1995, Changes in Channel-Stored Sediment, Redwood Creek, Northwestern California, 1947 to 1980: in Nolan, K.M., Kelsey, H.M., and Marron, D.C., editors, Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California: USGS Professional Paper 1454, pgs. O1- O27.

Madej, M. A., 1999, Appendix C-Sediment Budget for the Redwood Creek Watershed 1954-1980: Preliminary Draft, version on e-projects: RedwWA-Sept99.doc, p. 95-107.

Marshall, G. J, 2002, Rapid Review of Engineering Geologic Conditions for Specific Timber Harvesting Plans in the Elk River Watershed: California Division of Mines and Geology Memorandum to Ross Johnson, January 11, 32 p.

Matthews, G., 1999, Sediment Source Analysis and Preliminary Sediment Budget for Noyo River: Prepared for Tetra Tech, Inc., Contract 68-C7-0018, Work Assignment No. 0-18, May 1999, 92 p..

Meade, R.H., Yuzyk, T.R., and Day, T.J., 1990, Movement and Storage of Sediment in Rivers of the United States and Canada: in Wolman, M.G., and Riggs, H.C. (eds.), Surface Water Hydrology: Geological Society of America, Geology of North America, Boulder, CO, v.O-1, p. 255-280.

Merritts, D., and Vincent, K.R., 1989, Geomorphic Response of Coastal Streams to Low, Intermediate, and High Rates of Uplift, Mendocino Triple Junction Region, Northern California: Geological Society of America Bulletin, v. 101, p. 1373-1388, p. 1373-1388.

Milliman, J.D., and Meade, R.H., 1983, World-wide Delivery of River Sediment to the Oceans:

Milliman, J.D., and Syvitski, J.P.M., 1992, Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers: Journal of Geology, University of Chicago, v. 100, p. 525-544.

Nolan, K.M., and Janda, R.J., 1979, Stream Sediment in Northwestern California; in Field Trip to Observe natural and Resource Management-Related Erosion in Franciscan Terrane of Northwestern California, A Guidebook: U.S. Geological Survey, Menlo Park, p. IV-1 to IV-27.

Nolan, K. M., and Janda, R. J., 1995, Movement and Sediment Yield of Two Earthflows, Northwestern California: U.S. Geological Survey Professional Paper 1454-F, p. F1-F12.

Nolan, R.M., Lisle, T.E., and Kelsey, H.M., 1987, Bankfull Discharge and Sediment Transport in Northwestern California: International Association of Hydrological Sciences Publication 165, p. 439-449.

North Coast Regional Water Quality Control Board, 2001, Gualala River Watershed Technical Support Document for Sediment: 138 p.

North Coast Watershed Assessment Program, 2002, Mattole River Watershed Synthesis Report (March 22 Draft): State of California Resources Agency, Sacramento, CA, 306 p. plus Appendices. Available at: http://www.ncwatershed.ca.gov/mattole/synth-report.html.

Ohmori, H., 1993, Changes in the Hypsometric Curve through Mountain Building resulting from Concurrent Tectonics and Denudation: Geomorphology, v. 8, p. 263-277.

Pacific Watershed Associates, 1999, Sediment Source Investigation for the Van Duzen River: Final Report prepared for Tetra Tech and the U.S. Environmental Protection Agency. November, 46 p.

Pitlick, J., 1995, Sediment Routing in Tributaries of the Redwood Creek Basin, Northwestern California: in U.S. Geological Survey Professional Publication 1454-K, p. K1-K10.

Raines, M.A., and Kelsey, H.M., 1991, Sediment Budget for the Grouse Creek Basin, Humboldt County, California: Western Washington University Department of Geology, in cooperation with Six Rivers National Forest and the Bureau for Faculty Research, Western Washington University, Bellingham, WA, 110 p.

Rice, R.M., 1999, Erosion on Logging Roads in Redwood Creek, Northwestern California: Journal of the American Water Resources Association, v. 35, no. 5, p. 1171-1182.

Richardson, E., 2000, Uplift of Holocene Marine Terraces along the San Andreas Fault: Fort Ross to Gualala, California: in Merrits, D.J., Prentice, C.S., and Gardner, T.W. (eds), Paleoseismicity and Crustal Deformation along the Northern San Andreas Fault, Fort Ross to Point Arena, California, Thirteenth Keck Research Symposium in Geology Abstracts.

Ritter, J. R., and Brown, W. M. III, 1971, Turbidity and Suspended Sediment Transport in the Russian River Basin, California: U.S. Geological Survey Open File Report, Menlo Park, 100 p.

Robben, J., and Dent, L., 2002, BMP Compliance Monitoring Project, Final Report: Oregon Department of Forestry, Forest Practices Monitoring Program Technical Report No. 15.

Selby, M.J., 1982, Hillslope Materials and processes: *Oxford University Press, Oxford*, 264 p.

Sims, J.D., 1988, Late Quaternary Climate, *Tectonism, and Sedimentation in* Clear Lake, Northern California Coast Ranges: *in*: Sims, J.D., editor, Late Quaternary Climate, Tectonism, and *Sedimentation in* Clear Lake, Northern California Coast Ranges, Geological Society of America Special Paper 213, p.1-7.

Sloan, J. Miller, J.R., and Lancaster, N., 2001, Response and Recovery of the Eel River, California, and Its Tributaries to Floods in 1955, 1964, and 1997: Geomorphology, Elsevier, v.36, p. 129-154.

Smelser, M., 2002, Water Quality Complaint Investigation of Cloney Gulch and South Fork Freshwater Creek: California Geological Survey Memorandum to Gerald Marshall, August 26, 7 p.

Sommerfield, C.K., Drake, D.E., and Wheatcroft, R.A., 2002, *Shelf Record of Climatic Changes in* Flood Magnitude and Frequency, North-Coastal California: Geology, Geological Society of America, v. 30, no. 5, p. 395-398, May.

Sommerfield, C.K., *and Nittrouer, C.A., 1999, Modern Accumulation* Rates and a Sediment Budget for the Eel Shelf: A Flood Dominated Depositional Environment: Marine Geology, v. 154, p. 227-241.

Sommerfield, C.K., Nittrouer, C. A., and Alexander, C.R., 1999, ^7Be as a Tracer of Flood Sedimentation on the Northern California Continental Margin: Continental Shelf Research, v. 19, p. 335-361.

Sowma, J.A., 1989, Engineering Geologic Review of Timber Harvesting Plan 1-89-868 MEN: Division of Mines and Geology Memorandum to William T. Imboden, California Department of Forestry, December 29, 8 p.

Sowma, J.A., 1990, Engineering Addendum to Timber Harvesting Plan 1-89-868 MEN, Map Point S3 (Fish Rock Road): Division of Mines and Geology Memorandum to William T. Imboden, California Department of Forestry, January 5, 2 p.

Spittler, T.E., 1995, Engineering Geologic Review of Timber Harvesting Plan 1-95-256 SON: Division of Mines and Geology Memorandum to Lloyd Keefer, California Department of Forestry, July 26, 13p.

State Water Resources Control Board, 1987, Final Report of the Forest Practices Assessment Team to the State Water Resources Control Board: Sacramento, CA, 200 p.

Stillwater Sciences,1999a, Draft Jackson Demonstration State Forest HCP/SYP: Report prepared for the California Department of Forestry and Fire Protection.

Stillwater Sciences, 1999b, South Fork Eel TMDL: Sediment Source Analysis, Final Report: Prepared for Terra Tech, Inc., Fairfax, VA, August 3, 1999.

Swanston, D. N., Ziemer, R. R., and Janda, R. J., 1995, Rate and Mechanics of Progressive Hillslope Failure in the Redwood Creek Basin, Northwestern California: U.S. Geological Survey Professional Paper 1454-E, p. E1-E16.

Toppozada, T., Borchardt, G., Haydon, W., Petersen M., Olson, R., Lagorio, H. and Anvik, T., 1995, Planning Scenario in Humboldt and Del Norte Counties, California, for a Great Earthquake on the Cascadia Subduction Zone: California Division of Mines and Geology Special Publication 115, 151 p. plus Appendices.

U.S. Environmental Protection Agency, 1999, Van Duzen River and Yager Creek Total Maximum Daily Load for Sediment: December, 65 p. plus Attachment A.

U.S. Geological Survey, http://co.water.usgs.gov/sediment/

Wheatcroft, R.A., and Borgeld, J.C., 2000, Oceanic Flood Deposits on the Northern California Shelf: Large-Scale Distribution and Small-Scale Physical Properties: Continental Shelf Research, v. 20, p. 2059-2066.

Wolman, M. G., and Gerson, R., 1978, Relative Scales of Time and Effectiveness of Climate in Watershed Geomorphology: Earth Surface Processes, v. 3, p. 189-208.

Some Considerations About Monitoring Water Quality

Robert R. Ziemer, Humboldt State University, Dept. of Geology, Arcata

Abstract

A review of past efforts to monitor water quality reveals that success or failure depends on four components: monitoring design (asking the right question); making the right measurements; managing the data; and analyzing the data to answer the question. A failure of any one of these components will doom the monitoring study.

(1) Monitoring design. What is the question or hypothesis that is to be tested?

- A clear and detailed statement of the monitoring objective, including a precise description of what will be measured, where it will be measured, why it will be measured, how it will be measured, and when and how long it will be measured – including a detailed discussion of how these measurements will be used to address (solve) the stated monitoring objective.

(2) Making measurements.

- Selection of appropriate locations, instrumentation, data timing, frequency, and duration required to adequately address the objectives described in (1).
- Ability to successfully collect the appropriate data at the places and times needed.

(3) Managing data.

- Successful completion of required data collection, data validation (error checking and adjustment), and archiving.
- Adequate description of all procedures so that the data analysts can thoroughly understand the data, often years after collection.

(4) Analyzing data and drawing conclusions.

- Analysis staff has sufficient time and analytical skills to work with large and often messy data sets.
- Items (1), (2) and (3) were fully successful and allows for an analysis and final report that fully answers the objectives described in (1).
- The final report successfully addresses issues raised from rigorous external review of objectives, data, methods, analysis, and conclusions.
- There is wide-spread agreement that the monitoring objectives and results clearly meet the expectations and requirements of those, both internally and externally, responsible for judging the success or failure of the program.

Assessing Hillslope Inputs and Channel Change in Forested Watersheds

Lee H. MacDonald[1], Drew B.R. Coe[2], and N.E. Brown[3]

[1]Dept. of Forest, Rangeland, and Watershed Stewardship, Colorado State University, Fort Collins, CO 80523; leemac@cnr.colostate.edu.
[2]Forest Hydrologist, Nooksack Indian Tribe, Deming, WA 98244; dcoe@nooksack-tribe.org.
[3]Dept. of Geosciences, Colorado State University; brune@cnr.colostate.edu.

Abstract

Cumulative watershed effects (CWEs) result from multiple activities over time and space. The assessment of CWEs in the Sierra Nevada is severely limited by the lack of field data on the effects of a given action, the lack of models to predict the effects of multiple actions at the watershed scale, and the limited data relating stream channel conditions to measured or predicted changes in runoff and sediment yields. Since 1999 we have been measuring hillslope-scale sediment production rates from roads, timber harvest, wild and prescribed fires, and minimally-disturbed areas. From these and other data we are developing catchment-scale, spatially-explicit models to predict changes in discharge and sediment production from roads, fires, and timber harvest. The more difficult step in developing a reliable CWE model is to compare predicted changes in runoff and sediment production to stream channel conditions.

Channel conditions were measured in 28 pool-riffle reaches in the American and Cosumnes river basins. Contributing areas ranged from 2.9 to 70 km^2, and reach elevations ranged from 1200 to 1800 m. The basins were selected to encompass a wide range in the amount of natural and anthropogenic disturbance. The data collected for each reach included: gradient; drainage area; channel dimensions; number, depth, and size of pools; grain-size distributions in both pools and riffles; pool sediment infill; and amount of large wood. The variables used to characterize the amount of management within the contributing areas included road density, number of road crossings, modeled road sediment production, percent forest harvest by decade, and percent burned by wildfire by decade.

Drainage area, slope, and geology explained up to 50% of the variability in channel dimensions, bed-material particle size, and the amount of fine sediment in pools. After removing the effect of these variables, there were only a few significant correlations between channel characteristics and any of the management variables. There was a significant increase in the volume of fine sediment in pools and a significant decrease in the median particle size in pools with estimated road sediment production and the proportion of the basin with granitic soils. Predicted increases in the size of peak flows were not significantly correlated with any of the channel characteristics. The results indicate that: (1) management-induced increases in fine sediment are of greater concern than increases in the size of peak flows; and (2) other than large fires, unpaved roads are the most important source of fine sediment.

The limited number of significant correlations between channel characteristics and the different management indices can be attributed to a number of factors including: the lack of undisturbed basins to determine reference conditions; the complexity of factors that determine channel response; the difficulty of quantifying the magnitude of "disturbance" within a basin; the relatively low levels of recent human disturbance at the planning watershed scale; and the record flood event in early 1997. The 1997 flood may have effectively "reset" the stream channels, which makes it more difficult to detect cumulative watershed effects. The data from our work in the Sierra are compared to the results of similar studies on the Routt National Forest in Colorado and the Kootenai National Forest in northwestern Montana. Taken together, these studies indicate

that it will be a continuing challenge to establish rigorous criteria for stream channel characteristics in forested areas, and to validate predictive models for cumulative watershed effects.

References

MacDonald, L.H., and J.D. Stednick, 2003. Forests and water: a state-of-the-art review for Colorado. Colorado Water Resources Research Institute, Colorado State University, Fort Collins, CO. 65 pp.

MacDonald, L.H., D.B. Coe, and S.E. Litschert, in press. Measuring and modeling cumulative watershed effects in the Central Sierra Nevada. *Proceedings, Sierra Nevada Science Symposium*, 7-10 October, Lake Tahoe, CA. USFS PSW Tech. Report, approx. 8 pp. Available at: www.colostate.edu/frws/faculty/macdonald/publications.htm.

MacDonald, L.H., and S.L. Litschert, 2003. Delta-Q: a computer program for calculating changes in flow from forest management activities. Available at: www.colostate.edu/frws/faculty/macdonald/model.htm.

Montgomery, D.A, and L.H. MacDonald, 2002*. Diagnostic approach to stream channel assessment and monitoring. *Journal of the American Water Resources Association* 38(1):1-16.

Loftis, J.C., L.H. MacDonald, S. Streett, H.K. Iyer, and K. Bunte, 2001*. Detecting cumulative effects: the power of pairing. *Journal of Hydrology* 251: 49-64.

MacDonald, L.H., 2000*. Evaluating and managing cumulative effects: process and constraints. *Environmental Management* 26(3): 299-315.

Bunte, K., and L.H. MacDonald, 1999. Scale considerations and the detectability of sedimentary cumulative watershed effects. Technical Bulletin No. 776, National Council for Air and Stream Improvement, Research Triangle Park, NC. 327 pp.

Schnackenberg, E.S., and L.H. MacDonald, 1998*. Detecting cumulative effects in headwater streams on the Routt National Forest, Colorado. *Journal of American Water Resources Association* 34(5): 1163-1177.

MacDonald, L.H. E.E. Wohl, and S.W. Madsen, 1997. Validation of water yield thresholds on the Kootenai National Forest. Kootenai National Forest, Libby, Montana. 197 pp. plus app.

MacDonald, L.H. (with A. Smart and R.C. Wissmar), 1991. Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA/910/9-91-001, U.S. Environmental Protection Agency Region 10, Seattle, WA. 166 pp.

Reference (2) of 5

The Dynamic World of Mountain Drainage Basins

Dr. Lee Benda, Earth Systems Institute, Seattle, WA/Mt. Shasta, California

Abstract

Sediment budgets constructed in both managed and unmanaged mountain drainage basins across western United States and Canada using field surveys, aerial photography, simulation modeling, and radiocarbon and cosmogenic dating *all* point to mass wasting as being a very significant if not dominant source of sediment to streams and rivers (i.e., 40 to 80%). Moreover, wood budgets constructed primarily in California in both managed and unmanaged mountain drainage basins also have shown that streamside landslides and debris flows can contribute the majority of wood to streams along certain segments. The importance of mass wasting, including landslides, debris flows, earthflows, and flash flood-related gully erosion, stems from the mixture of steep topography, fire-prone vegetation, intense and/or prolonged precipitation, and often mechanically weak lithologies.

To help define the dynamic world of erosion and sediment supply to streams, it is helpful to consider the frequency and magnitude characteristics of both sediment supply and transport and its variation within watersheds. For instance, radiocarbon dating of charcoal in soil indicates that the frequency of shallow

landslides in convergent topography (i.e., swales or bedrock hollows) is on the order of several thousand years (500 to 6000 yrs). The frequency of debris flows in 1st and 2nd order channels has been estimated to range from a few hundred years to a few thousand years. Hence, the occurrence of landslides and debris flows are relatively rare at the scale of individual sites. However, watersheds contain thousands of natural landslide sites and hundreds of debris flow- or gully-prone headwater channels. At the scale of entire watersheds, landslides and debris flows are guaranteed to occur almost every year, even in unmanaged basins. Moreover, during years with large storms or fires, hundreds of landslides and debris flows can be triggered within a single, modest size watershed (order of hundreds of square kilometers).

The characteristic punctuated supply of sediment to streams by mass wasting, subsidized by flood-induced bank erosion, promotes a high degree of spatial and temporal variability in sediment transport, including bedload, suspended load, and turbidity. In addition, storage of sediment in bars, floodplains, terraces, and behind logjams creates lag times (years to decades) that complicate tracking sediment supply from hillslopes to its movement downstream in river networks. Consequently, water quality monitoring aimed at deciphering cause and effect linkages between specific land use practices and sediment transport levels should anticipate difficulties. The same holds true for efforts aimed at estimating natural background levels of erosion or sediment transport. Simulation models of watershed erosion suggest that the most appropriate measure of erosion rates is the probability distribution and measurement times needed to estimate it may range from a few centuries in headwater areas to many decades lower in networks. Because of the inherent inaccuracies involved in measuring a stochastic process, such as erosion or sediment transport (i.e., +/- 100s %), it could be argued that a more contextual and qualitative approach might be better suited to understand the dynamic world of mountain drainage basins.

The Side-Effects of Road Decommissioning: A Bitter Pill or No Big Deal?

Randy Klein, Redwood National & State Parks, Arcata

Abstract

Road decommissioning has become a common practice over the past decade as the sedimentation threats of poorly designed or maintained roads to downstream resources have become more widely recognized. While road decommissioning reduces the long-term erosional risks from forest roads, short-term erosional responses from stream crossing excavations can occur in the form of surface erosion, rilling, and gullying, channel scour, and minor slumping within excavations. Typically, most erosion and sediment delivery occurs within the first several years following excavation, and diminishes through time as vegetation grows on excavation side slopes and channels find stable grades and armor themselves with rock lag deposits and woody debris.

This presentation describes two projects designed to quantify the effects of stream crossing excavation on sediment delivery and water quality (turbidity): one in the Upper Mattole River for the Sanctuary Forest, Inc. (SFI), and another in Lost Man Creek within Redwood National and State Parks (RNSP). Study objectives in both cases were: 1) to quantify sediment delivery and effects on water quality following excavation stream crossings, and 2) to determine the need for and nature of any modifications to the style or rate of excavations that may be warranted to reduce and/or spread impacts over a longer time period.

Upstream/downstream sample pairs from both studies showed that turbidity increases within recently excavated stream crossings can be very large at times, and negligible at others. In addition, off site samples taken in a pair basin approach indicated elevated turbidity from basins with numerous stream crossing excavations compared to nearby basins where no road decommissioning took place, however, these increases were much smaller than with onsite samples. Also, in both studies, turbidity increases within crossings diminished through the winter runoff season, a phenomenon most likely due to "initial flushing" of easily eroded sediment.

In the Upper Mattole study, post-winter erosion/sediment delivery voids were also measured at a sample of 13 stream crossing excavations. Average sediment delivery was 15.5 cubic yards (cy) and ranged from a few cy to over fifty (this was a case of head cutting upstream from the excavation). To put this number in perspective, the estimated pre-treatment sediment delivery "potential" for 174 stream crossings in the area (from a widely-used road inventory methodology) was 110 cy per stream crossing. Thus, the measured post-treatment sediment delivery was 14% of estimated pre-treatment sediment delivery potential. And, as indicated by recent research, longer term sediment delivery from stream crossing excavations can approach twice that of first-year delivery, so post-treatment delivery may approach 28% of pre-treatment delivery potential.

While some level of post-treatment erosion must be viewed as a worthwhile trade-off between smaller short-term impacts and larger long-term impacts that would result without treatment, cost-effective measures are available to reduce post-treatment sediment delivery. Recommendations are given for reducing the potential for post-treatment erosion and sediment delivery so that the "side effects" of road decommissioning remain small relative to the benefits of the treatment.

Scales of Variability in Monitoring Changes in Channel Morphology

Mary Ann Madej, US Geological Survey, Western Ecological Research Center, Arcata

Abstract

Land managers are frequently concerned with the impact of increased sediment or changes in flow regime in stream channels. The effect of sediment input on channels is a function of the volume, particle size and timing of input as well as channel characteristics. Commonly, there is a progression of change, from changes in the suspended sediment relationships, to substrate changes, to channel geometry changes, to valley-wide channel pattern changes. This paper will focus on changes in channel morphology (width, depth, bed elevations, pool distributions, etc.).

Stream channel can change over several spatial and temporal scales, and channel monitoring results must be interpreted according to the appropriate scale. For example, a tree falling in a stream may cause localized scour of a pool and significant change in that cross-sectional transect, but the change may not be significant in terms of the channel reach scale. In contrast, a dispersed disturbance such as a wildfire can contribute a large volume of fine-grained sediment that fills in spaces among gravels and boulders but may not cause changes in channel width or depth.

A geomorphic change is initiated by some perturbation of the system (an increase or decrease in flow, sediment or wood, for example). The perturbation may be instantaneous (acute) or chronic (persisting over a long time). The system may change instantaneously, or exhibit a long lag time. Finally, the time it takes for a channel to recover also varies, and depends on the nature and size of the perturbation and the characteristics of the particular system. For example, some gravel-bed channels shift each year under moderate flow conditions, whereas other channels show little change until a high flow threshold is exceeded.

Important characteristics of channel change to consider are: the type, magnitude and frequency of change, its spatial distribution, the timing, duration and persistence of change, the range of variability and sources of variability. Even monitoring a single process may be approached differently by investigators. For example, geomorphologists may focus on the <u>magnitude</u> of change (depth of scour in a gravel channel), whereas a biologist may be more interested in the <u>timing</u> of change (are there salmon eggs present when scour occurs?) Although we can define statistical significance of channel change, defining the biological significance of a given change is more problematic.

References

My presentation is based on results from many studies. More complete explanations of the methods, analysis and results are given in the following:

Lisle, T. E., J. M. Nelson, J. Pitlick, M. A. Madej, and B. L. Barkett. 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. Water Resources Research. Vol. 36 No. 12, p. 3743-3755.

Lisle, T.E. and M.A. Madej. 1992. Spatial variation in armouring in a channel with high sediment supply. pp. 277-296 in Dynamics of Gravel-bed Rivers, P. Billi, R.D. Hey, C.R. Thorne, and P. Tacconi, eds. John Wiley and Sons, Inc. 673 pp.

Madej, M. A. 2001. Erosion and sediment delivery following removal of forest roads. Earth Surface Processes and Landforms. Vol. 26, No. 2, pp.175-190.

Madej, M. A., B. Barr, T. Curren, A. Bloom, and G. Gibbs. 2000. Effectiveness of road restoration in reducing sediment loads. Final Report. California Department of Fish and Game Agreement No. FG7354IF. 72 p. plus appendices. (See http://www.werc.usgs.gov/redwood/restoration.htm for entire data set and report (includes data forms used to monitor erosion on decommissioned roads)

Madej, M. A. 1999. A brief overview of channel monitoring in land management: Case Study #2. p. 70-77. In Using stream geomorphic characteristics as a long-term monitoring tool to assess watershed function. Proceedings of a workshop held March 18-19, 1999. Arcata, CA., R. N. Taylor. ed. 109 p.

Madej, M. A. 1999. Time, space and rates of change in channel monitoring. p. 15-27 In Using stream geomorphic characteristics as a long-term monitoring tool to assess watershed function. Proceedings of a workshop held March18-19, 1999. Arcata, CA., R. N. Taylor. ed. 109 p.

Madej, M.A. 1999. Temporal and spatial variability in thalweg profiles of a gravel bed river. Earth Surface Processes and Landforms. Vol. 24, p. 1153-1169.

Madej, M. A. 1999. What Can Thalweg Profiles Tell Us? A Case Study from Redwood Creek, California. Watershed Management Council Networker. Vol. 8 No. 4.

Madej, M.A. 1996. Measures of stream recovery after watershed restoration. p. 47-56 in Proceedings on Watershed Restoration Management: Physical, Chemical and Biological Considerations. J. J. McDonnell, J. B. Stribling, L.R. Neville, and D.J. Leopold, eds. American Water Resources Association. Syracuse, New York. 524 pp.

Madej, M.A. 1995. Changes in channel-stored sediment, Redwood Creek, Northwestern California, 1947-1980. Chapter O in U.S. Geological Survey Professional Paper 1454. Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K.M. Nolan, H.M. Kelsey, and D.C. Marron, eds.

Madej, M.A. 1987. Residence times of channel-stored sediment in Redwood Creek, northwestern California. pp. 429-438. In: R.L. Beschta, et al. (eds.) Erosion and Sedimentation in the Pacific Rim. Corvallis, Oregon. August 1987. International Association of Hydrological Sciences Publication No. 165. 510 pp.

Madej, M.A. and V. Ozaki. 1996 . Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms. Vol. 21, pp. 911-927.

Madej, M.A., W.E. Weaver, and D.K. Hagans. 1994. Analysis of bank erosion on the Merced River, Yosemite Valley, Yosemite National Park, California, USA. Environmental Management Vol. 18, No. 2, pp. 235-250.

Taylor, R. N. ed., 1999. Using stream geomorphic characteristics as a long-term monitoring tool to assess watershed function. Proceedings of a workshop held March 18-19, 1999. Arcata, CA., 109 p.

Sensitivity of Macroinvertebrate Metrics and Community Indices to Experimental Forest Harvest

Morgan Hannaford, Shasta College, Biology Dept., Redding

Abstract

Benthic macroinvertebrates are the most popular water quality indicator assemblage in streams. Benthic Macroinvertebrate Indices (BMI's) are used to describe a wide range of pollutants and habitat degradation. Because most BMI's were developed to identify in-stream organic pollution, their application for monitoring the health of upland environments, is tenuous. Five commonly used indices (related to taxa richness, EPT, and a biotic index) failed to discriminate between treatment and control reaches in two separate experimental harvests in Northern California. Species assemblage differences are identifiable using multivariate analysis; however, interpretation of observed multivariate result patterns is subjective and cannot be directly associated with habitat degradation.

References

Allan, J. D. 1995. Stream Ecology: structure and function of running waters. Chapman & Hall, London.

Metcalfe-Smith, J. L., 1994. Biological water-quality assessments of rivers: use of macroinvertebrate communities. Pgs. 144-169 in P. Calow, and G.E. Petts (eds). The Rivers Handbook Vol II, Blackwell Scientific Publications, London.

Resh, V. H., R. H. Norris, and M. T. Barbour. 1995. Design and implementation of rapid assessment approaches for water resource monitoring using benthic macroinvertebrates. Australian Journal of Ecology 20:108-121.

Rosenberg, D. M., and V. H. Resh. 1993. (eds) Freshwater Biomonitoring and Benthic Macroinvertebrates. Chapman and Hall, New York.

Wright, J. F., D. Moss, P. D. Armitage, and M. T. Furse. 1984. A preliminary classification of running water sites in Great Britain based on macroinvertebrate species and prediction of community type using environmental data. Freshwater Biology 14:221-256.

Development of the Forest Service PSW Regional Bioassessment Program: Results From Models Based on Multivariate RIVPACS and Multimetric Index of Biotic Integrity Methodologies

Joseph Furnish, USDA FS, Pacific Southwest Region, Vallejo

Abstract

The Clean Water Act (CWA) mandates the development of programs to "evaluate, maintain and restore the physical, chemical and biological integrity" of the nation's waters, yet the standard for biological integrity has not yet been systematically defined for the State of California. At present there are two basic methods for defining biological integrity: 1) the multi-metric based Benthic Index of Biotic Integrity (B-IBI) approach and 2) the multivariate, predictive model approach known as RIVPACS (River InVertebrate Prediction And Classification System). The US Forest Service is actively pursuing the use of both techniques for monitoring water quality to support many of its programs and activities. These include Best Management Practices (BMP) effectiveness monitoring, condition and trend monitoring mandated by Forest Service Land and Resource Management Plans, and the CWA Total Maximum Daily Load (TMDL) program.

A multi-metric Index of Biotic Integrity (Benthic-IBI) for coastal Southern California was prepared under contract with California Department of Fish & Game's Water Pollution Control Laboratory. Landscape disturbance within the watersheds sampled was characterized using Analytical Tools Interface for Landscape Assessments (ATILA) and histograms of disturbance attributes were examined to determine ranges for reference vs. test (disturbed) conditions. IBI metrics were chosen based on whether values showed a clear dose-response relationship with watershed disturbance. A total of seven metrics met the desired criteria: % collector-filterers and collector-gatherers, % non-insect taxa, % tolerant taxa, *Coleoptera* taxa, predator taxa, % intolerant individuals and number of EPT taxa.

During 2000, 174 sites were sampled on National Forest lands throughout the Pacific Southwest Region. During 2002, data available from 136 reference sites were used to prepare a RIVPACS predictive model. Discriminant functions analysis showed that variation in composition of macroinvertebrate assemblages was related to nine environmental factors (latitude, longitude, log conductivity, log watershed area, channel substrate size from 128-180 mm, log channel gradient, log mean water depth, mean watershed elevation and log sample date). Model performance can be expressed in terms of accuracy and precision. The model was accurate (i.e., slope of the regression of O/E was not different from 1, P>0.05) and moderately precise (r^2 = 0.57). Model error can be expressed as variation in the O/E ratio for reference site scores (SD = 0.19). The most precise RIVPACS models have standard deviations of about 0.15, so this model is slightly less precise than the best models. A second-generation model is under development based on data that are now available from 260 sites for the 2001 field season.

References

Barbour, M.T., J. Gerritsen, B.D. Snyder and J.B. Stribling. 1999. *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish,* Second Edition. EPA 481-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Barbour, M.T. and C. Hill. 2002. *The Status and Future of Biological Assessment for California Streams.* Prepared under contract by Tetra Tech, Inc. Owings Mills, MD. for the California State Water Resources Control Board. 42 pp. + Appendices.

Ebert, D.W. and J.E. Harrison. 2002. Analytical Tools Interface for Landscape Assessments (ATtILA), Version 3.0. US EPA, Office of Research and Development.

Hawkins, C.P. and D.M. Carlisle. 2001. Use of predictive models for assessing the biological integrity of wetlands and other aquatic habitats. pp. 59-83, *In* R.B. Rader, D.P Batzer and S.A. Wissinger [eds] *Bioassessment and Management of North American Freshwater Wetlands.* John Wiley and Sons, Inc. New York.

Hawkins, C.P., R.H. Norris, J.N. and J.M. Feminella. 2000. Development and evaluation of predictive models for measuring the biological integrity of streams. Ecological Applications 10: 1456-1477.

Hawkins, C.P., J. Ostermiller and M. Vinson. 2001. Stream invertebrate, periphyton and environmental sampling associated with biological water quality assessments. Field Protocols. Utah State University, Logan. (See http://www.usu.edu/buglab/monitor/sampling.html)

Lazorchak, J.M., D.J. Klemm and D.V. Peck. 1998. *Environmental Monitoring and Assessment Program-Surface Waters: Field Operations and Methods for Measuring the Ecological Conditon of Wadeable Streams.* Office of Research and Development, Research Triangle Park, North Carolina. EPA/620/R-94/004F. Available from http://www.epa.gov/emap/html/pubs/docs/groupdocs/surfwatr/field/Sec01.PDF.

Hughes, R.M. 1995. Defining acceptable biological status by comparing with reference conditions. pp. 31-47, *In* W.S. Davies and T.P. Simon (eds) *Biological Assessment and Criteria: Tools for Water Resource Planning and Decision Making.* Lewis Publishers, Ann Arbor.

Hughes, R.M., P.R. Kaufmann, A.T. Herlihy, T.M. Kincaid, L. Reynolds, and D.P. Larsen. 1998. A process for developing and evaluating indices of fish assemblage integrity. Canadian Journal of Fisheries and Aquatic Sciences 55: 1618-1631.

Karr, J.R. and E.W. Chu. 1999. Restoring Life in Running Waters - Better Biological Monitoring. Island Press, Covelo, CA.

Monitoring Fish Habitat Conditions

Gordon Reeves, USDA FS PNW Research Station, Corvallis, Oregon

Abstract

Much time and money is devoted to programs that monitor changes in fish habitat conditions. The programs generally evaluate changes associated with a specific action or activity, such as a timber sale, or they are concerned with changes in habitat features over a large area. In the former case, intensive efforts are expended to measure selected habitat features, which are assumed to be associated with or indicators of the condition fish populations. Evaluation of effects is generally made either by: (1) comparing the quantities of a feature before and after an action; or (2) comparison of the parameter in the treated area to the value in control area in a "pristine" system. In either case, a change from existing conditions or changed compared to the control is generally judged to be bad. An underlying but seldom recognized or appreciated assumption behind this approach is that aquatic systems are relatively static over time and that all systems and conditions within them should be similar at any point in time. These assumptions are being challenged by another emerging view that believes aquatic ecosystems are dynamic in space and time. Thus, the validity of previous approaches must be examined.

The movement to ecosystem/watershed and landscape management also confounds the issue of monitoring fish habitat. Each spatial scale has an appropriate temporal scale in which it should be viewed and a set of associated principles under which it operates. For example, the expected variation in conditions that may be observed at a small scale is greater than the variation at a large scale. Understanding the relationship between different spatial scales and integrating this knowledge into management activities at these various scales is imperative to successfully assess the effects of management policies for aquatic ecosystems in the future. The failure to articulate or to recognize this relationship contributes to the often intense and divisive debate about management policies and practices and impedes the development of viable options for managing aquatic ecosystems. Shifting the focus to ecosystems and landscape levels requires the recognition of the principles about hierarchy theory and the relation among levels of organization if future management and assessment policies are to be successful.

References

Benda, L.E. 1994. Stochastic geomorphology in a humid landscape. Ph.D. dissertation. University of Washington, Seattle, Washington.

Benda, L.E., D.J. Miller, T. Dunne, G.H. Reeves, and J.K. Agee. 1998. Dynamic landscape systems. Pages 261-288. *in* R.J. Naiman and R.E. Bilby, editors. River ecology and management: lessons from the Pacific Coastal ecoregion. Springer, New York.

May, C. 2001. Spatial and temporal dynamics of sediment and wood in headwater streams in the central Oregon Coast Range. Ph.D. dissertation. Oregon State University, Corvallis, Oregon.

O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A hierarchical concept of ecosystems. Monographs in Population Biology 23. Princeton University Press, Princeton, New Jersey.

Overton, W.S. 1977. A strategy for model construction. Pages 50-73. *in* C.A.S. Hall and J.W. Day, editors. Ecosystem modeling in theory and practice: an introduction with case histories. John Wiley and Sons, New York.

Reeves, G.H., K.M. Burnett, and S.V. Gregory. 2002. Fish and aquatic ecosystems in the Oregon Coast Range. Pages 68-98. *in* Hobbs, S.D., J.P. Hayes, R.L. Johnson, G.H. Reeves, T.A. Spies, J.C. Tappeiner II, and G.E. Wells, editors. Forest and stream management in the Oregon Coast Range. OSU Press, Corvallis, Oregon.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturburnce-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. *in* J. Nielsen, editor. Evolution in the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society Symposium 17. Bethesda, Maryland.

Wimberly, M.C., T.A. Spies, C.J. Long, and C. Whitlock. 2000. Simulating historical variability in the Oregon Coast Range. Conservation Biology 14: 167-180.

Small Stream Ecosystem Variability in the Southern Sierra Nevada

Dr. Carolyn T. Hunsaker, USDA FS, PSW Research Station

Abstract

The quality of aquatic and riparian ecosystems is a function of their condition and the integrity of adjacent uplands in their watershed. While small streams make up a large proportion of the overall stream network, our knowledge of how they function is still limited. The Kings River Experimental Watershed (KREW) was initiated in 2000 to quantify the variability in characteristics of small stream ecosystems and their associated watersheds in the Sierra Nevada of California. The primary management questions to be answered are the effects of prescribed fire and mechanical harvest on the riparian and stream physical, chemical, and biological conditions.

Two mixed-conifer sites are being developed on the Sierra National Forest. Data will be gathered for at least a 4-year reference period that started October 1, 2002. After fire and harvest treatments are applied, data will be gathered for at least five to seven years. Each site will have a control watershed that receives no treatments, a watershed that is burned, a watershed that is harvested, and a watershed that is both burned and harvested. The goal is to assess the integrated condition of the streams and their associated riparian and watershed areas (i.e., physical, chemical, and biological characteristics). The watersheds range in size from 49 to 228 hectares (120 to 562 acres); a size that can be consistently treated.

KREW is designed to be a collaborative research study area, and additional components can be added now during the early part of the pre-treatment period. Current collaborators include: University of Nevada, Reno; University of California, Santa Barbara; California State University, Fresno; Colorado State University, Ft. Collins; and U.S. Geological Survey, NAWQA in Sacramento, and Fire and Fire Surrogate Study in Kings Canyon National Park.

References

Hanson, C.L., D. Marks, and S.S. Van Vactor. 2001. Long-term climate database, Reynolds Creek Experimental Watershed, Idaho, United States. Water Resources Research 37:289-2841.

Harrelson, C.C., C.L. Rawlins, and J.P. Potyondy. 1994. Stream channel reference sites: An illustrated guide to field technique. U.S. Department of Agriculture, Forest Service General Technical Report RM-245. Fort Collins, Colorado.

Karr, J.R. 1998. Rivers as sentinels: Using the biology of rivers to guide landscape management. *In* R.J. Naiman, and R.E. Bilby, eds., River Ecology and Management, Lessons from the Pacific Coastal Ecoregion, pp. 502-528. Springer-Verlag, New York.

Naiman, R.J., and R.E. Bilby. 1998. River ecology and management in the Pacific Coastal Ecoregion. *In* R.J. Naiman and R.E. Bilby, eds., River Ecology and Management, Lessons from the Pacific Coastal Ecoregion, pp. 1-10. Springer-Verlag, New York.

Susfolk, R.B., and D.W. Johnson. 2002. Ion Exchange Resin Based Soil Solution Lysimeters and Snowmelt Solution Collectors. Community Soil Science Plant Analysis 33:1261-1275.

University of California, Davis. 1966. Summary of the Sierra Nevada Ecosystem Project. Centers for Water and Wildland Resources.

USDA Forest Service. 2001. Sierra Nevada Forest Plan Amendment: Final Environmental Impact Statement. USDA Forest Service, Pacific Southwest Region, Vallejo, California.

Stream Temperature Profiles and How They Relate to Logging Prescriptions

Cajun James, Sierra Pacific Industries, Redding

Abstract

Streams and riparian zones play an essential role in the structure and function of many ecological processes in forest landscapes. These ecosystems are dynamic environments that increase landscape connectivity, protect water quality, and support a high diversity of plant and animal species adapted to disturbance regimes over broad spatial and temporal scales. As streams and riparian zones are subject to disturbances that originate in adjacent upland forested areas, concerns about the impact of timber harvest operations on the long-term sustainability of riparian resources exist. Upland disturbances, such as logging, may result in changes in the biological, chemical, and physical properties of streams and riparian zones. As a result of timber harvest operations, aquatic ecosystems may be exposed to higher levels of light, and increased water temperature.

One method commonly used to reduce or eliminate logging impacts on streams and riparian zones is to maintain vegetative buffers along the stream bank that extend out into adjacent upland forest areas where timber harvest operations take place. Buffer strips are bounded on one side by a stream and on the other side by a timber harvest unit, thereby forming a transition or protective zone between the aquatic environment and the upland terrestrial forest environment that ameliorates the potential impacts of timber harvest operations.

Prior research has concluded that buffered streams and adjacent riparian zones have higher ecological function, greater biological diversity, better water quality, and will be better suited for the long-term sustainability of riparian landscapes than unbuffered streams. Review of previous research on stream and riparian zones has shown that vegetative buffers ranging from 10 ft. to 600 ft. in width are effective in protecting wetlands and streams under most conditions.

The practice of leaving riparian buffers along headwaters streams in forest landscapes has been recommended since the 1960s and is currently recommended in California on federal, state, and private lands. Streamside buffers have been legally mandated in the state of California since 1973, and the U.S. Forest Service's Forest Ecosystem Management Assessment Team (FEMAT) has standardized the practice on federal lands since 1993. Regulations guiding minimum buffer widths are usually based on some combination of stream conditions, fish-bearing characteristics, stream flow, and topography (slope).

As buffer strips are considered critical to the ecological structure, function, and long-term sustainability of stream and riparian zones adjacent to upland timber harvesting areas, there are many questions regarding their effectiveness. Since the late 1960s, scientists, regulators, and forest managers have sought to determine appropriate buffer widths and related characteristics for adequate protection of environmental resources. In forest landscapes managed for timber production, overprotection can result in economic loss, while under protection may reduce the ecological function and long-term sustainability of vital aquatic ecosystems. In a regulated environment, balancing adequate environmental protection vs. economic costs to the landowner is important to maintain effective public support.

This presentation will include information on appropriate methods of experimental design for water temperature studies, sampling frequency, measurement precision of various water temperature sensors and canopy cover measuring devices, sensor configurations for field applications, recommendations for sensor deployment in field conditions, the use of predictive water temperature models, a discussion on statistical significance and biological significance, and recommendations for future research and monitoring projects. These results are based on three long-term case studies (Millseat Creek, Bailey Creek, Judd Creek)

This presentation describes three case studies all designed to assess whether or not different riparian buffer widths adjacent to upland timber harvest units provide adequate protection to stream and riparian ecosystems. The three studies discussed today examine the effects of four riparian buffer widths on shade-producing canopy cover, and the temperature of stream water in both single and multiple clearcut harvest units adjacent to fish bearing (Class I) streams in Northern California. Data collected before and after timber harvest operations in years 1999, 2000, 2001, 2002 and 2003 was analyzed to determine changes in response variables to wider (175 ft.) or narrower (50 ft.) riparian buffers. Angular canopy cover was measured to be >85% at mid-stream and no less than 80% within the riparian buffer regardless of buffer width at all three study sites. Vertical canopy cover was measured to be 50% within the riparian buffer for each harvest unit following the timber operations. Changes in the water temperature patterns along each of the three experimental reaches differed at most only ±1.0 °C before and after timber harvest operations. The weekly maximum water temperature never exceeded 22.5 °C before or after harvest throughout any of the study areas.

These research projects occurred in California and all were subject to the California Forest Practice Rules (CFPR). Therefore, these studies examine not only the effectiveness of riparian buffers of different widths (50 ft., 75ft., 100 ft., and 175 ft.), but also evaluate whether or not the riparian buffer widths stipulated under the CFPR provide adequate protection to riparian ecosystems.

Water temperature results from these studies are consistent with previous research that concluded forested buffer strips either maintain stable water temperature patterns or sustain only minimal increases in daily maximum water temperatures (< 2 °C) after upslope timber harvesting. In this experiment, no practical differences in the shade-producing canopy cover or water temperature patterns were found between the wider 175-ft. and the narrower 50-ft. buffers. The lack of change in response variables was likely due to the very small measurable reduction in shade-producing canopy cover mid-stream and within the riparian buffer. In addition, the scale of these projects (1-3 clearcut units of 30-40 acre blocks interspersed with like sized unharvested blocks as mandated by the CFPR) was not large enough to clearly sort out logging effects from measuring device precision and uncontrollable climatic induced effects. Only minimal changes in the water temperature occurred despite the fact that 35% of the merchantable tree volume within the riparian buffer was removed during timber harvest operations in all three locations. Results from these studies show that 175-ft., 100-ft., 75-ft. or 50-ft., vegetative buffers that maintain at least 50% vertical or 80% angular canopy cover minimize potential negative impacts to the temperature of stream water from adjacent upslope clearcut harvest operations.

References

Beschta, R. L., R. E. Bilby, et al. (1987). Stream temperature and aquatic habitat: fisheries and forestry interactions. Streamside Management: Forestry and Fisheries Interactions:. E. O. Salo and T. W. Cundy. Seattle, Washington, Contribution No. 57, University of Washington, Institute of Forest Resources. 57.

Bottorff, R. L., and K. A. W. (1996). The Effects of Clearcut Logging on the Stream Biology of the North Fork of Casper Creek, Jackson Demonstration State Forest, Fort Bragg, CA: 1989-1994. Davis, California, California Department of Forestry and Fire Protection: 177.

Brazier, J. R., and G. W. Brown (1973). "Buffer strips for stream temperature control." Research Paper 15, Forest Research Laboratory.

Brown, G. W. (1969). "Predicting temperatures of small streams." Water Resources Research 5(1): 68-75.

Brown, G. W. (1970). "Predicting the effect of clearcutting on stream temperature." Journal of Soil and Water Conservation 25: 11-13.

Brown, G. W., and J. T. Krygier (1970). "Effects of clearcutting on stream temperature." Water Resources Research 6(4): 1133-1139.

Brown, G. W., G. W. Swank, et al. (1971). Water temperature in the Steamboat drainage. Portland, OR, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station: 17.

Brown, T. C., and D. Binkley (1993). "Laws and Programs for Contolling Nonpoint Source Pollution in Forest Areas." 1-13.

Brown, T. C., and D. Binkley (1994). Effect of management on water quality in North American forests. Fort Collins, CO, USDA Forest Service, General Technical Report, RM-248.

Cafferata, P. (1990). "Temperature regimes of small streams along the Mendocino coast." JDSF Newsletter: Jackson Demonstration State Forest No. 39: 4.

Cafferata, P. H. (1990). Watercourse Temperature Evaluation Guide, California Department of Forestry and Fire Protection.

Castelle, A. J., A. W. Johnson, et al. (1994). "Wetland and stream buffer size requirements-a review." Journal of Environmental Quality 23: 878-882.

Delay, W. H., and J. Seaders (1966). "Predicting temperatures in rivers and reservoirs." Proc. Am.Soc Civil Eng., J. San Eng. Div. 92: 115-134.

Feller, M. C. (1981). "Effects of clearcutting and slashburning on stream temperature in southwestern British Columbia." Water Resources Bulletin 17(5): 863-867.

James, C. (2003). "Southern Exposure Research Project: A Study Evaluating the Effectiveness of Riparian Buffers in Minimizing Impacts of Clearcut Timber Harvest Operations on Shade-Producing Canopy Cover, Microclimate, and Water Temperature along a Headwater Stream in Northern California" PhD. Dissertation, College of Natural Resources, University of California at Berkeley.

Levno, A., and J. Rothacher (1967). Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. Forest and Range Experiment Station, Portland, Oregon, USDA Forest Service.

McGurk, B. J. (1989). Predicting stream temperature after riparian vegetation removal. Berkeley, CA, USDA Forest Service Pacific Southwest Forest and Range Experiment Station: 157-164.

Naiman, R. J., and H. Decamps (1997). "The ecology of interfaces: riparian zones." Annual Review of Ecology and Systemantics 28: 621-658.

Patton, D. R. (1973). A literature review of timber harvesting effects on stream temperature. Ft. Collins, Colorado, Rocky Mountain Forest and Range Experiment Station, USDA Forest Service: 4.

Poole, G., J. Risley, et al. (2001). Issue Paper 3: Spatial and Temporal Patterns of Stream Temperature (Revised). Prepared as part of EPA Region 10 temperature water quality criteria guidance development project, US EPA, USGS, Washington Dept. of Ecology: 33.

Rishel, G. B., J. A. Lynch, et al. (1982). "Seasonal stream temperature changes following forest harvesting." Journal of Environmental Quality 11(1): 112-116.

Robards, T. A., M. W. Berbach, et al. (2000). "A comparision of Techniques for Measuring Canopy in Watercourse and Lake Protection Zones." California Forestry Notes June 2000(No. 115).

Salo, E. O., and T. W. Cundy (1987). Streamside Management: Forestry and fishery interactions. Seattle, Washington, Institute of Forest Resources, University of Washington.

Sinokrot, B. A., and H. G. Stefan (1992). Determine modeling of stream water temperatures: Development and application to climate change effects on fish habitat. Minneapolis, MN, St. Anthony Falls Hydraul. Lab.

Steinblums, I. J., H. A. Froehlich, et al. (1984). "Designing Stable Buffer Strips for Stream Protection." Journal of Forestry 82: 49-52.

Sullivan, K., J. Tooley, et al. (1990). Evaluation of prediction models and characterization of stream temperature regimes in Washington. Olympia, Washington Department Natural Resources: 224.

Swift, L. W. J., and S. E. Baker (1973). Lower water temperatures within a streamside buffer strip, USDA Forest Service, Research Note, SE-193.

Zwieniecki, M. A., and M. Newton (1999). "Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon." Western Journal of Applied Forestry 14(2): 106-113.

MONITORING TURBIDITY

Limitations of Turbidity Measurements in Water Quality Monitoring

Rand Eads, USDA FS PSW Research Station, Redwood Sciences Lab, Arcata

Abstract

The monitoring of turbidity in rivers has increased in recent years, partly due to the improvement in sensor technology, and because turbidity measurements are often required to comply with water quality regulations. Because turbidity is now reasonably easy to measure, comparisons of turbidity measurements from rivers and streams that are physically dissimilar are often made without understanding the measurement limitations.

Turbidity is an optical property of water defined as a decrease in transparency due to the presence of suspended or dissolved substances that cause the incident light to be scattered, reflected, or attenuated. Turbidity is not a direct measure of suspended sediment. Several factors control how a sensor responds to changes in turbidity. A sensor's optical geometry refers to the angle between the transmitted and received light. Nephelometric sensors typically emit infrared radiation and detect scattered light at an angle between 90 and 160 degrees. Transmissometers measure attenuated light as it travels in a straight line. Laboratory meters often use a combination of methods that are ratio-metric. Each optical configuration is likely to report a different turbidity value for a given stream sample and differences of 50 to 100 percent can be expected. The volume of water-sediment mixture viewed by the optics will affect the measurement variability. A large sample volume reduces variance but increases the chance of viewing nearby objects. Manufacturers are now aiming for a sample volume about the size of a tennis ball. Sensor or data logger software that uses the median value of multiple turbidity readings is more effective at rejecting outlier values when floating debris enters the optical viewing area than either a single point or mean measurement. Mounting the sensor in a protective housing that is attached to an articulating boom positions the sensor in the channel and reduces damage from impacts and fouling from debris. Changes in the characteristics of suspended particles, especially size, color, and shape, in addition to the influences of optical fouling, the entrainment of air bubbles, and the fine organics, can have profound effects on turbidity measurements. For instance, in laboratory testing using a backscatter sensor, fine particles produce about a 15-fold increase in turbidity response when compared to sand particles of the same concentration. Although particle size variations during a storm event would not be expected to produce this extreme response, a number of studies document temporal variation in suspended sediment.

If SSC samples are not collected during storm events, it is often impossible to determine if the turbidity response is valid and any references to SSC are meaningless. An automated method for driving sediment

sample collection, called Turbidity Threshold Sampling (TTS), relies on turbidity as a real-time surrogate for SSC. Samples are collected under data logger control when pre-defined turbidity thresholds are detected. The relations between SSC and turbidity are often very good and allow for an accurate and nearly continuous record of estimated SSC during the sampled period.

References

Davies-Colley, R. J. and D. G. Smith (2001). Turbidity, suspended sediment, and water clarity: a review. Journal of the American Water Resources Association **37**(5): 1085-1100.

Eads, Rand, and Jack Lewis. 2002. Continuous turbidity monitoring in streams of northwestern California. *In:* Turbidity and other sediment surrogates workshop (ed. by G.D. Glysson & J.R. Gray). 30 April - 02 May 2002, Reno, Nevada. 3 p.

Foster, I. D. L., R. Millington, et al. (1992). The impact of particle size controls on stream turbidity measurement; some implications for suspended sediment yield estimation. Erosion and Sediment Transport Monitoring Programmes in River Basins 210: 51-62.

Gippel, C. J. (1995). Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrological Processes 9: 83-97.

Lewis, Jack. 2002. Turbidity-controlled sampling for suspended sediment load estimation. Extended abstract *in:* Erosion and Sediment Transport Measurement: Technological and Methodological Advances. Oslo Workshop, 19–21 June 2002.

Lewis, Jack, and Rand Eads. 2001. Turbidity threshold sampling for suspended sediment load estimation. In: Proceedings, 7th Federal Interagency Sedimentation Conference, 25-29 Mar 2001, Reno, Nevada.

Redwood Sciences Laboratory. Turbidity Threshold Sampling. http://www.fs.fed.us/psw/rsl/projects/water/tts_webpage/tts_main.html

Sadar, Mike. 2002. Turbidity instrumentation-an overview of today's available technology. *In:* Turbidity and other sediment surrogates workshop (ed. by G.D. Glysson & J.R. Gray). 30 April - 02 May 2002, Reno, Nevada. 3 p.

Ziegler, Andrew. 2002. Issues related to use of turbidity measurements as a surrogate for suspended sediment. *In:* Turbidity and other sediment surrogates workshop (ed. by G.D. Glysson & J.R. Gray). 30 April - 02 May 2002, Reno, Nevada. 3 p.

The Importance of Pre-Treatment Data: Illustrations From Caspar Creek

Jack Lewis, USDA FS PSW Research Station, Redwood Sciences Lab, Arcata

Abstract

Land managers and natural resource users are expected to understand and limit the impacts of their activities on water resources and the people and organisms that depend on them. Many are attempting to gain that understanding through stream water quality monitoring programs emplaced after watersheds are disturbed. In forested lands of California, this often involves comparing suspended sediment or turbidity in a disturbed watershed with that in a nearby control watershed. Comparisons require an assumption that the two watersheds had similar water quality prior to the disturbance. The assumption may seem quite reasonable if the watersheds have similar vegetation, soils, climate, and management history. But the natural variability between watersheds in the factors that affect suspended sediment transport are often much greater than one might expect. Direct comparisons of sediment yields after logging apparently similar watersheds can lead to very wrong conclusions. This is illustrated by suspended sediment data collected at 14 stream gaging stations in the 1168-acre North Fork Caspar Creek watershed in the Jackson Demonstration State Forest near Fort Bragg, California. These stations have been intensively monitored since 1985 using automatic pumping samplers programmed to collect samples during storm events. At the beginning of the study, the watersheds supported second-growth redwood

and Douglas-fir forest that had not been logged since 1860-1904. Before renewed logging began in 1990-91, the range in storm mean suspended sediment concentrations (yield divided by flow) at the 14 locations spanned an order of magnitude for a given size storm, and the range in storm loads, normalized by watershed area, spanned up to two orders of magnitude.

Four approaches to evaluating change in suspended sediments are illustrated. Control and treated watersheds are compared with respect to (1) storm event loads, (2) paired simultaneous concentrations, (3) sediment rating curves, and (4) concentration distribution functions. Without pretreatment information none of these methods was effective in detecting management-related changes that occurred immediately after logging at Caspar Creek. Long-term monitoring might eventually reveal trends suggestive of recovery, but reliable interpretation of cause is difficult without baseline measurements of pretreatment conditions.

Retrospective studies can be designed to distinguish treated and untreated sites, but they require enough sites that groups of treated and untreated sites can be reasonably assumed to originate from the same populations. Potential confounding factors must be roughly equally represented in both groups. If response differences due to confounding factors are very large, and this may often be the case for suspended sediments, then a very large number of sites must be included. The effects of covariates can sometimes be accounted for using empirical models, but this approach, too, requires large numbers of study sites.

To reliably quantify and explain changes in water quality after a disturbance at a particular location requires both control and pretreatment measurements as well as observations of channel and hillslope processes.

References

Keppeler E; Lewis, J; and Lisle, T. 2003. Effects of Forest Management on Streamflow, Sediment Yield, and Erosion, Caspar Creek Experimental Watersheds. In: Renard, Kenneth G., McElroy, Stephen A., Gburek, William J., Canfield,

H. Evan and Scott, Russell L., eds. 2003. *First Interagency Conference on Research in the Watersheds*, October 27-30, 2003. U.S. Department of Agriculture, Agricultural Research Service. http://www.tucson.ars.ag.gov/icrw/Proceedings/Keppeler.pdf

Smith, Eric P. 2002. BACI design. In: El-Shaarawi, Abdel H., Piegorsch, Walter W., eds. 2002. *Encyclopedia of Environmetrics*, Vol. 1. John Wiley & Sons, Chichester. pp. 141-148.

http://filebox.vt.edu/artsci/stats/vining/smith/B001-_o.pdf

Ziemer, Robert R, technical coordinator. 1998. *Proceedings of the conference on coastal watersheds: the Caspar Creek story.* 1998 May 6; Ukiah, CA. General Tech. Rep. PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 149 p.

http://www.fs.fed.us/psw/publications/documents/gtr-168/gtr-168-pdfindex.html

Variation in Turbidity at the THP Scale

Kate Sullivan, Pacific Lumber Company, Scotia

Abstract

We initiated a water quality grab sampling program at the THP scale during storm events to identify sediment sources that may result from forest operations within harvest units and from roads. Turbidity was used as an indicator of suspended sediment. Streams were traversed and turbidity samples were collected at all stream junctions and at numerous locations between stream links in harvest units averaging 15-30 acres in size. Typically 15-30 samples were collected from each unit, depending on configuration. Watercourse crossings

were sampled above and below the road prism to examine the effect of road use on stream turbidity throughout the watershed.

A total of 649 water samples were collected on units were sampled on 14 THP's with 48 individual harvest units. Sources were identified by comparing the turbidity of pairs of samples. For example, an incoming tributary was compared to the turbidity of the main stream above the junction. The methodology was able to detect local sediment sources. Investigators were sent to look for suspected sources. Evidence for a source was very strong when the downstream sample averaged 300% greater than its pair. In this case, a source was nearly always found when we searched. A total of 16 sources were found, of which only 2 originated within a harvest unit. Most were small landslides, occurring out of the unit, bank sloughing in riparian areas, or old legacy road features such as deteriorating Humboldt crossings.

Turbidity sampling at this fine scale allowed a glimpse at the variability of turbidity in small headwater streams. We observed local variability up to about 40% above background that were not persistent, and were not associated with a local source. This level of difference among pairs appears to suggest the natural variability of sediment introduction to streams.

The effect of road crossings was assessed by comparing the turbidity of samples collected above and below the road. Road crossings were sampled at least 3 times and some were sampled as many as 10 times. Approximately 400 samples were collected at 87 crossings. Combining all samples, the effect of the road on turbidity was within 20% above background in 82% of the samples. Some crossings were chronically impacted by the road, while most others were either never or occasionally affected.

References

National Council of the Paper Industry for Air and Stream Improvement, Inc. (NCASI). 1999. Scale considerations and the detectability of sedimentary cumulative watershed effects. Technical Bulletin No. 776. Research Triangle Park, N.C.

Oregon Department of Forestry 1996 Storms Impacts Study: From Monitoring to Policy

Dr. E. George Robison, Assistant Professor Forest and Watershed Management Department and Associate Director Institute of Forest and Watershed Management Humboldt State University, Arcata

Abstract

After a series of severe warm rainstorms that affected Oregon in February 1996, the Oregon Department of Forestry dedicated significant resources to conducting a monitoring study of landslide occurrence and effects on stream channel systems in western Oregon that was completed in 1999. This study's findings included a critique on the use of air photo analysis in landslide detection, landslide occurrence in different aged forest stands, the immediate effects of landslides on stream morphology and habitat, and other issues. The results of this study have had profound effects on forest regulatory policy in Oregon including:

- the de-emphasis of the use of air photos in landside detection in areas of heavy forest cover,
- aiding a policy shift regarding landslide policy from a sole emphasis on prevention to one of landslide "quality" when they fail,
- raised serious debate of landslide rates and behavior in intermediate aged stands (i.e. 10-100 years post harvest),
- clarification of methods used to screen landslides, and
- use of results in rules and guidance that identify landslide debris flow behavior along with occurrence when determining areas of high risk to property or life.

The bulk of this presentation will describe some of the key findings and then illustrate how these findings affected forest policy specifically now nearly eight years after the initiation of the study and over four years since the final report was completed. Also discussed will be what attributes of the study that lended to it being so widely used in policy formation including:

- the pooling of considerable resources to go after the key monitoring questions adequately,
- extensive peer review early in the process,
- the formation of key monitoring questions and hypotheses before measurements occurred,
- the tying of measurements and monitoring to regulatory questions making them relevant,
- quality assurance procedure early in the process before extensive measurements taken,
- extensive input into the process via a workshop, and
- extensive peer review at the end of the process with transparency in responses to review along with making the underlying data widely available for follow-up analysis.

While this study represented a "once in a lifetime opportunity" with concern and resources not normally associated with a typical forest monitoring study, I believe many of the attributes listed above represent steps that can be taken to enable monitoring results to more effectively be used in forest policy here in California or in other jurisdictions.

References

The Study Itself:

Robison, E. G., K. Mills, J. T. Paul, L. Dent, and A. Skaugset. 1999. Oregon Department of Forestry 1996 Storm Impacts Monitoring Project: Final Report. Forest Practices Technical Report #4. Oregon Department of Forestry, Salem, Oregon. 141 pp.

Can be downloaded at: http://www.odf.state.or.us/divisions/protection/forest_practices/fpmp/Projects/Storm_Impacts/StormFinalReport.pdf

Example of Policy Documents that have been influenced by Landslide study:

Forest Practices Advisory Committee on Salmon and Watersheds (FPAC). 2000. Final report. Available from Oregon Department of Forestry, 2600 State Street. Salem Oregon. Also available from: http://www.odf.state.or.us/divisions/protection/forest_practices/refslist.asp?id=403010606

Independent Multidisciplinary Science Team (IMST). 1999. Recovery of Wild Salmonids in Western Oregon Forests: Oregon Forest Practices Act Rules and the Measures in the Oregon Plan for Salmon and Watersheds. Technical Report 1999-1 to the Oregon Plan for Salmon and Watersheds, Governor's Natural Resources Office, Salem, Oregon.

Mills, K. and J. Hinkle (eds.). 2001. Forestry, landslides and public safety an issue paper prepared for the Oregon Board of Forestry. Landslides and public safety team. Oregon Department of Forestry, 2600 State Street, Salem, Oregon. 81 p.

Oregon Department of Forestry (ODF) and Oregon Department of Environmental Quality (DEQ). 2002 The Oregon Department of Forestry and Department of Environmental Quality Sufficiency Analysis: A Statewide Evaluation of FPA Effectiveness in Protecting Water Quality. Available from Oregon Department of Forestry 2600 State Street Salem Oregon or at: http://www.odf.state.or.us/DIVISIONS/protection/forest_practices

Some Related Works on Similar Subjects:

Benda, L. and T. Cundy. 1990. Predicting Deposition of Debris Flows in Mountain Channels. Canadian Geotechnical Journal. Volume 27, Number 4, pp. 409-417.

Fannin, R.J., and T.P. Rollerson. 1993. Debris Flows: Some Physical Characteristics and Behavior. Can. Geotech. J. Vol. 30, pp. 71-81.

Ketcheson, G. and H.A. Froehlich. 1978. Hydrologic Factors and Environmental Impacts of Mass Soil Movements In The Oregon Coast Range. Water Resources Research Institute Bulletin 56, Oregon State University, Corvallis, Oregon.

Pyles, M.R. and H. A. Froehlich. 1987. Discussion of "Rates of landsliding as Impacted by timber management Activities in Northwestern California" by M. Wolfe and J. Williams. Bulletin of the Association of Engineering Geologists. Vol XXIV, No. 3, pp 425-431.

Reeves, G.H., L.E. Benda, K.M Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. Amer. Fish Soc. Sup. 17: 334-349.

Even-Aged Management and Landslide Inventory, Jackson Demonstration State Forest, Mendocino County, California

Julie A. Bawcom, Engineering Geologist

Abstract

Jackson Demonstration State Forest (JDSF) is a managed working forest in the northern Coast Ranges of California that facilitates research and demonstrates diverse timber management practices. The forest is composed of almost 50,000 acres with about 1800 acres (4%) clearcut between 1980 and 1995 in various sizes within 4 different watersheds. About 43% of the clearcut units were broadcast burned and all units were planted.

The goal of this landslide inventory is to study the relationship between vegetation removal in a predominantly second-growth redwood forest and the incidence of shallow landslides that deliver sediment to watercourses. Larger dormant and relic deep-seated landslide features were also mapped both in the field and on aerial photographs to record any reactivation within the areas of vegetation removal. Sedimentary rocks of the Coastal Belt Franciscan Complex underlie the JDSF clearcuts.

The study includes 55 days of geologic field mapping 50 clearcut units, characterizing any landslides by failure type; apparent cause and age related to the clearcut and related rainfall. Sediment delivery along with stream classification was estimated for each recent landslide. Results are discussed including the cost-effective benefits for forest management and what landowners can learn from this type of field intensive study to reduce anthropogenic sediment sources that continue to affect water quality today.

Of the 32 landslide features mapped, all but four are associated with older roads, landings and skidtrails. This demonstrates that tree removal associated with clearcutting in a coastal redwood forest does not of itself initiate numerous sediment delivering shallow landslides and leads to the identification of other related anthropogenic sediment sources.

It was found that numerous sediment delivering shallow landslides and erosion from older roads and landings are responsible for the major increases of sediment to streams. Results support the current trend of forest landowners to focus on watershed restoration by increasing road rehabilitation and decommissioning.

References

Abe, K., and Ziemer, R.R., 1991, Effect of Tree Roots on Shallow-Seated Landslides: Technical Session on Geomorphic Hazards in Managed Forests, USDA Forest Service General Technical Report PSW-GTR-130, pp. 11-20.

Best, T.C., 2002, Engineering Geologic Review: Booth THP; Campbell Timberland Management, for Timber Harvesting Plan 1-03-043 MEN, 55 pp.

Bishop, D.M. and Stevens, M.E., 1964, Landslides on logged areas in southeast Alaska: U.S.D.A. Forest Service, Northern Forest Experiment Station, Research Paper NOR-1, pp. 18.

Cafferata P.H. and Spittler, T.E., 1998, Logging Impacts of the 1970's vs. the 1990's in the Caspar Creek Watershed *in* Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story: USDA Pacific Southwest Research Station, PSW-GTR-168, pp. 103-115. http://www.psw.fs.fed.us/Tech_Pub/Documents/gtr-168/13cafferata.pdf

California Department of Forestry and Fire Protection, 2002, Jackson Demonstration State Forest Management Plan. http://www.fire.ca.gov/MiscDocuments/jdsf_mgt_plan.asp

California Department of Forestry and Fire Protection, 1999, Draft Habitat Conservation Plan and Sustained Yield Plan for Jackson Demonstration State Forest dated June 1999. Prepared by Stillwater Sciences, Berkeley, California.

Gray, D.H., 1970, Effects of forest clearcutting on the stability of natural slopes: Bulletin of the Association of Engineering Geologists, Volume VII, pp. 45-67.

Henry, N., 1998, Overview of the Caspar Creek Watershed Study: *in* Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story: USDA Pacific Southwest Research Station, PSW-GTR-168, pp. 1-9. http://www.psw.fs.fed.us/Tech_Pub/Documents/gtr-168/01henry.pdf

Kilbourne, R.T., 1982, Geology and Geomorphic Features Related to Landsliding Glenblair NW 7.5' Quadrangle, Mendocino County California: California Department of Conservation, Division of Mines and Geology Open File Report OFR 82-25 S.F., 1:24,000.

Kilbourne, R.T. and Mata-Sol, A.R., 1983, Geology and Geomorphic Features Related to Landsliding Glenblair SW 7.5' Quadrangle, Mendocino County California: California Department of Conservation, Division of Mines and Geology Open File Report OFR 83-20 S.F., 1:24,000.

Manson, M.W., Bawcom, J.A., and Parker, T. 2001, Noyo River Watershed Geologic and Geomorphic Features, California Geological Survey, Watershed Mapping Series, Map Set 1, Sheet B, Western Portion, Scale 1:24,000.

Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., and Dietrich, W.E., 2000, Forest clearing and regional landsliding: Geology, Volume 28, Number 4, pp. 311-314.

Napolitano, M.B., 1998, Persistence of Historical Logging Impacts on Channel Form in Mainstem North Fork Caspar Creek: *in* Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story: USDA Pacific Southwest Research Station, PSW-GTR-168, pp.97-101. http://www.psw.fs.fed.us/Tech_Pub/Documents/gtr-168/12napolitano.pdf

Napolitano, M. Francis, J., and Caffarata, P. 1989, A History of Logging in the Caspar Creek Basin, Jackson Demonstration State Forest Newsletter, No. 33, April 1989, p. 4-7. http://www.rsl.psw.fs.fed.us/projects/water/JDSF89.pdf

O'Loughlin, C.L., 1974, The effect of timber removal on the stability of forest soils: Journal of Hydrology (N.Z.), Volume 13, pp. 121-134.

Short, W.R. and Spittler, T.E. , 2001, Preliminary Map of Geologic and Geomorphic Features related to Landsliding, Jackson Demonstration State Forest, Mendocino, County, California: California Geological Survey: Watershed Mapping Series, Map Set 2, Sheet B, Scale 1:24,000.

Spittler, T.E. and McKittrick, M.A. 1995, Geologic and Geomorphic Features Related to Landsliding, North and South Forks of Caspar Creek, Mendocino County, California, California Division of Mines and Geology, Open-File Report 95-08, Scale 1:12,000. http://www.rsl.psw.fs.fed.us/projects/water/Caspar_Geology.pdf

Swanston, D.N., and Swanson, F.J., 1976, Timber Harvesting, Mass Erosion, and Steepland Forest Geomorphology in the Pacific Northwest:Dowden, Hutchinson & Ross, Stroudsburg, PA, in, Coates, D. R., Geomorphology and Engineering, pp. 199-221.

Wu, T.H., and Swantston, D.N., 1980, Risk of Landslides in Shallow Soils and its Relation to Clearcutting in Southeastern Alaska: Forest Science, Volume 26, Number 3, pp. 495-510.

Ziemer, R.R., 1981, Roots and the stability of forested slopes: in, Erosion and Sediment Transport in Pacific Rim Steeplands: International Association of Hydrological Sciences, Publication Number 132, p. 343-361. http://www.rsl.psw.fs.fed.us/projects/water/ZiemerIAHS.PDF

Ziemer, R.R., 1998, Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story: USDA, Pacific Southwest Research Station GTR PSW-GTR-168, 149 pp. http://www.psw.fs.fed.us/Tech_Pub/Documents/gtr-168/gtr-168-pdfindex.html

WATER QUALITY PROJECTS

French Creek Watershed Monitoring Program, 1992-2003

Sari Sommarstrom, Ph.D., for the French Creek Watershed Advisory Group, Etna, California

Abstract

An innovative watershed management partnership in the Scott River sub-basin of the Klamath River Basin of northern California has succeeded in significantly reducing stream sedimentation from road sources. By focusing on controlling the primary source of nonpoint pollution, water quality and salmon and steelhead habitat have improved visually and measurably. This watershed was selected in 1990 by the State Board of Forestry for a cooperative watershed process because of prevailing conflict among the federal, private timber, and residential ownerships over timber-related management, particularly in addressing cumulative watershed effects. A partnership of 13 diverse stakeholders– the French Creek Watershed Advisory Group (WAG) - was formed to address the situation, with UC Davis serving as the project facilitator and coordinator for the initial 2 ½ years.

Brief Background: Excessive sand-sized sediment in French Creek was the symptom of cumulative watershed impact in this 21,000-acre granitic, forested watershed. In 1992, the WAG adopted a Road Management Plan, since roads were found to contribute over 60% of the sediment (Sommarstrom, Kellogg, & Kellogg 1990), and a Monitoring Plan to help address the partnership's goal of reducing the sediment yield into French Creek. Improvements to private and public roads began immediately: over 38 miles of unsurfaced road were recontoured and rocked, 4 miles of road put to bed, many miles of road closed to wet season use; 20,000 trees planted on cut and fill slopes; rock breast wall and rock mulch placed by County on large roadcuts, 4 miles of private residential driveways near streams were rocked.

V* Method: This fairly simple water quality evaluation method measures the relative volume of fine sediment in pools, using the Lisle & Hinton (1992) method developed at the USFS Redwood Sciences Lab. The volume of fines in pools relative to the potential pool volume (minus the fines) provides an index of the amount of mobile sediment in the stream system. A trained team of 3 people can measure a reach of 12 pools using tape measures and a probe in about 2 days of field work. Measurements are done during low flow conditions of late summer-early fall.

Results: The V* level in this reach of French Creek in 1992 was 32%, meaning that about 1/3 of each pool on the average was filled with fine sediment. From 1993 through 1996, the level lowered to an average of over 9%. After the 1997 New Year's Day flood, the index increased to 17% due to two culverts blowing out, but was reduced to 12% by 1999 and dropped again to 7% in 2001. Note that a level of 10% is considered to be "background" level (Dr. Tom Lisle, USFS Redwood Sciences Lab., personal communication). Monitoring is now only occurring in alternate years.

Juvenile fish monitoring since 1990 indicates fluctuations in steelhead density and biomass at different reaches, but an increasing presence of coho juveniles since 1993.

The group's goal "to reduce the sediment yield in the French Creek watershed" was achieved and is being sustained. The North Coast RWQCB cites French Creek as a positive example of improved water quality through better watershed management. And our joint monitoring efforts continue!

References

French Creek Watershed Advisory Group. 1992. French Creek Watershed Monitoring Plan. Etna CA. 13 p.

French Creek Watershed Advisory Group. 1992. French Creek Watershed Road Management Plan. Etna CA. 10 p.

French Creek Watershed Advisory Group. 1994. "The French Creek watershed story: moving mountains to keep a mountain from moving", video (17 min).

Lisle, T.E. 1993. The fraction of pool volume filled with fine sediment in Northern California: relation to basin geology and sediment yield. Final report to the Calif. Dept. of Forestry and Fire Protection. USFS-PSW Research Station, Arcata CA. 15 p.

Lisle, T.E. and S. Hilton. 1992. The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams. *Water Resources Bulletin* 28(2):371-383.

Lisle, T.E. and S. Hilton. 1999. Fine bed material in pools of natural gravel bed channels. *Water Resources Research* 35(4):1291-1304.

Maria, D. 2002. French Creek juvenile steelhead and coho data, 1990-2002. Unpublished data. Calif. Dept. of Fish and Game, Yreka, CA.

National Forum on Nonpoint Source Pollution. 1996. "French Creek Watershed Project", *Water: taking a new tack on nonpoint water pollution.* Washington, D.C. p. 36

Power, J. 1999. "1999 Summary – French Creek V*". Memorandum to file, 11/99. USFS Klamath National Forest, Scott River Ranger District, Fort Jones CA. 2 p.

Power, J. 2003. French Creek V* sediment data, 1992-2003. Unpublished data. USFS Klamath National Forest, Scott River Ranger District, Fort Jones CA.

Sommarstrom, S. 1994. Moving mountains to keep a mountain from moving: the French Creek watershed case study. pp. 45-48 in: *Proceedings of the Fourth Biennial Conference on Watershed Management* (J. Woled, ed.), U.C. Davis Water Resources Center Report No. 81, Davis CA.

Sommarstrom, S., Kellogg, E., and J. Kellogg. 1990. *Scott River basin granitic sediment study.* Prepared for the Siskiyou Resource Conservation District and the U.S. Fish and Wildlife Service. Etna CA. 160 p.

Cooperative Monitoring in the Gualala River Watershed: Stream Profiling and Other Useful Tools

Kathleen Morgan, Henry Alden, Gualala River Watershed Council, Gualala

Abstract

Introduction

The Gualala River is a coastal watershed located 110 miles north of San Francisco. The river flows through 298 square miles of watershed along the coast of southwestern Mendocino County and northwestern Sonoma County, entering the Pacific Ocean near the town of Gualala. Coho salmon naturally inhabited the streams flowing from coniferous forest but were likely sub-dominant to steelhead in interior basin areas.

The watershed is primarily private timberland with well over 60% of the watershed zoned timber production. The remainder of the watershed is largely grazing land, with a smaller amount of land holdings associated with rural residential and agricultural operations such as orchards and vineyards. The key beneficial uses are anadromous fisheries and domestic water supply.

The Gualala River Watershed Council (GRWC) is a consensus based organization and was formed *in part* to address water quality concerns. The Council acts as a local forum for landowners, resource managers, public agencies and interested citizens to communicate about the health of the ecosystem and land uses within the watershed.

The GRWC Cooperative Monitoring Program was developed in 2000 with the assistance of Gualala Redwoods, Inc. (GRI) an industrial timber company actively operating on approximately 30,000 acres in the lower basin. This collaboration between the Council and one of the watershed's larger stakeholders enabled the Council to share resources and design a monitoring program that capitalized on existing data.

Program

The Cooperative Monitoring Program is designed to assess watershed conditions through collaboration between private landowners, community groups, and public agencies. The Council collects information on the physical condition of the watershed which allows us to evaluate ecological events, trends, the effects of Best Management Practices (BMPs), and the results of restoration projects. Oversight of the program comes from a Technical Advisory Committee comprised of representatives from the GRWC, SRCD, CGS, CDF, NCRWCQB and DFG. The GRWC monitoring program is comprehensive and employs a Quality Assurance Plan approved by the North Coast Regional Water Quality Control Board. The *Quality Assurance Project Plan (QAPP) for Monitoring Sediment Reduction in the Gualala River Watershed* (Williams, K., and Morgan, K., 2002) was developed and implemented by the GRWC and the Sotoyome Resource Conservation District (SRCD) and is the first QAPP to be approved for North Coast watersheds. The QAPP outlines procedures for monitoring water temperature; thalweg profiles; cross-sections; substrate size; riparian composition & LWD recruitment potential; LWD in-stream inventory; and canopy density. Twenty-nine monitoring reaches are already installed on 12 tributaries along with 40 temperature monitoring sites.

Funding is provided from DFG, Senate Bill 271: Gualala River Watershed Enhancement Program and Gualala River Assessment & Planning, and under the State Water Board, Federal Clean Water Act 319h: The Gualala River Sediment Reduction program.

Results

Data collected over the past six years demonstrate the program's effectiveness in assessing natural and/or anthropogenic changes to the environment.

The thalweg profile is one of the most useful metrics to monitor habitat suitability for salmonids. The installation of stream reaches throughout the basin allows the tracking of pool formation, residual pool volume, pool depth, and streambed aggradation/degradation.

Streambed elevation measurements show fairly stable channels with a slight trend toward degradation. Pool formation, depth and volume demonstrate the same trend towards stability.

Stream reach monitoring is a powerful tool, which can successfully measure the effectiveness of in-stream restoration projects. The placement of large wood in monitoring reaches where pre-project thalweg data is available has enabled the Council to closely monitor changes in the streambed. Data collected from restoration project reaches show an increase in pool formation, pool depth and stream complexity.

References

FFFC, 1996. Aquatic Field Protocols Adopted by the Fish, Farm, and Forest Communities (FFFC) Technical Committee, Compiled by Ross Taylor.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins. 1998. *California Salmonid Stream Habitat Restoration Manual*, State of California, The Resources Agency, California Department of Fish and Game, Inland Fisheries Division, Sacramento, CA.

FSP, 1998. *Forest Science Project Technical Notes.* Forest Science Project, Humboldt State University Foundation, Arcata, CA

OCSRI, 1996. Stream Temperature Protocol. *Oregon Coastal Salmon Restoration Initiative*, Salem, OR.

ODF, 1994. Water temperature monitoring protocol. *Forest Stream Cooperative Monitoring*, Oregon Department of Forestry, Forest Practices Section, Salem, OR,

Richards, K. 1982. *Rivers: Form and Process in Alluvial Channels.* Methuen. New York, NY.

Schumm, S.A. 1977. *The Fluvial System.* Wiley-Interscience, New York, NY.

Spence, B.C., G.A. Lomnicky, R.M. Hughes, and R.P. Novitzki. 1996. *An Ecosystem Approach to Salmonid Conservation.* TR-4501-96-6057, Management Technology, Corvallis, OR.

TFW, 1993. Stream Temperature Module. *1993 TFW Ambient Monitoring Manual*, Timber-Fish-Wildlife Ambient Monitoring Program, Northwest Indian Fisheries Commission, Olympia, WA.

Harrelson, Cheryl C., C. L. Rawlins, John P. Potyondy, (1994) *Stream Channel Reference Sites: An Illustrated Guide to Field Technique*, USFS General Technical Report RM-245.

Jackson, Dennis; Marcus, Laurel (1999) *Creating a Watershed Atlas and Monitoring Program, Watershed Stewardship Workbook.*

Leopold, Luna B. 1994, *A View of the River*, Harvard University Press, Cambridge, MA.

Mary Ann Madej (1999), *What Can Thalweg Profiles Tell Us? A Case Study from Redwood Creek, California*, USGS-BRD Redwood Field Station, Arcata, California

In Search of the Holy Grail: Evolution of an Integrated Aquatic Monitoring Program on Private Timberlands

Lowell Diller, Matt House and Brian Michaels Simpson Resource Company, Korbel

Abstract

Simpson has been developing an aquatic monitoring program for its coastal Northern California timberlands over the last 10 years. The overall goal was to determine potential impacts of Simpson's management activities on aquatic resources. Initially, the expectation was that we could develop a program with few or even a single

non-subjective methodology that would accurately record trends in water quality and instream habitat conditions. In addition to recording water temperature using HOBO data recorders, the first monitoring work, which was deployed in 1993, utilized randomly selected 300-foot fixed stream reaches. Cross sections were established at 10-foot intervals within each fixed reach and a variety of variables were measured along each transect (Platts et al. 1983). The monitoring approach was based on the premise that instream habitat conditions would provide an accurate reflection of trends in watershed conditions. This monitoring approach was abandoned after two years, because fixed reaches were not responsive to the dynamic nature of streams and many of the variables measured were flow dependent. In 1995, the Platt's methodology was replaced by a monitoring approach developed by Bill Trush for Simpson that was designed to use changes in instream channel conditions as a reflection of overall trends in the watershed. This technique also used fixed stream reaches, but they were much longer (2-3 meander wavelengths, which in most of our streams was 2000-3000 feet long). Under ideal circumstances, the reaches selected were in the first depositional reach below the upper transport reaches in a watershed. Initially, the methodology included measuring and creating a detailed map of many variables including active and bankfull channel widths, thalweg profiles, pebble counts, cross sections, residual pool depth, radius of curvature, LWD size and distribution, V* and others. In 1997, we hired a statistician to evaluate the program, which resulted in some major shifts towards only utilizing those variables that could be measured with repeatability and minimal subjectivity, and statistically analyzed. In March 1999, there was a channel process and function workshop where we presented our long-term channel monitoring methodology along with an analysis of the preliminary data. Following some intense criticism during the workshop, Simpson further modified the protocols to streamline the field work by using a total station and eliminating additional subjectively measured variables.

During the time that we were going through the pains of modifying and adapting existing protocols, it became apparent that single or small suites of monitoring protocols were not likely to satisfy our overall monitoring objectives for aquatic resources. As part of development of an aquatic Habitat Conservation Plan, there was a paradigm shift in which the goal was to develop an integrated monitoring approach that focused on identifying a suite of aquatic response variables that had the greatest potential to be impacted by timber management, were of critical importance to an aquatic resource and were conducive to monitoring (i.e. minimum subjectivity in measurement, amenable to statistical analysis and minimal time lag between disturbance and measured impact). After wrestling with the reality that most response variables of interest fit into some, but not all of the criteria described above, we developed a hierarchical approach to monitoring based primarily on how long it would take to detect a significant effect. The categories are listed in the table below:

Rapid Response Monitoring	Response Monitoring	Long-term Trend Monitoring/Research

• Water Temperature
  - Property-wide
  - Class II BACI design
• Spawning Substrate Permeability
• Road-related Sediment Delivery (Turbidity)
• Headwater Amphibians
  - Tailed Frog
  - Southern Torrent Salamander
	• Class I Channel
	• Class III Sediment
		• Road-Related Mass Wasting
		• Steep Streamside Slopes
		• Mass Wasting Assessment
		• Long Term Habitat Assessments
		• LWD Monitoring
		• Summer Juvenile Salmonid Population Estimates
		• Outmigrant Trapping

In addition to the general monitoring program, we also established four experimental watersheds that are geographically distributed across the ownership. The goal for the experimental watersheds is to develop cooperative state-of-the-art experimental studies with academic, state or federal scientists to test fundamental assumptions concerning how best to mitigate and avoid aquatic impacts of timber management activities.

References

Water Temperature Monitoring:

Green, R.H. (1979) Sampling design and statistical methods for environmental biologists, New York: John Wiley and Sons, 257 pages.

McDonald, T.L., W.P. Erickson, and L.L. McDonald (2000) "Analysis of count data from before-after control-impact studies", Journal of Agricultural, Biological, and Ecological Statistics 5(3), p. 262-279.

Moran, P.A.P. (1950) "Notes on continuous stochastic phenomena". Biometrika 37:17-23.

Stewart-Oaten, A., W.W. Murdoch, and K.R. Parker, (1986) "Environmental impact assessment: pseudoreplication in time?", Ecology 67(4), p. 929-940.

Thomas, R.E., J.A. Gharrett, M.G. Carls, S.D. Rice, A. Moles, S. Korn. 1986. Effects of fluctuating temperature on mortality, stress, and energy reserves of juvenile coho salmon. Transactions of the American Fisheries Society 115:52-59.

Spawning Substrate Permeability Monitoring:

Barnard, K. and S. McBain. 1994. Standpipe to determine permeability, dissolved oxygen, and vertical particle size distribution in salmonid spawning gravels. Fish Habitat Relationships Technical Bulletin No. 15. U. S. Forest Service.

Chapman, D. W. 1988. Critical review of variables used to define effects of fines in redds of large salmonids. Transactions of the American Fisheries Society, 117(1)1-21.

Klatte, B. 1998. Redwood National Park (RNP). Monitoring the impacts and persistence of fine sediment in the Prairie Creek watershed. Unpublished Masters Thesis Data.

Koski, K. V. 1966. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergence in three Oregon coastal streams. Master's thesis. Oregon State University, Corvallis.

McBain and Trush. 2000. Spawning gravel composition and permeability within the Garcia River watershed, CA: Final Report. Report to the Mendocino County Resource Conservation District and CA Department of Forestry, April 2000.

McCuddin, M. E. 1977. Survival of salmon and trout embryos and fry in gravel-sand mixtures. Master's thesis. University of Idaho, Moscow.

Mendocino Redwood Company (MRC). Unpublished data from the MRC monitoring program.

Mesick, C.M. 2000. Use of permeability monitoring to evaluate the quality of salmon spawning gravels in the Stanislaus River. Unpublished Report.

Pollard, R. A. 1955. Measuring seepage through salmon spawning gravel. J Fish. Res. Bd. Canada, 12(5): 706-741.

Tagart, J. V. 1976. The survival from egg deposition to emergence of coho salmon in the Clearwater River, Jefferson County, Washington. Master's thesis. University of Washington, Seattle.

Tappel, P. D. and T. C. Bjornn. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. North American Journal of Fisheries Management 3: 123-135.

Terhune, L. D. B. 1958. The Mark VI groundwater standpipe for measuring seepage through salmon spawning gravel. Journal of the Fisheries Research Board of Canada 15: 1027-1063.

Young, M. K., W. A. Hubert, and T. A. Wesche. 1989. Evaluation of variation in permeability measurements when using the MARK VI standpipe. Canadian Journal of Fisheries and Aquatic Sciences 46: 1-4.

Headwater Amphibian Monitoring:

Tailed Frogs:

Bury, R. B. 1968. The distribution of *Ascaphus truei* in California. Herpetologica. 24(1):39-46.

______. 1983. Differences in amphibian populations in logged and old growth forests. Northwest Sci. 57:167-178.

Metter, D. E. 1964. A morphological and ecological comparison of two populations of the tailed frog, *Ascaphus truei* Stejneger. Copeia 1964:181-195.

Nussbaum, R. A., E. D. Brodie, Jr., and R. M. Storm. 1983. Amphibians and Reptiles of the Pacific Northwest. Univ. Press of Idaho, Moscow.

Wallace, R. L. and L. V. Diller. 1998. Length of the larval Cycle of *Ascaphus truei* in coastal streams of the Redwood Region, Northern California. Journal of Herpetology 32(3):404-409.

Welsh, H. H., Jr. 1990. Relictual amphibians and old-growth forests. Conserv. Biol. 4:309-319.

Southern Torrent Salamanders:

Diller, L. V. and R. L. Wallace. 1996. Distribution and habitat of *Rhyacotriton variegatus* in managed, young growth forests in north coastal California. J. Herpetol. 30:184-191.

McDonald, T. L., W. E. Erickson and L. L. McDonald. 2000. Analysis of count data from before-after control-impact studies. Journal of Agricultural, Biological, and Environmental Statistics, 5(3): 262-279.

Nijhuis, M.J., and R.H. Kaplan. 1998. Movement patterns and life history characteristics in a population of the Cascade torrent salamander (*Rhyacotriton cascadae*) in the Columbia River gorge, Oregon. J. Herpetol., 32:301-304.

Nussbaum, R. A., E. D. Brodie, Jr., and R. M. Storm. 1983. Amphibians and Reptiles of the Pacific Northwest. Univ. Press of Idaho, Moscow.

Nussbaum, R. A. and C. K. Tait. 1977. Aspects of the life history and ecology of the Olympic salamander, *Rhyacotriton olympicus* (Gaige). Amer. Midl. Natur. 98:176-199.

Skalski, J. R., and D. S. Robson. 1992. Techniques for wildlife investigations, design and analysis of capture data. New York: Academic.

Welsh, H. H. Jr., and A. J. Lind. 1992. Population ecology of two relictual salamanders from the Klamath Mountains of northwestern California. In D. R. McCullough and R. H. Barrett (eds.), Wildlife 2000:Populations, pp. 419-437. Elsevier Applied Science, New York.

Class I Channel Monitoring:

Cressie, N.A.C. (1991). Statistics for Spatial Data, New York: John Wiley and Sons.

McDonald, T.L. (1998). Analysis of Channel Monitoring Data at Canon, Hunter, and Canyon Creek. West Report #98-4. July 7, 1998. Western EcoSystems Technology, Inc. Cheyene, WY. 23 pp.

Manly, B.F.J. (1997). Computer intensive methods in biology, 2nd edition. Chapman and Hall, London.

Neter, J., W. Wasserman, and M.H. Kutner (1991). Applied Linear Statistical Models, 4th edition, Homewood, Illinois: Richard D. Irwin Inc.

Class III Sediment Monitoring:

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and sediment transport in the Caspar Creek watersheds. In: Ziemer, Robert R., technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story, 6 May 1998; Ukiah, California. General Tech. Rep. PSW GTR-168. Albany, California: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 55-69.

Britton, S.L. Robinson, K.M., and Barfield, B.J. 2001. Modeling the effectiveness of silt fence. Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25 to29, Reno, Nevada. Volume 2, Part V, pp75-82.

Road-related Turbidity and Suspended Sediment Monitoring:

Platts, W. S., W. F. Megahan, and G. W. Minshall. 1983. Methods of evaluating stream, riparian, and biotic conditions. USDA Forest Service, Gen. Tech. Rept. GTR- INT 138, Ogden, Utah.

Channel and stream Habitat Assessments:

Flosi, G. and F.L. Reynolds. 1994. California salmonid stream habitat restoration manual. Second Edition. IFD, CDFG, Sacramento, CA.

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins. 1998. California salmonid stream habitat restoration manual. Third Edition. IFD, CDFG, Sacramento, CA.

Hopelain. 1995. California salmonid stream habitat restoration manual. IFD, CDFG, Sacramento, CA.

LWD Assessment:

Flosi, G., S. Downie, J. Hopelain, M. Bird, R. Coey, and B. Collins. 1998. California salmonid stream habitat restoration manual. Third Edition. IFD, CDFG, Sacramento, CA.

Rosgen, D.L. 1996. Applied River Morphology. Printed Media Companies, Minneapolis, Minnesota.

Summer Juvenile Salmonid Population Monitoring:

Dolloff, C.A., D.G. Hankin, G.H. Reeves. 1993. Basinwide estimation of habitat and fish populations in streams. USDA Forest Service, General Technical Report SE-83.

Hankin, D.G, 1999. Unpublished MS, a modification of the "Hankin and Reeves" (1988) survey designs, as summarized in detail by Dolloff et al. (1993).

Hankin, D.G. and G.H. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Canadian Journal of Fisheries and Aquatic Sciences 45: 834-844.

Robson, D.S. and J.H. Whitlock. 1964. Estimation of truncation point. Biometrika 51: 33-39.

Outmigrant Trapping:

Bjorkstedt, E.P. 2000. DARR (Darroch Analysis with Rank-Reduction): A method for analysis of stratified mark-recapture data from small populations, with application to estimating abundance of smolts from outmigrant trap data. U.S. Department of Commerce, NOAA, NMFS, SWFSC, Admin. Rep., Santa Cruz, SC-00-02. 261 Kb, 28 p.

Measuring Nutrient and Sediment Loads in Tahoe Basin Streams: A Cautionary Tale

Robert Coats, Hydroikos, San Rafael

Abstract

Driven by concern over the progressive eutrophication and loss of clarity in Lake Tahoe, the Lahontan Regional Water Quality Control Board has launched a program to develop Total Maximum Daily Load (TMDL) allocations for the watersheds in the Tahoe Basin. Two data sets will form the basis for the TMDL: 1) the data from the Lake Tahoe Interagency Monitoring Program (LTIMP). This data set comprises daily discharge and concentration for 7 constituents from 20 stations for up to 11 years; 2) Stormwater discharge and concentration data for 9 constituents from 12 urbanized sites that are currently monitored with automated samplers.

Unbiased and precise estimates of total constituent loads will be an important for the development of TMDLs, but the best methods for estimating loads are not immediately obvious. We used a Monte Carlo procedure to test the accuracy and precision of four methods of calculating total constituent loads for nitrate-nitrogen, soluble reactive phosphorus (SRP), particulate phosphorus, total phosphorus (TP), and suspended sediment, in Blackwood Creek, a major tributary of the lake. The methods tested were two forms of the Beale's Ratio Estimator, the Period Weighted Sample (PWS), and the Rating Curve. Intensive sampling in 1985 (a dry year) and 1986 (a wet year) provided a basis for estimating loads by the "worked record" method, for comparison with estimates based on resampling 200 times, with 20, 40, 60, 80 and 100 samples per trial. The results show that 1) the Period Weighted Sample was far superior to the other methods for nitrate-N, and is preferable for soluble reactive phosphorus; 2) all of the methods were biased and imprecise for total phosphorus; 3) the Rating Curve method gave accurate and precise estimates only for suspended sediment in 1986.

Based on these results, the Tahoe Research Group is using the Period Weighted Sample method for dissolved constituents (nitrate-N, ammonium-N, and SRP), and a two-variable rating curve method for particulate constituents (TP and suspended sediment). Total loads of TKN, with both particulate and dissolved phases, are being estimated by both the PWS and the modified rating curve method.

Modification of the present sampling program may be necessary to improve the measurement of total phosphorus loads in basin streams.

Results of the load estimates will be used to 1) develop predictive equations relating total constituent loads to watershed characteristics, including land use; and 2) to help the hydrologic modeling team to calibrate and verify their model estimates of nutrient and sediment loads. The results also suggest that the LTIMP's present sampling intensity–about 30 samples per station per year–cannot estimate total P loads closer than about +/- 60 percent of the actual load.

References

Coats, R.N, F. Liu and C.R. Goldman. 2002. A Monte Carlo test of load calculation methods, Lake Tahoe Basin, California-Nevada. Jour. Am Water Resour. Assoc. 38(3): 719-730.

Coats, R.N., and C. R. Goldman, 2001. Patterns of Nitrogen Transport in Streams of the Lake Tahoe Basin, California-Nevada. Water Resources Research 37(2): 405-416.

Cohn, T.A., 1995. Recent Advances in Statistical Methods for the Estimation of Sediment and Nutrient Transport in Rivers. Reviews of Geophysics, Supplement: 1117-1123.

Dann, M.S., J. A. Lynch, and E. S. Corbett, 1986. Comparison of Methods for Estimating Sulfate Export from a Forested Watershed. Journal of Environmental Quality 15(2): 140-145.

Ferguson, R.I., 1986. River Loads Underestimated by Rating Curves. Water Resources Research 22(1): 74-76.

Ferguson, R.I., 1987. Accuracy and Precision of Methods for Estimating River Loads. Earth Surface Processes and Landforms 12(1): 95-104.

Hatch, L.K., J. E. Reuter, and C. R. Goldman, 1999. Daily Phosphorus Variation in a Mountain Stream. Water Resources Research 35(12): 3783-3791.

Hill, A.R., 1986. Stream Nitrate-N Loads in Relation to Variations in Annual and Seasonal Runoff Regimes. Water Resources Bulletin 22(5): 829-839.

Jassby, A.D., C. R. Goldman and J. E. Reuter, 1995. Long-term Change in Lake Tahoe (California-Nevada, U.S.A.) and its Relation to Atmospheric Deposition of Algal Nutrients. Archive f□r. Hydrobiologie 135: 1-21.

Johnson, A.H., 1979. Estimating Solute Transport in Streams from Grab Samples. Water Resources Research. 15(5): 1224-1228.

Preston, S.D., V. J. Bierman Jr., and S. E. Silliman, 1989. An Evaluation of Methods for the Estimation of Tributary Mass Loads. Water Resources Research 25(6): 1379-1389.

Richards, R.P., and J. Holloway, 1987. Monte Carlo Studies of Sampling Strategies for Estimating Tributary Loads. Water Resources Research 23(10): 1939-1948.

Robertson, D.M., 2003. Influence of different temporal sampling strategies on estimating total phosphorus and suspended sediment concentration and transport in small streams. Jour. Am. Water Resour. Assoc. 39(5):1281-1308.

Contact Information for Speakers

Lastname	Firstname	Address1	Address2	Address3	City	State	Zipcode	Phone	Email
Bawcom	Julie	California Geological Survey	17501 N. Hwy. 101		Willits	CA	95490	707-456-1814	Julie.Bawcom@fire.ca.gov
Benda	Lee	Earth Systems Institute	310 N. Mt. Shasta Blvd., Suite 6		Mt. Shasta	CA	96067	530-926-1066	leebenda@aol.com
Coats	Bob	Hydroikos	2175 E. Francisco Blvd., Suite A		San Rafael	CA	94901	415-482-8173	coats@hydroikos.com
Diller	Lowell	Simpson Resource Company	PO Box 68		Korbel	CA	95550	707-668-4428	ldiller@simpson.com
Eads	Rand	USDA FS PSW	Redwood Sciences Lab	1700 Bayview Drive	Arcata	CA	95521	707-825-2925	reads@fs.fed.us
Furnish	Joseph	USDA FS	Ecosystem Conservation	1323 Club Drive	Vallejo	CA	94592	707-562-8952	jfurnish01@fs.fed.us
Hannaford	Morgan	Shasta College, Biology Dept.	PO Box 496006		Redding	CA	96049-6006	530-225-4637	mhannaford@shastacollege.edu
Hunsaker	Carolyn T.	USDA FS, PSW Research Station	Sierra Nevada Research Center	2081 E. Sierra Avenue	Fresno	CA	93710	559-323-3211	chunsaker@fs.fed.us
James	Cajun	Sierra Pacific Industries	PO Box 496014		Redding	CA	96049-6014	530-378-8000	cjames@spi-ind.com
Klein	Randy	Redwood National & State Parks	1655 Heindon Road		Arcata	CA	95521	707-825-5111	Randy_Klein@nps.gov
Lewis	Jack	USDA FS PSW	Redwood Sciences Lab	1700 Bayview Drive	Arcata	CA	95521	707-825-2929	jlewis01@fs.fed.us
MacDonald	Lee	Colorado State University	Dept. of Forest, Rangeland & Watershed		Fort Collins	CO	80523-1472	970-491-6109	leemac@cnr.colostate.edu
Madej	Mary Ann	USGS Western Ecological Res. Ctr.	Redwood Field Station	1655 Heindon Road	Arcata	CA	95521	707-825-5148	mary_ann_madej@usgs.gov
Morgan	Kathleen	Gualala River Watershed Council	P.O. Box 1269		Gualala	CA	95446	707-785-2525	kmorgan@mcn.org
Reeves	Gordon	USDA FS PNW Research Station	3200 SW Jefferson Way		Corvallis	OR	9731	541-750-7314	greeves@fs.fed.us
Robison	E. George	Humboldt State University	One Harpst Street		Arcata	CA	95521-8299	707-826-3258	egr2@humboldt.edu
Sommarstrom	Sari	Sari Sommarstrom & Associates	PO Box 219		Etna	CA	96027	530-467-5783	sari@sisqtel.net
Sullivan	Kate	Pacific Lumber Company	PO Box 37		Scotia	CA	95565	707-764-4492	ksullivan@scopac.com
Ziemer	Robert	Humboldt State University	Dept. of Geology	1700 Bayview Drive	Arcata	CA	95521	707-825-2936	rrz7001@humboldt.edu

Impacts of Logging on Storm Peak Flows, Flow Volumes and Suspended Sediment Loads in Caspar Creek, California

Jack Lewis, Sylvia R. Mori, Elizabeth T. Keppeler, Robert R. Ziemer

ABSTRACT

Models are fit to 11 years of storm peak flows, flow volumes, and suspended sediment loads on a network of 14 stream gaging stations in the North Fork Caspar Creek, a 473-ha coastal watershed bearing a second-growth forest of redwood and Douglas-fir. For the first 4 years of monitoring, the watershed was in a relatively undisturbed state, having last been logged prior to 1904, with only a county road traversing the ridgetops. Nearly half the watershed was clear-cut over a period of 3 years, and yarded primarily using uphill skyline cable systems to spur roads constructed high on the slopes. Three tributaries were maintained as controls and left undisturbed. Four years of data were collected after logging was completed. Exploratory analysis and model fitting permit characterization and quantification of the effects of watershed disturbances, watershed area, antecedent wetness, and time since disturbance on storm runoff and suspended sediment. Model interpretations provide insight into the nature of certain types of cumulative watershed effects.

INTRODUCTION

This paired-watershed study in the North Fork of Caspar Creek was motivated by a desire to understand how a particular logging system affects storm peak flows, flow volumes, and suspended sediment loads in a second-growth coastal redwood forest. The logging system consisted of clear-cutting with streamside buffers, and yarding primarily by skyline to spur roads located on upper slopes and ridges. Primary objectives were to quantify how impacts vary with different levels of disturbance and how the effects of a given disturbance vary downstream. Pursuant to these objectives, a statistical model was developed for a treatment-and-control experimental design involving multiple watersheds. The study was also an opportunity for testing new technologies, and demonstrates two new automated schemes for suspended sediment sampling. Techniques for estimating sediment loads from these samples are tested and applied.

Storm Peaks

Throughout much of the Pacific Northwest, a large soil moisture deficit develops during the dry summer. With the onset of the rainy season in the fall, the dry soil profile begins to be recharged with moisture. In the H.J. Andrews Experimental Forest in the Oregon Cascades, the first storms of the fall produced streamflow peaks from a 96-ha clear-cut watershed that ranged from 40% to 200% larger than those predicted from the pre-logging relationship [Rothacher, 1971; 1973]. In the Alsea watershed near the Oregon coast, Harris [1977] found no significant change in the mean peak flow after clear-cutting a 71-ha watershed or patch cutting 25% of an adjacent 303-ha watershed. However, when Harr [1976] added an additional 30 smaller early winter runoff events to the data, average fall peak flow was increased 122%. In Caspar Creek, Ziemer [1981] reported that selection cutting and tractor yarding of an 85-year-old second-growth redwood and Douglas-fir forest increased the first streamflow peaks in the fall about

300% after logging. The effect of logging on peak flow at Caspar Creek was best predicted by the percentage of area logged divided by the sequential storm number, beginning with the first storm in the fall. These first rains and consequent streamflow in the fall are usually small and geomorphically inconsequential in the Pacific Northwest. The large peak flows, which tend to modify stream channels and transport most of the sediment, usually occur during mid-winter after the soil moisture deficits have been satisfied in both the logged and unlogged watersheds.

Studies of large peak flows in the Pacific Northwest have not detected significant changes after logging. Rothacher [1971, 1973] found no appreciable increase in peak flows for the largest floods attributable to clear-cutting. Paired watershed studies in the Oregon Cascades [Harr et al., 1979], Oregon Coast Range [Harr et al., 1975; Harr, 1976; Harris, 1977], and at Caspar Creek [Ziemer, 1981; Wright et al., 1990] similarly suggested that logging did not significantly increase the size of the largest peak flows that occurred when the ground was saturated.

Using longer streamflow records of 34 to 55 years, Jones and Grant [1996] evaluated changes in peak flow from timber harvest and road building from a set of three small basins (0.6 to 1 km^2) and three pairs of large basins (60 to 600 km^2) in the Oregon Cascades. In the small basins, they reported that changes in small peak flows were greater than changes in large flows. In their category of "large" peaks (recurrence interval greater than 0.4 years), flows were significantly increased in one of the two treated small basins, but the 10 *largest* flows were apparently unaffected by treatment. Jones and Grant [1996] reported that forest harvesting increased peak discharges by as much as 100% in the large basins over the past 50 years, but they did not discuss whether the largest peak flows in the large basins were significantly affected by land management activities. Two subsequent analyses of the same data used by Jones and Grant concluded that a relationship could not be found between forest harvesting and peak discharge in the large basins [Beschta et al., 1997; Thomas and Megahan, 1998].

There are several explanations why relationships between land management activities and a change in storm peaks have been difficult to document. First, the land management activity may actually have no effect on the size of storm peaks. Second, because major storms are infrequent, the range of observations may not adequately cover the range of interest. Third, if the variability in response is large relative to the magnitude of change, it may be difficult to detect an effect without a large number of observations. Fourth, land-use changes in a large watershed are often gradual, occurring over several years or decades. The use of an untreated control watershed whose flows are well-correlated with the treated watershed can greatly increase statistical power, if both watersheds are monitored for an adequate number of years before and after the treatment is applied. The variability about the relation between the two watersheds can be critical. For example, when the South Fork (pre-treatment RMSE = 0.232) was used as the control, no change in peak streamflow was detected at the North Fork Caspar Creek weir after about 50% of the 473-ha watershed had been clear-cut logged. However, when the uncut tributaries within the North Fork (pre-treatment RMSE = 0.118) were used as the controls, an increase in peaks was detected [Ziemer, 1998]. In the analyses described in this paper, uncut tributaries in the North Fork will be used as controls for treated subwatersheds in the North Fork.

Sediment Loads

Paired watershed studies have been utilized to study the effects of logging activities on sediment loads as well as peak flows. Detecting changes in sediment loads is even more difficult than for peak flows, because sediment loads are more variable and more costly to measure. Studies are often dominated by a single extreme event [Grant and Wolff, 1991; Rice et al., 1979; Olive and Rieger, 1991], making the results more difficult to interpret. Most studies have utilized annual sediment loads [Harris, 1977; Rice et al., 1979; O'Loughlin et al., 1980; Grant and Wolff, 1991; Megahan et al., 1995], usually determined by surveys of settling basins behind impoundments. Sediment passing over a spillway is typically determined using sediment rating curves that relate suspended sediment concentration and water discharge.

Only one of these studies has been conducted in the redwood region. Rice et al. [1979] reported the suspended sediment load was 270% above that predicted for 1 year following roading of the South Fork of Caspar Creek, and the debris basin deposit 50% above that predicted. Lewis [1998] estimated an increase of 212% in suspended load in the 6 years following logging of the South Fork, despite a 3300 m^3 landslide contributing directly to the stream in the control watershed.

In the Alsea watershed in coastal Oregon, Brown and Krygier [1971] found a doubling of sediment loads in the year after roading in two different watersheds. In the watershed that was completely clear-cut and burned to the mineral soil the next year, sediment loads increased more than 10-fold the first year, then gradually declined in 7 years to near pretreatment levels [Harris, 1977]. In the watershed that was 25% clear-cut in three small units and remained mostly unburned, the road effect diminished in the second year, and measured increases in loads were not statistically different from the pretreatment relationship. Differences between sediment yields from the two treated watersheds were attributed primarily to the burning.

Sample sizes are necessarily rather limited in analyses using annual loads, an unfortunate situation, considering the variability in response. It is rare to find studies with more than 5 years of pretreatment measurements of sediment on both control and treated watersheds. Exceptions are the experiments in the Alsea [Harris, 1977] and the Silver Creek [Megahan et al., 1995] watersheds, which had 7 and 11 years' pretreatment data, respectively. Many studies have used no pretreatment measurements at all [Plamondon, 1981; O'Loughlin et al., 1980; Leaf, 1970]. These must rely on unproven assumptions about the relation between control and treated watersheds. Post-treatment sample sizes are limited by the rapidly changing conditions that usually follow a disturbance. In analyses based on annual loads, conditions might return to pretreatment levels before enough data are available to demonstrate a change occurred. Even if a change can be detected, it is difficult to establish reasonable bounds on the magnitude of change in the face of such high variability and small sample sizes.

Some paired watershed studies have attempted to look at changes in sediment concentrations. In the Alsea watershed study, an analysis of changes in sediment rating curves was less effective than an analysis of annual loads [Brown and Krygier, 1971]. Such analyses will usually be limited by the inadequacy of models relating sediment concentration to flow. Olive and Rieger [1991] were unable to establish a useful calibration using sediment concentrations, attributing the failure to the highly variable hydrologic environment. Fredricksen [1963] used paired specimens (collected within 1 hour of each other) to analyze changes in the H.J. Andrews concentrations, but found it necessary to discard 8 of 83 data points that represented "unpredictable events" and "sudden movements of soil". Considering the episodic nature of sediment transport, it is not surprising that simul-taneous specimens from adjacent watersheds are poorly related. Such episodic events should probably be focused upon rather than discarded.

Utilizing storm sediment loads circumvents the problems of properly pairing concentration data and permits much larger sample sizes than are possible in analyses of annual loads. Larger sample sizes permit more powerful statistical analyses and construction of confidence limits and prediction limits for responses. Because of the cost of reliably estimating storm loads, studies based upon them are rare. Miller [1984] estimated storm loads from three control and three treated watersheds using pumped specimens triggered at regular time intervals. Although no pretreatment data were collected, the replication of both treatment and control permitted an analysis of variance on storm ranks each year following the treatment. But sampling at regular time intervals will tend to miss peak concentrations in flashy watersheds unless the intervals are very short, in which case more field and lab work is required. In our study we used schemes that increased the probability of sampling during high flows and turbidities.

Cumulative Effects

A great deal of concern has been focused on the cumulative watershed effects of forest harvesting activities. This study design includes multiple gaging stations in the same watershed in order to evaluate cumulative effects. According to the U.S. Council on Environmental Quality's interpretation of the National Environmental Policy Act, a "cumulative impact" is the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions, regardless of what agency…or person undertakes such other actions [CEQ guidelines, 40 CFR 1508.7, issued 23 April 1971]. An activity's importance may depend heavily upon the context of historic and future land use. An infinite variety of interactions is imaginable. We attempt to answer three questions that arise with regard to cumulative watershed effects of logging activities :

1. How are impacts related to the total amount of disturbance? In particular, were the effects of multiple disturbances additive in a given watershed?
2. How do impacts propagate downstream? In particular, were downstream changes greater than would be expected from the proportion of area disturbed?
3. Can activities that produce acceptable local impacts result in impacts that are unacceptable by the same standard at downstream locations? In particular, were sediment loads in the lower watershed elevated to higher levels than in the tributaries?

The scope of these questions is limited here in order to permit scientific investigation. For example, question (2) does not consider that larger watersheds may experience different types of impacts than contributing watersheds upstream, and question (3) does not consider that different standards may be appropriate downstream because different resources may be at risk. Nevertheless, partial answers to these questions can be provided with regards to storm peak flows, flow volumes, and suspended sediment loads through watershed experiments and mathematical modelling.

Environment and History

The Caspar Creek Experimental Watersheds are a pair of rain-dominated forested catchments in the Jackson Demonstration State Forest on the coast of northern California. The 473-ha North Fork and the 424-ha South Fork are both located in the headwaters of the 2,167-ha Caspar Creek, which discharges into the Pacific Ocean near the town of Caspar. Uplifted marine terraces, to 320 m in elevation, are deeply incised by antecedent drainages resulting in a topography composed of steep slopes near the stream channel and broad rounded ridgetops. About one third of the basin's slopes are less than 17° and only 7% are greater than 35°. The watershed receives an average of 1200 mm of rainfall each year, 90% falling in the months of October through April. The forest is composed mainly of redwood (*Sequoia sempervirens* [D.Don.] Endl.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), grand fir (*Abies grandis* [Dougl. ex D.Don] Lindl.), and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). The well-drained clay loam soils developed in sandstone and shale units of the Franciscan assemblage [Bailey et al., 1964] and are highly erodible.

Streamside landslides, gully erosion, and debris flows are the major erosional processes delivering sediment to the channel system. Soil pipes, common in the unchannelized swales, and steep ephemeral tributaries discharge to the Caspar Creek main stems. Based on debris basin surveys and suspended sediment measurements, the perennial, gravel-bed North Fork channel typically transports about 70% of its sediment load in suspension, and sand rarely exceeds 50% of the suspension. Gravel bars associated with woody debris jams and debris-induced bank erosion furnish the bulk of bedload transported during peak flows. Finer sediments cap the highest gravel bars and are stored in pools for transport during modest storm flows [Lisle and Napolitano, 1998].

Between 1860 and 1904, the old-growth forest in the Caspar Creek watersheds was clear-cut and burned. Log drives were triggered by opening the spillway gates of log crib along the main-stem reaches of both the North Fork and the South Fork, profoundly affecting channel morphology during the earliest logging effort [Napolitano, 1998]. These gave way to semi-mechanized yarding of tributary catchments using railway inclines (tramways) and steam donkeys [Henry, 1998]. A historic stage coach route and a mid-1900's era forest road totaling 11.4 km in length follow the watershed divide along the north and east of the North Fork.

In 1962, Caspar Creek became the site of a paired watershed experiment. In 1968, the South Fork watershed was roaded, and from 1971-1973, it was selectively logged by tractor, while the North Fork watershed was maintained as an undisturbed control [Rice et al., 1979; Ziemer, 1981; Wright et al., 1990; Keppeler and Ziemer, 1990]. In 1985 and 1986, 59 ha of an ungaged tributary basin in the lower North Fork was clear-cut. The present study of cumulative impacts began in 1985 in the 384-ha Arfstein subwatershed (ARF), gaged on the North Fork's main stem just above the confluence with the ungaged tributary (Figure 1). When the stability of ARF's discharge rating equation recently came into question, we decided to use the larger North Fork watershed (NFC) in place of ARF for the analysis of storm peaks and flow volumes. ARF was retained, however, for the sediment analyses because roughly 40% of the suspended sediment settles in a debris basin immediately above the North Fork weir and thus is not measured at the NFC gaging station.

METHODS

Treatment

The treatment design was based on compliance with the California Forest Practice Rules in effect in the late 1980's, except that the proportion of the watershed cut in a 3-year period was atypically high for a watershed of that size. Streams bearing fish or aquatic habitat were protected with selectively logged buffer zones 15 to 46 m in width, depending on stream classification and slope steepness.

Logging began in the headwaters of the North Fork in May 1989 and ended in the lower watershed in January 1992 (Figure 1). Clear-cuts totalled 169 ha (43% of ARF) in blocks of 9 to 60 ha and occupied 30% to 98% of treated subwatersheds. Total logged areas, including timber selectively removed from stream buffer zones, are slightly larger (Table 1). The 60 ha cutblock was composed of two adjacent subwatersheds (CAR and GIB), and an exemption was required from the maximum clear-cut size permitted under California Forest Practice Rules in effect at the time. Of the clear-cut areas, 81% was skyline yarded to landings on spur roads built on the upper hillslopes away from the creeks. Logs only had to be suspended at one point, but in most cases full suspension was achieved by setting the chokers near the middle of the log. This prevented ground dragging except near landings and convex slope breaks. The remaining 19% of the clear-cut area was tractor yarded and was limited to ridgetop areas where slopes were generally less than 20°. In addition, about 34% of the timber was selectively removed from 19 ha of stream buffer zones. New roads, landings, skid trails, and firelines occupied from 1.9% to 8.5% of treated subwatersheds. Four cut units, totalling 92 ha, were broadcast burned following harvest.

Three subwatersheds (HEN, IVE, and MUN) within the North Fork were retained in an unlogged condition for use as controls. In addition, the South Fork watershed, unlogged since 1973, was monitored for possible use as a control.

Gaging Stations

A total of 15 gaging stations were monitored: the North and South Fork weirs (NFC and SFC), four stations on the main stem of the North Fork, and nine on tributaries of the North Fork (Figure 1). The channel control structures at the North and South Fork gaging stations are 120° V-notch weirs with concrete upper rectangular sections. The lowest three main-stem stations (ARF, FLY, and LAN) are rectangular plywood sections, rated by discharge measurements. Each rated section has a natural bottom and a stable downstream sill installed to control bed elevation within the rated section. Discharge at the upper main-stem station (JOH) and the nine tributaries is measured with Parshall flumes. Although the rated sections and flume installations were not designed to guarantee complete capture of subsurface intergravel flows, frequent inspections (before, during, and after storms) were made and regular maintenance was performed at these sites to ensure stable discharge estimates throughout the length of the study. Discharge ratings were validated with new measurements each year, and only station ARF required rating equation changes.

Suspended Sediment Data Collection

Selection At List Time (1986-1995). Selection At List Time (SALT) is a variable probability sampling method similar to PPS (probability proportional to size) sampling with replacement [Hansen and Hurwitz, 1943]. Their estimation formulas are identical. Both methods utilize an auxiliary variable, easily measurable for the entire population, to assign inclusion probabilities to each sampling unit of the population. (We have defined a sampling unit of the sediment population as the suspended sediment load passing a gaged cross-section in 10 min.) The variance is minimized for auxiliary variables that are proportional to the variable of interest. PPS requires enumerating the population and measuring the auxiliary variable on the whole population before sampling. SALT was developed as an alternative to PPS for populations which cannot be enumerated before sampling [Norick, 1969]. SALT inclusion probabilities are computed from an estimate of the auxiliary variable total. Immediately upon measuring each unit's auxiliary variable, a decision is made whether or not to select the sampling unit. The auxiliary variable might be a flow-based prediction of unit yield from a sediment rating curve [Thomas, 1985]. This results in a sampling rate that is proportional to predicted sediment yield. If the discharge and sediment rating curves are power functions of stage (water depth), the sampling rate will also be a power function of stage. In practice, we had to set an upper limit to the sampling rate and modify the parameters of the power function in order to sample small storms as well as large ones [Thomas, 1989].

To implement SALT, at each gaging station we interfaced an HP-71 calculator with an automatic pumping sampler and a transducer mounted in a stilling well. The calculator was programmed to "wake up" every 10 min, read the transducer stage height, calculate the auxiliary variable, and, using the SALT algorithm and a set of stored random numbers, decide whether to sample or not. If the decision was to sample, a signal was sent via an interface circuit board to the pumping sampler, which would then collect a specimen (to avoid ambiguity, the word "sample" is reserved to refer to a selected set of "specimens" or "bottles") from a fixed intake nozzle positioned in the center of the channel. Date, time, stage, and other bookkeeping details were recorded on the calculator for subsequent uploading.

Turbidity-controlled sampling (1996). After 10 years of monitoring, the number of gaging sites was reduced to eight: the North and South Fork weirs (NFC and SFC), two controls (HEN and IVE), one main-stem station (ARF), and three tributary stations (CAR, DOL, and EAG). At that time, SALT and the HP-71's were replaced by a turbidity-controlled sampling system utilizing programmable data loggers and *in situ* turbidity probes. Date, time, stage, turbidity, and sampling information are recorded at 10-min intervals. The nephelometric turbidimeters we are using emit infrared light and measure the amount scattered back to the probe. In lab tests, they respond linearly to sediments of a given size distribution. In the field, with mixed-size sediments present, departures from linearity are usually minor. During each storm event, when certain prespecified turbidity thresholds are reached, the data logger sends a signal to the pumping sampler to collect a concentration specimen. A separate set of thresholds is specified for falling and rising stage conditions. This system reduced sample sizes and field expenses considerably, while still permitting accurate estimation of sediment loads [Lewis, 1996].

Data quality control. Field crews typically visited each gaging station one to three times per 24-hour period during storms to check on flumes and equipment, record manual stage observations, measure discharge at rated cross-sections, and collect depth-integrated suspended sediment specimens. Chart recorders provided back-up data. When problems were encountered with the electronic stage record, they were corrected using observer records or digitized data from back-up chart recorders. In a few instances, portions of discharge records were corrected based on correlation with selected alternate gaging stations. All stage data were coded to indicate the quality of the data.

Storms with poor quality or reconstructed peak data were treated as missing data in the peaks analysis. Storms with 25% or more of the flow volume derived from poor quality stage data were treated as missing data in the flow volumes analysis.

In addition to the suspended sediment specimens collected by the SALT algorithm, auxiliary pumped specimens were manually initiated for comparison with simultaneous depth-integrated DH-48 specimens or to augment the sampling algorithm. On occasions when the HP-71/pumping sampler interface failed and could not be immediately repaired, the sampler was set to collect specimens at fixed time intervals. A total of 21,880 bottles were collected: 19,572 under SALT, 378 under the turbidity threshold algorithm, 1048 auxiliary, 686 depth-integrated, and 196 fixed-time specimens.

Suspended sediment concentration was determined in the laboratory using vacuum filtration. Specimens were coded to indicate such conditions as spillage, organic matter content, low volumes, and weighing errors. Those with serious errors were omitted from the analysis. Those with minor errors were re-examined in the context of the whole storm.

Field crews also noted conditions affecting discharge or sediment data including landslides, windthrow, and culvert blockages and diversions. Post-storm surveys of the watershed stream channels and roads were made to document erosion sources potentially affecting sediment loads.

Storm Definition and Feature Identification

A total of 59 storm events occurred during the 11-year study. Storm events were generally included in the study when the peak discharge at SFC exceeded 0.0016 $m^3s^{-1}ha^{-1}$ (recurrence interval about 7 times per year). A few smaller peaks were included in dry years. Multiple peak hydrographs were treated as multiple storms when more than 24 hours separated the peaks and the discharge dropped by at least 50% in the intervening period. When multiple peak hydrographs were treated as a single storm, the discharge for the peaks analysis was identified by selecting the feature corresponding to the highest peak at NFC. Thus the same feature was used at all stations, even if it were not the highest peak of the hydrograph at all stations. However, differences in peak discharge caused by this procedure were very small.

The start of a storm was chosen by seeking a point on the hydrograph, identifiable at all stations, where the discharge began to rise. The start times differed by no more than a few hours at the various stations. At the end of a storm, distinctive hydrograph features are more difficult to identify, unless a new start of rise is encountered. We therefore decided to use the same ending time for a given storm at all stations. The ending time was selected by observing the storm hydrograph for all stations and determining either the time of the next storm, the next significant rainfall, or a stable low-flow recession at all hydrographs, usually within about 3 days after the peak. The end of each storm was always well below the quickflow hydrograph separation point described by Hewlett and Hibbert [1967], except when the recession was interrupted by a new storm.

Dependent Variables

The response variables of interest in this study are storm runoff peak (instantaneous discharge), storm runoff volume (total discharge), and storm suspended sediment load (mass of particles greater than 1 micron in diameter). All are expressed on a unit area (per hectare) basis. The runoff variables were derived from the 10-min electronic record of stage and rating equations relating discharge to stage at each station. The computation of sediment loads is more involved and is described in the next section.

Computation of Suspended Sediment Loads

Correction to obtain cross-sectional average concentration. The pumping sampler intakes were oriented downstream and centered in the inclined throat sections of the Parshall Flumes. In the rated sections (ARF, FLY, and LAN), the intakes were similarly oriented at a fixed position about 9 cm off the bed. To determine whether the specimens were starved or enriched because of sampler efficiency or nozzle orientation or position, simultaneous ISCO and DH-48 depth-integrated (equal transit rate) specimens were collected throughout the study. A log-log regression of depth integrated concentration versus fixed intake concentration was developed for each station. Although only six of thirteen regressions differed significantly from the line $y=x$ (experimentwise α=0.05 with Bonferroni [Miller, 1981] adjustment), all fixed intake concentrations were adjusted using the back-transformed regression equations and corrected for bias [Baskerville, 1972] before storm loads were computed.

Load estimation in 1986-1995. Although sediment sampling followed SALT protocol in hydrologic years 1986-1995, we ultimately applied non-SALT methods of estimation to these samples for two reasons:

1. SALT does not provide a way to estimate sediment loads for periods when the sampling algorithm was inoperative due to equipment problems. Other methods can interpolate over such periods and utilize manually-initiated auxiliary specimens and those collected in fixed-time mode.
2. Using computer simulations on intensively collected storm data, other methods were found to have lower mean squared errors than SALT.

Although unbiased estimates of variance are not available for the alternate methodologies, the simulations strongly suggested that SALT variance estimates could be used as very conservative upper bounds on the variance. Two alternate methods were considered. In both of these methods the total load is computed by summing the products of water discharge and estimated concentration over all 10-min periods in the storm. The concentration, c, between adjacent sampled times t_1 and t_2 is modelled as either

1. a linear function of time: $c = c_1 + (t - t_1)(c_2 - c_1)/(t_2 - t_1)$, or
2. a power function of stage: $c = as^b$, where

$$b = \frac{\log c_2 - \log c_1}{\log s_2 - \log s_1}, \quad a = \frac{c_1}{s_1^b} \tag{1}$$

in which the subscripts identify concentrations and stages at times t_1 and t_2. These methods will be referred to as "time interpolation" and "stage interpolation" respectively. Stage interpolation has a better physical basis, but computational difficulties frequently arise when s_1 and s_2 are similar or equal, or when c_1 or c_2 is equal to zero. Therefore, time interpolation was substituted for stage interpolation when the power function defined by a pair of stages and sampled concentrations could not be computed or its exponent was not in the range between 1 and 10. If no specimens had been sampled within 10 hours prior to the start of the storm, the starting sediment concentration was assigned a value of zero and time interpolation was applied. An analogous procedure was followed for the end of the storm. The next section describes simulations leading to the decision that stage interpolation be used for estimating the sediment loads in 1986-1995.

Simulations comparing SALT and interpolation estimators. In addition to the usual SALT sampling, in 1994 and 1995 sediment concentration and turbidity at ARF was sampled at 10-min intervals for five storm events. This data, described in greater detail by Lewis [1996], provided realistic populations with known sediment loads that could be used in simulations to evaluate the performance of different load estimation methods. In addition to these five populations, eight storm populations were available from previous studies on the North Fork of the Mad River in northwestern California: three storms from December 1982, January 1983 and December 1983 [Thomas and Lewis, 1995] and five storms from February 1983 [Thomas and Lewis, 1993]. The Mad River concentrations were derived from turbidity charts and form a smoother, less realistic, time series than the ARF measurements.

In the simulations, 5000 independent SALT samples were selected from each storm event using SALT sampling parameters that were in use at ARF in 1995 and parameters thought to be optimal at Mad River. The sediment load was estimated for each of the 5000 samples using SALT and time and stage interpolation. The simulation results are strictly applicable only to comparing these estimators under a specific SALT sampling protocol.

The simulation results are summarized in Table 2. While SALT was unbiased as expected, it consistently has much higher root mean square error (RMSE) than the interpolated estimators. This can be attributed to the interpolation methods that take advantage of local trends in concentration that SALT ignores. Because the Mad River storm populations were smoother than those from ARF, they indicate a somewhat greater advantage for the interpolated estimators.

While time interpolation appears to have slightly less bias than stage interpolation, the differences in both bias and RMSE are small relative to the loads. Real data differ from these simulated data in that unexpected time gaps are created during unavoidable equipment malfunctions. Stage interpolation is expected to mimic true concentrations better than time interpolation over large time gaps, so the latter method (with the exceptions noted earlier) was chosen for this study during the SALT years (1986-1995).

Quality control for load estimates (1986-1995). Determining which calculated sediment load data were of high enough quality to include in the analysis was a subjective process and involved an examination of plots showing the storm hydrograph, sediment concentrations, and quality codes. The primary considerations were the number of known concentrations (sample size) and their temporal distribution relative to the hydrograph. Out of 51 storms and 15 stations (765 combinations), 74% of the load estimates were judged acceptable. Because sample sizes were in proportion to the size of storm events, most of the discarded loads were from small events. In those events that were retained, the median sample size was 20 and the median standard error from SALT was 14% of the estimated load. Based on the simulations (Table 2) and the fact that SALT estimates did not utilize all the available concentrations, it is likely that the median error from the interpolated estimates is well under 10% of the estimated load.

Load estimation in 1996. With turbidity-controlled sediment sampling in place in 1996, sediment loads were computed using "turbidity rating curves". Concentration was predicted by linear regressions of concentration on turbidity fit to each storm. This method was shown in simulations [Lewis, 1996], based on the same five ARF populations as shown in Table 2, to produce load estimates with RMSE of 8% or better while sample sizes were reduced to between 4 and 11, depending on storm size and sampling parameters. The interpolation methods used for 1986-1995 would not be as accurate for the generally smaller sample sizes obtained under turbidity-controlled sampling. However, because of intermittent fouling of the turbidity probes with debris and sediment, valid turbidities were not always available. During such periods, if enough concentration measurements were available (and extras were often triggered by false high turbidities), then time or stage interpolation was used. As a last resort, a sediment rating curve derived from nearby data was used to estimate concentrations. Out of 8 stations and 8 storms in 1996, a total of 46 sediment load estimates were judged to be of acceptable quality. The median sample size was 5 from these events.

Derivation of Independent Variables Used in the Analysis

The complete data set included both map-derived and field-derived variables. All disturbance variables were coded as proportions of watershed area. The basic watershed descriptors and variables that were useful in the analyses are shown in Table 1.

Topographic contours and streams were digitized from U.S. Geological Survey 7.5 min quadrangle maps. The mapped stream channels in harvest units were then extended to include all channels showing field evidence of annual scour and/or sediment transport before logging. Watershed boundaries were field-mapped using conventional tape-and-compass surveys, respecting diversions of surface runoff where road drainage structures directed flow into or out of the topographic watersheds. During road maintenance, efforts were made to limit changes in drainage due to ruts and berms. Harvest unit boundaries and roads were surveyed using differentially corrected GPS. All these lines were transferred to GIS coverages from which geographic variables were extracted. Burned areas, stratified into two severity classes, and herbicided areas were transferred to the GIS from field maps. For each variable measured, the area within 150 feet of a stream channel, and the length of channel within the affected area were extracted from the GIS.

The areal extent of ground disturbance from roads, landings, skid trails, firelines, and corridors created by dragging logs up the slope by cable were each determined from exhaustive field transects. The areas within 150 feet of a stream channel, and the number of stream crossings were also recorded for these variables.

Cutting age was calculated as the difference in hydrologic year of a given storm and the hydrologic year an area was logged. For watersheds with areas cut at different times, a weighted average cutting age was calculated using the cut unit areas as weights.

An antecedent wetness index intended to reflect seasonal differences in hydrograph response was derived using mean daily discharges from SFC. The daily discharges were accumulated and decayed using a 30-day half-life, i.e.

$$w_i = Aw_{i-1} + q_i \tag{2}$$

where w_i denotes the wetness index on day i, and q_i denotes the daily mean discharge at SFC on day i and the constant $A = 0.97716$ satisfies the relation A^{30}=0.5. The decision to use streamflow rather than precipitation to calculate antecedent conditions was based on the assumption that the history of the streamflow response would be a better predictor of streamflow than would the history of rainfall. The response of streamflow to precipitation is delayed as soil moisture deficit is recharged. A half-life of 30 days was selected to smooth the high frequency variation in streamflow, creating an index that would decline significantly only after lengthy dry periods. No optimization was done on the half-life, but it was found that $\log(w_i)$ made a slightly better predictor. The wetness index time series over the 11-year study period is displayed in Figure 2, with solid circles indicating the wetness level at the start of each storm. The wetness index varied from 13 to 150 at the onset of storms occurring in November and December, but assumed the full range from 13 to 562 at the onset of storms occurring in January, February and March. For two storms that occurred in May, the values of the index were 49 and 84.

Statistical Methods

Initially, simple log-log linear regressions were computed for each dependent watershed against selected control watersheds prior to treatment. The Chow test [Chow, 1960; Wilson, 1978] was used to test whether the post-treatment data differed in either intercept or slope from the pre-treatment regressions. Following Bonferroni's procedure [Miller, 1981] for these tests, an experimentwise error rate of 0.05 for 10 tests required setting the nominal α to 0.005 for each test. Because of their limited sample sizes, these tests, while easy to interpret, are not as powerful as models based on all of the data.

Models incorporating all of the watersheds were initially built up in a stepwise fashion using least squares estimation. At each step, residuals were plotted against candidate predictors to select the next variable and the appropriate transformation or form of interaction. Because a non-standard covariance model was employed, models were ultimately fitted using maximum likelihood estimation and selected using a combination of exploratory and diagnostic techniques.

Models for runoff (storm peaks and flow volumes). Consider the following pretreatment model:

$$\log(y_{ij}) = \beta_{0i} + \beta_{1i}\log(y_{Cj}) + \varepsilon_{ij} \tag{3}$$

where

y_{ij} = unit area response (peak or flow) at treated watershed i, storm j,
y_{Cj} = unit area response at control watershed in storm j,
ε_{ij} = non-independent normally distributed errors (see *Covariance Models* below),
and β_{0i} and β_{1i} are "location" parameters to be estimated for each watershed *i*. The log transformations are used in order that ε_{ij} appear to be normally distributed. The pretreatment model can be considered as a special case of the following model:

$$\begin{aligned}\log(y_{ij}) = &\left(\beta_{0i} + \beta_4 D_{ij} + \beta_6 D_{ij}\log(w_j) + \beta_7 D_{ij} a_i\right)\\ &+ \left(\beta_{1i} + \beta_5 D_{ij}\right)\log(y_{Cj}) + \varepsilon_{ij}\end{aligned} \tag{4}$$

where

D_{ij} = some measure of disturbance per unit area in watershed *i* at storm *j*,
w_j = wetness index at start of storm *j*,
a_i = drainage area of watershed *i*,
and β_4, β_5, β_6, and β_7 are parameters to be estimated. The log transformation of w_j is not critical, but was found to improve its explanatory value. Wetness enters the equation only as an interaction with D_{ij} because in the absence of disturbance wetness did not affect the relation between y_{ij} and y_{Cj}. As an interaction, it implies that the effect of disturbance on y_{ij} varies linearly with antecedent wetness. The $D_{ij}a_i$ term implies that the disturbance effect also varies linearly with watershed area and it is the key term in this model for detecting a cumulative effect. It describes how watershed impacts propagate downstream and we use it to test the null hypothesis that a unit area disturbance has the same unit area effect in watersheds of all sizes.

The first line of equation (4) permits the intercept of the relation between y_{ij} and y_{Cj} to change following disturbance. The second line, via the $D_{ij}\log(y_{Cj})$ term, permits the slope of that relation to change following disturbance. Equation (4) can be rearranged as

$$\begin{aligned}\log(y_{ij}) = &\beta_{0i} + \beta_{1i}\log(y_{Cj}) + \varepsilon_{ij}\\ &+ D_{ij}\left[\beta_4 + \beta_5\log(y_{Cj}) + \beta_6\log(w_j) + \beta_7 a_i\right]\end{aligned} \tag{5}$$

We now model the disturbance term using logged area and cutting age to represent loss of transpiration and interception following logging. Compacted areas such as roads, landings, skid trails, and firelines were not found to be useful predictors. Since relatively little transpiration occurs at Caspar Creek in the fall and winter, we treat areas logged in the fall or winter prior to the occurrence of a storm as special cases. Let

$$D_{ij} = f(t_{ij})(c_{ij}) + g(c'_{ij}) \tag{6}$$

where

t_{ij} = area-weighted mean cutting age (number of summers passed) in watershed *i* for areas logged in water years (defined as Aug.1 - July 31) preceding that of storm *j*
c_{ij} = proportion of watershed *i* logged in water years prior to that of storm *j*, and
c'_{ij} = proportion of watershed *i* logged prior to storm *j* but in the same water year

We model a linear recovery declining from a maximum of unity the year after cutting:

$$f(t_{ij}) = 1 - \beta_2 (t_{ij} - 1) \tag{7}$$

where β_2 is a parameter representing the recovery rate, and we assume the effect of newly cut areas depends only on the season they were cut:

$$g(c'_{ij}) = \beta_3^{(k)} c'_{ij} \tag{8}$$

where $\beta_3^{(k)}$ are parameters for the effect of cutting in the fall (k=1) and winter (k=2) immediately preceding storm j. Equation (6) becomes

$$D_{ij} = \left(1 - \beta_2 (t_{ij} - 1)\right) c_{ij} + \beta_3^{(k)} c'_{ij} \tag{9}$$

and the complete model is

$$\begin{aligned} \log(y_{ij}) &= \beta_{0i} + \beta_{1i} \log(y_{Cj}) + \varepsilon_{ij} \\ &+ \left[\left(1 - \beta_2 (t_{ij} - 1)\right) c_{ij} + \beta_3^{(k)} c'_{ij} \right] \\ &\times \left[\beta_4 + \beta_5 \log(y_{Cj}) + \beta_6 \log(w_j) + \beta_7 a_i \right] \end{aligned} \tag{10}$$

To investigate whether unit area response increases downstream independently of disturbance, we can look for a relation between β_{0i} and a_i. Alternatively, we can replace β_{0i} with the linear expression $\beta_0^{(1)} + \beta_0^{(2)} a_i$ and test the hypothesis $H_0{:}\beta_0^{(2)} = 0$. If unit area responses tend to increase downstream, then cumulative impacts might occur where a response threshold of acceptability is exceeded only below some point in the stream network, even though unit area disturbance is no greater in that point's watershed than in watersheds further upstream.

Model (10) is not a linear model because it involves products of the parameters to be estimated. The non-linearity was introduced as a parsimonious way of modelling recovery with time since logging. It avoids introducing separate recovery parameters for each of the terms in equation (4) that involve D_{ij}.

Models for suspended sediment loads. Suspended sediment load from an untreated control watershed was found to be a much better predictor of sediment load at treated watersheds than water discharge at either location. However, the change in storm flow in the treated watershed, relative to that in the control, was found to be the next best predictor in a model for suspended sediment loads. The change in flow, Δq, was formulated two ways:

1. The residual from the flow model with D_{ij} set to zero

$$\Delta q_{ij}^{(1)} = \log(y_{ij}) - \left(b_{0i} + b_{1i} \log(y_{Cj})\right) \tag{11}$$

where b_{0i} and b_{1i} are estimates of the flow model parameters β_{0i} and β_{1i}.

2. The log of the ratio of the flows between the treated and control watersheds:

$$\Delta q_{ij}^{(2)} = \log\left(y_{ij} / y_{Cj}\right) = \log\left(y_{ij}\right) - \log\left(y_{Cj}\right) \tag{12}$$

The first form makes better sense hydrologically, but treating it as an independent variable may not be statistically legitimate later when estimating precision later on, because it involves parameter estimates from another model. Nevertheless, both forms of Δq were considered. These variables are not useful in a predictive setting because the flows are not known in advance, but the main purpose of these models is explanatory. If prediction is needed, then a third form might be substituted as an approximation to $\Delta q_{ij}^{(1)}$:

3. The predicted change in $\log(y_{ij})$ from equation (10):

$$\Delta q_{ij}^{(3)} = \left[\left(1 - b_2(t_{ij} - 1)\right)c_{ij} + b_3^{(k)}c_{ij}'\right] \times \left[b_4 + b_5 \log(y_{Cj}) + b_6 \log(w_j) + b_7 a_i\right] \quad (13)$$

where the b's are estimates of the β's in equation (10).

After Δq and one or two disturbance variables were included in the model, no further gains were realized in the sediment models by including factors such as antecedent wetness and cutting age. So, unlike the runoff models, the sediment models remain linear in their parameters:

$$\begin{aligned} \log(y_{ij}) = {} & \beta_{0i} + \beta_{1i}\mathrm{bg}(y_{Cj}) + \beta_2 \Delta q_{ij} \\ & + \left(\beta_3 + \beta_4 \mathrm{bg}(y_{Cj}) + \beta_5 a_i\right)x_{ij}^{(1)} \\ & + \left(\beta_6 + \beta_7 \mathrm{bg}(y_{Cj}) + \beta_8 a_i\right)x_{ij}^{(2)} + \varepsilon_{ij} \end{aligned} \quad (14)$$

where

y_{ij} = unit area sediment load at treated watershed i, storm j,
y_{Cj} = unit area sediment load at control watershed in storm j,
Δq_{ij} = change in flow as defined by (11) or (12) in watershed i, storm j,
a_i = drainage area of watershed i,
$x_{ij}^{(1)}$ = a measure of unit area disturbance in watershed i, storm j,
$x_{ij}^{(2)}$ = a second measure of unit area disturbance in watershed i, storm j,
ε_{ij} = non-independent normally distributed errors (see *Covariance Models* below),

and the β's are parameters to be estimated. The logic behind the interaction terms involving $\log(y_{Cj})\, x_{ij}^{(k)}$ and $a_i x_{ij}^{(k)}$ is the same as in the runoff models. And, as with model (10), we can replace β_{0i} in (14) with the expression $\beta_0^{(1)} + \beta_0^{(2)} a_i$ to investigate whether unit area loads increase downstream independently of disturbance.

Covariance models. The residual covariance was found to depend upon watershed size and location. The correlations decreased with increasing distance between watershed centroids and the variance decreased with increasing watershed size. Serial autocorrelation in the residuals for most watersheds was weak or absent, so responses from different storms were considered independent. The errors were thus assumed to follow a multivariate normal distribution with a covariance matrix for each storm. The dimensions of this square matrix are equal to the number of treated watersheds having good data in that storm. The covariances in the matrix for storm j are modelled as:

$$Cov(\varepsilon_{i_1 j}, \varepsilon_{i_2 j}) = \sigma_{i_1 i_2}^2 = \rho_{i_1 i_2}\sigma_{i_1}\sigma_{i_2} \quad (15)$$

where

$\rho_{i_1 i_2}$ = the correlation between $\varepsilon_{i_1 j}$ and $\varepsilon_{i_2 j}$,
σ_{i_1} and σ_{i_2} = the standard deviations of $\varepsilon_{i_1 j}$ and $\varepsilon_{i_2 j}$
$\varepsilon_{i_1 j}$ and $\varepsilon_{i_2 j}$ = errors for watersheds i_1 and i_2 in storm j

Subscripts j have been omitted from $\rho_{i_1 i_2}$, σ_{i_1} and σ_{i_2} because these terms are assumed to be independent of storm number and are, in fact, modelled upon the errors from all storms. Two models for the correlation $\rho_{i_1 i_2}$ were found to fit the runoff and sediment data.

1. Exponential decline with distance:

$$\rho_{i_1i_2} = \frac{\exp(-\theta_1 d_{i_1i_2}) + \theta_2}{1+\theta_2} \tag{16}$$

where $d_{i_1i_2}$ is the distance separating watersheds i_1 and i_2, and θ_1 and θ_2 are parameters to be estimated. In this model the correlations decline asymptotically from unity to the value $\theta_2/(1+\theta_2)$.

2. Linear decline with distance:

$$\rho_{i_1i_2} = \begin{cases} 1, & d_{i_1i_2} = 0 \\ \theta_1 - \theta_2 d_{i_1i_2}, & d_{i_1i_2} > 0 \end{cases} \tag{17}$$

The standard deviations σ_i were modelled as a declining power function of watershed area:

$$\sigma_i = \theta_3 a_i^{-\theta_4} \tag{18}$$

where θ_3 and θ_4 are parameters to be estimated. All peaks models discussed in this paper (other than the least squares fits) employed equations (15), (16), and (18). The flow and sediment models employed equations (15), (17), and (18)

Method of estimation. The parameters of the model were estimated using the method of maximum likelihood [Mood et al., 1974]. The likelihood function is assumed to be the multivariate normal density of the ε_{ij} treated as a function of the β and θ parameters. In practice we minimize the negative of the log likelihood. In this problem, the log-likelihood is equal to the sum of the independent storm-wise log-likelihoods. Thus, the dimension of the multivariate density function is the number of watersheds represented in a given storm, a maximum of 10. The log-likelihood functions and their gradients (derivative vectors) are shown in APPENDIX B. They were programmed in S-Plus [Statistical Sciences, 1995] and FORTRAN, and solved using the S-Plus function *nlminb* (nonlinear minimization subject to bound-constrained parameters). Least squares estimates of the parameters were used as starting guesses in these iterative numeric calculations.

Model size. The inclusion of up to 31 parameters in these models raises questions about overfitting. These questions were addressed by cross-validation (discussed below) after a model was selected, but the proper model size was selected with the objective of minimizing a variant of Akaike's information criterion [Burnham and Anderson, 1998],

$$\text{AIC}_c = -2\log(L) + 2K\left(\frac{n}{n-K-1}\right) \tag{19}$$

where L is the maximum likelihood, K is the number of parameters estimated, and n is the sample size. This criterion is recommended over the unmodified AIC when the ratio n/K is small (less than about 40). The inclusion of the 20 location parameters β_{0i} and β_{1i} is strongly supported by AIC$_c$. Its value increased by 14 to 88 units in the various models when one or two parameters were substituted for either β_{0i} or β_{1i}. Increases of 10 or more AIC units indicate clearly inferior models [Burnham and Anderson, 1998]. Because of the computational time required to fit each model, it was impractical to obtain the likelihoods of all alternative models. For that reason, parameters other than β_{0i} and β_{1i} were evaluated using hypothesis tests based on the normal distribution, and AIC$_c$ was computed only for the more promising candidate models.

Hypothesis testing. Maximum likelihood parameter estimates are approximately multivariate-normally distributed for large samples [Rao, 1973]. The estimated covariance matrix of the estimates was obtained by inverting the observed information matrix, using a finite difference approximation to the Hessian, or matrix of second derivatives of the log-likelihood function [Bishop et al., 1975; McCullagh and Nelder, 1989]. (The observed information matrix is the negative of the Hessian, evaluated at the maximum likelihood estimates.) The standard errors, s_b, of the estimated parameters are the square roots of the diagonal of the covariance matrix. Since the parameter estimates are asymptotically normal, a simple test of the hypothesis H_0: $\beta_i = c$ is provided by observing whether or not the statistic $(b_i - c) / s_b$ is in the rejection zone of the standard normal distribution. The p-values from these hypothesis tests are identified as p_N in this paper. Tests with $p_N < 0.01$ are considered significant in this paper. Tests with $0.01 < p_N < 0.05$ are considered "suggestive" but not conclusive.

Observed change in response. "Observed change" in response was calculated by comparing the observed response, y_{ij}, with an estimate of the expected response, $E(y'_{ij})$, from the same storm and watershed in an undisturbed condition. We define the percentage change in response as

$$p_{ij} = 100\left(\frac{y_{ij} - E(y'_{ij})}{E(y'_{ij})}\right) = 100\left(\frac{y_{ij}}{E(y'_{ij})} - 1\right) \tag{20}$$

The expected undisturbed response, $E(y'_{ij})$, is a function of $E\left(\log(y'_{ij})\right)$:

$$E(y'_{ij}) = \exp\left[E\left(\log(y'_{ij})\right) + \tfrac{1}{2}\sigma_i^2\right] \tag{21}$$

Setting disturbance to zero in either model (10) or (14) above, we have $E\left(\log(y'_{ij})\right) = \beta_{0i} + \beta_{1i}\log(y_{Cj})$. The variances σ_i^2 are a function of θ_3 and θ_4 given by model (18). A nearly unbiased estimator of $E(y'_{ij})$ is given by

$$\hat{y}'_{ij} = \exp\left[b_{0i} + b_{1i}\log(y_{Cj}) + \tfrac{1}{2}\left(\hat{\theta}_3 a_i^{\hat{\theta}_4}\right)^2\right] \tag{22}$$

where b_{0i}, b_{1i}, $\hat{\theta}_3$, and $\hat{\theta}_4$ are the maximum likelihood estimates of β_{0i}, β_{1i}, θ_3, and θ_4, respectively. The term $\frac{1}{2}\hat{\sigma}_i^2 = \frac{1}{2}\left(\hat{\theta}_3 a_i^{\hat{\theta}_4}\right)^2$ is often called the Baskerville [1972] bias correction. An approximation for p_{ij} that we will call the "observed change in response" is obtained by substituting $\hat{y}'_{ij}$ for $E(y'_{ij})$ in (20):

$$\tilde{p}_{ij} = 100\left(\frac{y_{ij}}{\hat{y}'_{ij}} - 1\right). \tag{23}$$

Of course we are not just interested in the changes in response for the particular values of the explanatory variables encountered during the study. We would like to study the percentage change, p_0, for an arbitrary vector, $\mathbf{x}_0$, of explanatory variables. An unbiased estimator and confidence interval for $E(p_0)$ as well as a prediction interval for p_0 are derived in APPENDIX C. The confidence interval represents the uncertainty of the mean, $E(p_0)$, given $\mathbf{x}_0$. The prediction interval indicates the variability in the individual response p_0, given $\mathbf{x}_0$. Prediction intervals are wider than confidence intervals because they include the variability in the response about its mean value as well as the variability due to uncertainty in the mean itself.

Cross-validation of models. To investigate the possibility that the models were overfitted to the data, ten-fold cross-validation was used [Efron and Tibshirani, 1993]. The data are split into ten groups. Each observation is predicted from a model based on all of the data except that group to which the observation belongs. The RMSE of these predictions is called the cross-validation prediction error and it may be compared with the RMSE of the models fitted with all the data to assess overfitting.

A regression of the observed responses on the fitted values, known as the *calibration*, should have an intercept near zero and slope near unity. The regression of the observed responses on the cross-validated predictions is expected, in general, to have a slope less than one [Copas, 1983]. This phenomenon, known as *shrinkage*, implies that predictions of high or low response values tend to be too extreme. The degree of departure of the calibration slope from unity provides another measure of overfitting.

Because the data were not independent, the cross-validation was repeated using two different methods for splitting the data:

1. Data were randomly divided into groups of equal size.
2. Post-treatment data were omitted systematically, one station at a time.

The latter method does not provide cross-validated predictions for the pre-treatment data, but if all the data from a station, say watershed *i*, are omitted, it becomes impossible to estimate β_{0i} and β_{1i}, which are required to make predictions for that watershed. Nevertheless, the one-station-at-a-time method is probably a more rigorous validation for the inclusion of alternative disturbance variables because it will give higher error rates for models that include variables correlated with the response due to just one or two watersheds.

RESULTS

Storm Peaks

The analysis included 226 pre-treatment and 300 post-treatment observations representing 59 storms on the 10 treated watersheds. For the 226 pretreatment peaks, the control watersheds correlating best with watersheds to be treated were tributaries HEN and IVE, and MUN (Figure 3). The mean of the peaks at HEN and IVE (designated HI), or at HEN, IVE, and MUN (designated HIM), had higher correlations than did peaks from either HEN, IVE, or MUN individually. Because MUN was not monitored the last year of the study, HI was chosen as the control for the peaks analysis.

The Chow tests [Chow, 1960; Wilson, 1978], based on the HI control, revealed strong evidence that post-treatment data differed from pre-treatment regressions. Eight of the 10 watersheds departed ($p < 0.005$) from these regressions after logging commenced. The other two, FLY and LAN on the main stem, had p-values less than 0.05. Departures from the pre-logging regression were greatest in the clear-cut tributaries: BAN, CAR, EAG, GIB, and KJE (Figure 4).

Seasonal patterns in the departures from the pre-treatment regressions were evident in most of the treated watersheds. For example, Figure 5 shows the post-logging departures for watershed EAG plotted against storm number. The largest percentage departures occurred early in the season. These were usually, but not always, relatively small storms. Storms 28 and 29 did not show treatment effects, apparently because logging had just taken place the same winter, so insufficient time had elapsed for soil moisture differences to develop between the controls and the logged area. This exemplifies the situation that necessitated modelling of the disturbance term using equation (9).

To develop an overall model, an intercept and slope for each watershed (equation (3)) was initially fit by least squares. The residuals from this model show a strong interaction between proportion of area logged and antecedent wetness (Figure 6). Area logged includes clear-cut areas and a portion of each buffer zone corresponding to the proportion of timber removed (Table 1). The relation of the residuals with area logged is linear, the slope decreasing from strongly positive with increasing wetness (Figure 6, top row). The relation with log(wetness) is linear, the slope becoming strongly negative with increasing logged area (Figure 6, bottom row). These relations imply a product term is an appropriate expression of the interaction, and the coefficient is expected to be negative. The fact that the average residual increases with different categories of area logged but not with wetness shows that a solo logged area term is needed in the model as well as the interaction product, but a solo wetness term is not. No variables related to roads, skid trails, landings, firelines, burning or herbicide application were found to improve the fit of the linear least squares model that includes logged area and its interaction with wetness. Adding logged area and the wetness interaction to the model, a plot of post-treatment residuals against time after logging (Figure 7) indicates an approximately linear recovery trend in the first 7 years.

When model (10) was fit to the data, the coefficient b_7 on the cumulative effect term did not differ significantly from zero (Table 3, p_N= 0.21). The coefficient b_5 was negative but not highly significant (p_N=0.047), weakly suggesting that the effect of logged area on peak flows tends to diminish in larger storms. The coefficient b_4 on logged area was positive as expected and its interaction with wetness, b_6, was negative as expected. The recovery coefficient, b_2, indicates an average recovery rate of about 8% per year. The null hypothesis for each of the parameters $\beta_3^{(k)}$ is $H_0 : \beta_3^{(k)} = 1$, because the recovery model assumes a value of unity the year after logging. The coefficient $b_3^{(1)} = 0.59$ (standard error 0.10) indicates a reduced effect from fall logging on peaks in the following winter and $b_3^{(2)} = 0.00$ suggests that the effects of winter logging on peak flow are delayed until a growing season has passed.

There was no indication of a dependency on watershed area in either the coefficients b_{0i} or b_{1i} from model (10). When we replaced β_{0i} in model (10) with the expression $\beta_0^{(1)} + \beta_0^{(2)} a_i$, the coefficient $b_0^{(2)}$ was not significantly different from zero (p_N=0.58), indicating no trend of unit area storm peak with watershed area.

The exponentially declining correlation model (18) was used when solving model (10) for peak flows (with β_7 fixed at zero), and it can be seen to be a reasonable fit (Figure 8). The variance model (18) also seems reasonable (Figure 9). The Box-Pierce test [Shumway, 1988] did not indicate the presence of serial autocorrelation at any of the stations (minimum p=0.089). The residuals conform very well to the normal distribution (Figure 10), as do plots for individual stations (not shown), validating our choice of likelihood function. The lone outlier is from a storm at GIB that produced 2 peaks at all stations except GIB. (The first peak was selected for the storm but was identifiable only as a shoulder of the hydrograph at GIB.) The model fits the data very well (Figure 11). For the regression between observed and fitted values, $r^2 = 0.946$. This compares with $r^2 = 0.848$ for a model with no disturbance variables and $r^2 = 0.937$ for model (3) fit to only the pre-treatment data, so the model fits the post-treatment data as well as the pre-treatment data.

Magnitude of observed changes. Maximum peak flow increases based on equations (22) and (23) were about 300%, but most were less than 100% (Figure 12). The mean percentage increase declined with wetness but was still positive even under the wettest conditions of the study ($w_i > 500$), when it was 23% for clear-cuts but only 3% in partially cut watersheds. Increases more than 100% generally only occurred in clear-cuts under relatively dry conditions ($w_i < 50$) and when peaks in the control were less than 0.0025 $m^3s^{-1}ha^{-1}$ (return period 3-4 times per year). Large increases occurred less frequently as the winters progressed, but increases over 100% did occur in January and February. The mean percentage increase in peak flow declined with storm size and then levelled at an average increase of 35% in clear-cuts and 16% in partially cut watersheds for peaks greater than 0.004 $m^3s^{-1}ha^{-1}$ (return periods longer than 0.5 years) (Figure 13). For a storm size having a 2-year return period, the average peak-flow increase in 100% clear-cuts was 27% [Ziemer, 1998].

Figure 14 shows 95% confidence intervals for the modelled mean response in a 20-ha watershed that has been 50% clear-cut, for two wetness conditions and two cutting ages within the range of our data. The effect of antecedent wetness is a greater influence on the response than time since cutting, although the recovery data only span 7 years. Prediction intervals are much wider than confidence intervals, revealing post-treatment variability that is greater than the treatment effect itself.

Storm Runoff Volume

The analysis included 527 observations representing 59 storms. For the same reasons as in the peaks analysis, HI (the mean of HEN and IVE) was chosen as the control. The modeling results are similar to the peaks analysis results, except that the watershed area interaction b_7 was marginally significant (Table 4, p_N=0.012) and watershed correlations were found to decline linearly with distance, so model (17) was used instead of (16) in the covariance model. For the sake of brevity, the modeling results for storm runoff volume are omitted, and we report only the coefficients (Table 4) and the magnitude of observed changes.

Magnitude of observed changes. The maximum storm runoff volume increase from equations (22) and (23) was 400%, but most were less than 100%. The mean percentage increase declined with wetness but was still positive even under the wettest conditions of the study ($w_i > 500$), when it was 27% for clear-cuts and 16% in partially cut watersheds. Increases more than 100% generally only occurred in clear-cuts under relatively dry conditions ($w_i < 100$) and when runoff volume in the control was less than 250 m^3ha^{-1}. Large increases occurred less frequently as the winters progressed, but in-creases over 100% did occur in January and February. The mean percentage increase in storm runoff volume declined with storm size and then leveled at an average increase of 30% in clear-cuts and 13% in partially cut watersheds for storm runoff greater than 250 m^3ha^{-1}.

Annual storm runoff volume (sum of storms) increased an average of 58% (1119 m^3ha^{-1}) in clear-cut watersheds and 23% (415 m^3ha^{-1}) in partly clear-cut watersheds (Table 5). Based on the complete discharge record at NFC, the runoff volume for the storms included in this analysis represents 41 to 49% of the total annual runoff volume in individual tributaries.

Figure 15 shows confidence intervals and prediction intervals for storm runoff volume in a 20-ha watershed that has been 50% clear-cut, under two wetness conditions and two cutting ages within the range of our data.

Suspended Sediment Loads

The relatively large number of missing observations resulting from quality control screening complicated the selection of controls for the sediment analysis. The use of synthetic controls such as HI and HIM permitted larger sample sizes because these means could be computed from any combination of non-missing controls. Thus the sample size was 376 with the HIM control, but only 333 with the HI control, and less than 300 with HEN or IVE alone. Although HIM control permitted the largest sample size, its correlations tended to be lower than those of HI (Figure 16). We therefore present the analysis twice, once with the HIM control and once with the HI control.

Chow tests [Chow, 1960; Wilson, 1978] for treatment effects at individual stations gave mixed results (Table 6). Only 2 of the tests were significant when HIM was used as the control and 3 were significant with the HI control. The tributaries all had more significant changes than the main-stem stations. Figure 17(top row) indicates that suspended sediment loads increased in all the clear-cut tributaries except KJE, where loads appear to have decreased after logging. The only partly clear-cut watershed on a tributary (DOL) also showed highly significant increases in sediment loads. The upper main-stem stations (JOH and LAN) showed no effect after logging, and the lower main-stem stations (FLY and ARF) experienced increases only in smaller storms. Summing suspended sediment over *all* storms, the four main-stem stations all showed little or no change (Table 7). Sediment loads at the North Fork weir, below ARF, increased by about 89%

per year, mainly as a result of a large landslide in the ungaged subwatershed that enters between ARF and NFC.

Models with HI control. The analysis included 333 observations representing 43 storms. In these models (14), the change in storm flow volume $\Delta q_{ij}^{(1)}$ was found to be the best explanatory variable after sediment load from the HI control, y_{HI}. Figure 18 shows the relation between the post-treatment sediment departures from pretreatment model (3)) and $\Delta q_{ij}^{(1)}$. Since both variables are differences in logarithms, it is convenient to express them as ratios of observed to predicted response, obtained by exponentiating the differences. The linear correlation between the sediment and flow departures is 0.54.

After $\Delta q_{ij}^{(1)}$ is in the model, disturbance variables explain only a very small part of the remaining variation (Figure 19). The length of unbuffered stream channel in clear-cut areas was one of the more useful disturbance variables in the sediment models. Under California Forest Practice Rules in effect during the North Fork logging, vegetation buffers were not required for stream channels that do not include aquatic habitat. The best models were found when this variable was separated into channels in burned clear-cuts and channels in unburned clear-cuts. The variable did not need to be separated, however, in the interaction terms. Thus the model (14) was modified to:

$$\begin{aligned} \log(y_{ij}) = \beta_{0i} + \beta_{1i}\log(y_{(\text{HI})j}) + \beta_2\Delta q_{ij}^{(1)} \\ + \beta_3 x_{ij}^{(1)} + \beta_4 x_{ij}^{(2)} + \beta_5(x_{ij}^{(1)} + x_{ij}^{(2)})\log(y_{(\text{HI})j}) \\ + \beta_6(x_{ij}^{(1)} + x_{ij}^{(2)})a_i + \varepsilon_{ij} \end{aligned} \quad (24)$$

where

$x_{ij}^{(1)}$ = length of stream channel in burned clear-cuts, and

$x_{ij}^{(2)}$ = length of stream channel in unburned clear-cuts

To indicate the relative contribution of the various terms in model (24), the increase in residual sum of squares is shown for least squares models after dropping each explanatory variable (Table 8).

The maximum likelihood estimates for model (24) are shown in Table 9. The coefficient estimate b_3 is about 1.8 times b_4, suggesting that streams in burned clear-cuts contribute more sediment than those in unburned clear-cuts. The estimate, b_5, of the storm size interaction is negative, suggesting that the ratio between post-treatment and pretreatment sediment loads diminishes for larger events. The estimate, b_6, of the cumulative effect coefficient in this model was negative and was found marginally significant ($p_N = 0.044$). This interaction in the sediment model only partly offsets the small positive interaction that was noted in the runoff model and is hidden in the term $\Delta q_{ij}^{(1)}$.. Other variables being equal, the model still predicts larger unit area sediment loads from larger watersheds (Figure 20). Because of its marginal significance, the β_6 term was dropped from the model for the remainder of this section.

The fitted intercepts b_{0i} from model (24), with β_6 fixed at zero, tend to increase with watershed area (Figure 21), with the exceptions of KJE (K) and JOH (J). This pattern in the intercepts is confirmed by substituting $\beta_0^{(1)} + \beta_0^{(2)}a_i$ for the term β_{0i}. The fitted coefficient $b_0^{(2)}$ is positive and differs significantly from zero (p_N=0.0031). The slope coefficients b_{1i}, are all between 0.8 and 1, except BAN (0.73) and EAG (1.06), and show no trend with area. Thus, ignoring the anomalous KJE and JOH for the moment, the unit area sediment loads from the watersheds prior to disturbance (Figure 22) tend to be highest in the four largest watersheds (ARF, FLY, LAN, and DOL), followed by the tributaries CAR, GIB, and EAG, and are lowest in the smallest watershed BAN.

Although there are signs of positive or negative trends in some individual watersheds, the residuals from model (24) display little if any trend with time (Figure 23). If the anomalous JOH and KJE, which did not show treatment effects, are omitted, hints of a recovery trend disappear entirely.

The covariance model fit rather well for the sediment models based on HI. Correlations declined linearly with watershed separation (Figure 24) and variance declined as a power function of watershed area (Figure 25). The Box-Pierce test [Shumway, 1988] indicated (using an experimentwise error rate of 0.05) the presence of serial autocorrelation at four stations (ARF, BAN, GIB, and KJE) and suggests that we conservatively assess marginally significant terms in the model. The residuals again conform very well to the normal distribution and there is only one outlier (associated with stream bank collapses in EAG). The regression between observed and fitted values has $r^2 = 0.915$. This compares with $r^2 = 0.828$ for a model with no disturbance variables and $r^2 = 0.948$ for model (3) fit to only the pre-treatment data. So the complete model (without the cumulative effects term) explains (0.915 – 0.828) / (0.948 – 0.828) = 72% of the variation introduced by the post-treatment data.

Models with HIM control. This analysis included 376 observations representing 51 storms. In models developed with the HIM control, the log-ratio flow variable $\Delta q_{ij}^{(2)}$ was found to be a better explanatory variable than the flow model residual $\Delta q_{ij}^{(1)}$. The most important disturbance variable in these models is proportion of the watershed occupied by road cuts and fills. The length of stream channel in clear-cuts and the interaction terms in model (24) were not significant when tested in maximum likelihood models with the HIM control. This is partly explained by a high correlation (0.80) between road cut/fills and stream length in burned areas. A negative interaction between road cut/fills and watershed area was marginally significant (p_N=0.037). The maximum likelihood estimates for the model

$$\begin{aligned}\log(y_{ij}) = \beta_{0i} + \beta_{1i}\log(y_{(\mathrm{HIM})j}) \\ + \beta_2\Delta q_{ij}^{(2)} + \beta_3 x_{ij} + \beta_4 x_{ij} a_i + \varepsilon_{ij}\end{aligned} \quad (25)$$

where x_{ij} is the proportion of the watershed occupied by road cuts and fills, are shown in Table 10. As with model (24), the interaction only serves to partly offset the positive interaction hidden in the $\Delta q_{ij}^{(2)}$ term, and we do not consider it significant. The trend in intercepts that was seen for model (24) is also present in model (25). Setting β_4 to zero, and substituting $\beta_0^{(1)} + \beta_0^{(2)} a_i$ for β_{0i}, we test $\beta_0^{(2)}$ and again find that it is positive and differs significantly from zero (p_N=0.0023). The residuals from model (25), with β_4 fixed at zero, do not display a significant trend with time since logging.

Magnitude of observed changes. Sediment load increases were calculated using equations (22) and (23) with the coefficients estimated from model (25). Median increases were 64% in partly clear-cut watersheds and 107% in clear-cut watersheds (Figure 26). Absolute increases were similar in clear-cut and partly clear-cut watersheds (Figure 27). Most of the larger percentage increases in clear-cuts were from small events and equated to relatively minor absolute increases in load. As one would expect, there is a tendency for percentage increases to decrease with storm size, and for absolute increases to increase with storm size. Figure 28 shows 95% confidence intervals and prediction intervals for the sediment model (25), with the area×disturbance interaction, β_4, set to zero. The watersheds are ranked by increasing proportion of road cuts and fills (x_{ij}). The uncertainty in the model and the variability in suspended sediment loads is much greater than for peak flow or storm runoff volume.

Summing storms by year, annual suspended sediment loads increased an average of 212% (262 kg·ha^{-1}yr^{-1}) in clear-cut watersheds and 73% (263 kg·ha^{-1}yr^{-1}) in partly clear-cut watersheds (Table 11). The absolute increases are heavily influenced by outlying data points that tend to occur in wet years (1993 and 1995), while the percentage increases weight all years approximately equally. If the extreme outlier in the partly clear-cut population (Figure 27) is omitted, the mean increase in that category drops to

67% (180 kg·ha^{-1}yr^{-1}). Because of the highly skewed distribution of sediment loads, median increases were much smaller: 109% (59 kg·ha^{-1}yr^{-1}) in clear-cut watersheds and 52% (46 kg·ha^{-1}yr^{-1}) in partly clear-cut watersheds. Based on the complete discharge record at NFC, the storms included in this analysis represent 36 to 43% of the total annual runoff in individual tributaries. However, these storms include roughly 90% of the annual suspended sediment load [Rice et al., 1979].

Cross-Validation of Models for Runoff Peaks, Volumes, and Sediment Loads

Predictions of storm runoff from random 10-fold cross-validation had RMSE only 2 to 3% (peaks) and 4% (volumes) higher than those from the original fitted models, for both pre-treatment and post-treatment responses (Table 12). The systematic cross-validation, omitting the post-treatment data one station at a time, gave RMSE 5% and 7% higher than the apparent post-treatment RMSE from the original runoff peaks and volume models, respectively. The systematically cross-validated RMSE values of 0.1739 and 0.1676 for logarithms of peaks and volumes correspond to prediction errors of about 20% for the untransformed responses. Calibration slopes (for regression of the observed versus predicted runoff) are very close to unity (Table 13) for both peaks and volumes. Both the random and systematic cross-validation calibrations are nearly indistinguishable from $y = x$ on 600 dpi letter-size plots. Both the RMSE and calibration results indicate the models for runoff peaks and volumes are not overfit. Remarkably, they appear to predict independent data nearly as well as the data to which the models were fit.

Predictions of suspended sediment loads from random cross-validation had RMSE 7% (HI control) and 4% (HIM control) higher than those from the original fitted models, for both pre-treatment and post-treatment responses (Table 12). On the other hand, the systematic cross-validation gave RMSE 32% (HIM control) and 50% (HI control) higher than the apparent post-treatment RMSE from the original sediment models. The systematically cross-validated RMSE values of 0.6724 and 0.6966 for logarithms of sediment loads correspond to prediction errors of about 100% for the untransformed responses. Calibration slopes for the sediment models are similar to the original models for the random cross-validation, but the systematic cross-validation has calibration slopes significantly smaller (Table 13), indicating substantial shrinkage in prediction of data from subwatersheds not used in model-fitting. The cross-validations indicate that the sediment models are not likely to predict future sediment loads well, and the associations identified between sediment loads and the disturbance variables in these models may be coincidental.

DISCUSSION

Storm Peaks

The effect of logging second-growth forests on streamflow peaks in Caspar Creek is consistent with the results from studies conducted over the past several decades throughout the Pacific Northwest. That is, the greatest effect of logging on streamflow peaks is to increase the size of the smallest peaks occurring during the driest antecedent conditions, with that effect declining as storm size and watershed wetness increases. However, increases were still apparent even in the largest storm of this study, which had a recurrence interval of 7 years at NFC.

Although the relative increases in peak flows tend to decline as storm size increases, the effects on large storms may still be important when recurrence intervals of a given size peak are considered. The curve for m=2, for example, in Figure 29 shows the increase in peak needed to reach a size that formerly had twice the recurrence interval, based on a curve fitted to the 28-year pre-logging partial duration series at NFC. Equivalently these are the increases necessary to halve the recurrence interval of the peaks that would result from the increased flow regime. Under such a flow regime, the frequency of large peaks of a given size would double, roughly doubling the geomorphic work performed on the channel. For comparison, the increased peak flows observed in this study (Figure 13) have been included in Figure 29, assuming unit-area flow frequencies in the tributaries are the same as at NFC. Although the variability is very great, it appears that the average observed increases in clear-cuts are great enough to roughly halve the recurrence intervals for storm sizes greater than 0.004 $m^3s^{-1}ha^{-1}$ (return periods longer than 0.5 years). Average observed increases in partly cut watersheds were smaller.

Accounting for the amount of watershed disturbance, there was no evidence that either storm peaks or the logging effect on peaks was related to watershed size. Peaks in the smallest drainages tended to have greater responses to logging than in larger watersheds, but this was because the smaller watersheds had greater proportions disturbed. That is the typical pattern because Forest Practice Rules and economics usually limit the amount of intense activity occurring within any given watershed in any year. Therefore, it is possible for entire small first-order watersheds to be logged within a single year. However, as the size of the watershed increases, a smaller proportion of the watershed is likely to be logged in any given year. In the largest watersheds, harvesting may be spread over decades, within which time the earliest harvested areas will have revegetated.

The data from the streamflow, pipeflow [Ziemer, 1992; Keppeler and Brown, 1998], and soil moisture studies [Keppeler et al., 1994] at Caspar Creek all suggest that the peak flow response to logging is related to a reduction in vegetative cover. Reducing vegetative cover, in turn, reduces transpiration and rainfall interception. Since little soil moisture recharge occurs during the spring and summer growing season at Caspar Creek, large differences in soil moisture can develop between logged and unlogged watersheds by late summer because of differences in evapotranspiration. For example, by late summer, a single mature pine tree in the northern Sierra Nevada depleted soil moisture to a depth of about 6 m and to a distance of 12 m from the trunk [Ziemer, 1968]. This single tree transpired about 88 m^3 more water than the surrounding logged area, equivalent to about 180 mm of rainfall over the affected area. In the South Fork of Caspar Creek, the largest changes in peak streamflow after logging were found to be for the first storms after lengthy dry periods [Ziemer, 1981]. Similarly, after logging the North Fork, there was a strong interaction between the proportion of the area logged and watershed wetness that explained differences in streamflow peaks.

Evaporation of rainfall intercepted by the forest canopy can result in a substantial reduction in the amount of water that reaches the ground. Preliminary measurements at Caspar Creek suggest that average rainfall interception is about 20% of gross winter rainfall. Studies elsewhere have also reported that a large portion of annual rainfall is intercepted and evaporated from the forest canopy. For example, Rothacher [1963] reported that under dense Douglas-fir stands in the Oregon Cascades, canopy interception loss averaged 24% of gross summer precipitation and 14% gross winter precipitation. Percentage interception losses are greatest during low-intensity rainfall interspersed with periods of no rain. As with transpiration, rainfall interception can contribute to important differences in antecedent conditions between logged and unlogged watersheds. And during the large high-intensity storms that result in large streamflow peaks, rainfall interception is still important; about 18% of the rainfall from a 96-mm 24-hour storm was intercepted by the forest canopy at Caspar Creek. Differences in interception loss between logged and unlogged areas probably explain most of the observed increases in the larger winter peaks, when transpiration is at its annual minimum.

Road construction and logging were not applied as separate treatments in this study. And, because they are correlated, it is difficult to distinguish their effects statistically. However, soil compaction from roads and timber harvest represents only 3.2% of the North Fork watershed and ranges from 1.9% to 8.5% for the tributary watersheds. Further, roads, landings, and skid-trails in the North Fork are all located near the ridges and well away from any streams. Consequently, roads, soil compaction, and overland flow probably did not produce important changes in peak flow response of the North Fork watersheds. The recovery rate of about 8% per year for storm peaks supports the hypothesis that changes in peak flows are largely controlled by changes in vegetation.

Storm Runoff Volume

Analogous to the storm peaks model, the model for storm flow volumes showed that flow increases could be largely explained by the proportion of a watershed logged, an antecedent wetness index, and time since logging. Logging probably impacted both storm peaks and flow volumes via the same mechanisms: reduction of rainfall interception and transpiration.

Suspended Sediment Loads

The most important explanatory variable identified by the sediment models was increased volume of streamflow during storms after logging. This result is not unexpected because, after logging, increased storm flows in the treated watersheds provide additional energy to deliver and transport available sediment and perhaps to generate additional sediment through channel and bank erosion.

Whereas individual watersheds show trends indicating increasing or decreasing sediment loads, there is no overall pattern of recovery apparent in a trend analysis of the residuals from the model (Figure 23). This is in contrast with the parallel model for storm flow volume, and suggests that some of the sediment increases are unrelated to flow increases.

Other variables found to be significant, depending on the control watersheds used, were road cut and fill area and length of unbuffered stream channel, particularly in burned areas. One must be cautious about drawing conclusions about cause and effect when treatments are not randomly assigned to experimental units and replication is limited. Increases in sediment load in one or two watersheds can create associations with any variable that happens to have higher values in those watersheds, whether or not those variables are physically related to the increases. In this study, the contrast in response was primarily between watershed KJE, where sediment loads decreased, versus watersheds BAN, CAR, DOL, EAG, and GIB. Watershed KJE was unburned and also had the smallest amount of unbuffered stream of all the cut units. Watersheds EAG and GIB were burned and had the greatest amount of unbuffered stream in burned areas. Watershed EAG experienced the largest sediment increases and also had the greatest proportion of road cut and fill area. EAG was not unusually high in road surface area, and the larger road cut and fill area in EAG reflects roads that are on steeper terrain than in the other cut units.

Road systems would typically be expected to account for much of the sediment. During storm events frequent cutbank failures and culvert blockages along the pre-existing North Fork perimeter all-season road (dating back more than half a century) resulted in drainage diversions and sediment input to North Fork tributaries both before and after logging. But there is little field evidence of sediment delivery from the *new* spur roads in the North Fork watershed. In an inventory of failures greater than 7.6 m^3, only 8 of 96 failures, and 1,686 of 7,343 m^3 of erosion were related to roads and none were associated with the new roads. Based on 129 random erosion plots [Rice, 1996; Lewis, 1998] in the North Fork, the road erosion in EAG was 9.3 m^3ha^{-1}, compared to 34.5 m^3ha^{-1} for KJE and 16.6 m^3ha^{-1} for all roads in the North Fork. Thus it seems that the appearance of road cuts and fills in the model resulted from a spurious correlation. The *new* roads were relatively unimportant as a sediment source in the North Fork, probably because of their generally stable locations on upper hillslopes far from stream channels, the use of outsloping and frequent rolling-dips (drains), and negligible rainy season use.

Field evidence suggesting that unbuffered stream channels contributed to suspended sediment loads is more consistent. Channel reaches subjected to intense broadcast burns showed increased erosion from the loss of woody debris that stores sediment and enhances channel roughness. Annual surveys evaluating bank stability, vegetative cover, and sediment storage potential suggest the greatest sediment production and transport potential existed in the burned channel reaches. Bank disturbances from timber falling and yarding were evident in the unburned channels, but slash and residual woody debris provided both potential energy dissipation and sediment storage sites for moderating sediment transport. Increased flows, accompanied by soil disruption and burning in headwater swales, may have accelerated channel headward expansion and soil pipe enlargements and collapses observed in watershed KJE [Ziemer, 1992] and in EAG, DOL, and LAN.

Based on 175 random 0.08-ha erosion plots in harvest areas [Rice, 1996; Lewis, 1998] in the North Fork, total erosion after logging in the burned watersheds EAG and GIB was 153 m^3ha^{-1} and 77 m^3ha^{-1}, respectively, higher than all other watersheds. Total erosion for the unburned clear-cut watersheds BAN, CAR, and KJE averaged 37 m^3ha^{-1}. These figures include estimates of sheet erosion, which is difficult to measure and may be biased towards burned areas because it was easier to see the ground where the slash had been burned. About 72% of EAG and 82% of GIB were judged to be thoroughly or intensely burned, and the remainder was burned lightly or incompletely. It is unknown how much of this hillslope erosion was delivered to stream channels, but the proportion of watershed burned was not a useful explanatory variable for suspended sediment transport. A plausible conclusion is that only burned areas in or adjacent to stream channels contributed appreciable amount of sediment to the streams.

The inventory of failures greater than 7.6 m^3 identified windthrow as another fairly important source of sediment. Of failures greater than 7.6 m^3, 68% were from windthrow. While these amounted to only 18% of the failure volume measured, 91% of them were within 15 m of a stream, and 49% were in or adjacent to a stream channel. Because of the proximity of windthrows to streams, sediment delivery from windthrow would be expected to be high. Windthrows are also important as contributors of woody debris to these channels, and play a key role in pool formation. Because woody debris traps sediment in transport, the net effect of windthrow on sediment transport can be either positive or negative. Woody debris inputs into the channel have been unusually high in the years since logging, partly because of a number of severe windstorms and partly because of the buffer strip design [Reid and Hilton, 1998]. While this has led to substantial bank cutting and channel reworking, the bulk of the increased sediment loads after logging watersheds BAN, CAR, EAG, and GIB has not yet reached the main stem stations FLY and ARF, much of it having been stored in reaches affected by blowdown [Lisle and Napoletano, 1998].

Cumulative effects. We have considered three types of information that the sediment models provide about the cumulative effects of logging activity on (unit area) suspended sediment loads. Keep in mind that the response being considered in all these questions is the suspended sediment load per unit watershed area for a given storm event and that watershed area was used in the model to represent distance downstream.

Question 1. Were the effects of multiple disturbances additive in a given watershed? This question may be answered partly by looking at the forms of the storm flow and sediment models. Analyses of residuals and covariance structures provide good evidence that the models are appropriate for the data, including the use of a logarithmic response variable. A logarithmic response implies a multiplicative effect for predictors that enter linearly and a power function for predictors that enter as logarithms. The flow response to logged area in model (10) is multiplicative, and the sediment response to flow increases in models (24) and (25) is a power function because Δq (equations (11), (12)) is equivalent to the log of a ratio. We next examine how much these relations differ from an additive relationship in the range of data we observed.

Consider $E(r_{ij})$, the expected value of the ratio between an observation and its expectation in an unlogged condition. From equations (9) and APPENDIX C, equations (35) and (36),

$$E(r_{ij}) = \exp\left[D_{ij}T_{ij}\right] \tag{26}$$

where $T_{ij} = \beta_4 + \beta_5 \log(\chi_{cj}) + \beta_6 \log(w_j) + \beta_7 a_i$. The expected effect of combining two simultaneous disturbances D_1 and D_2 is

$$E(r_{1+2}) = \exp\left[(D_1 + D_2)T_{ij}\right] = E(r_1)E(r_2) \tag{27}$$

where $E(r_1) = \exp[D_1 T_{ij}]$ and $E(r_2) = \exp[D_2 T_{ij}]$ are the expected effects of the individual disturbances. The combined effect departs most from additive when $E(r_1) = E(r_2)$. For example, disturbances that individually would result in 10% and 30% increases in the response produce a combined increase of 43% ($1.10 \times 1.30 = 1.43$), while disturbances that individually would result in 20% increases, produce a greater combined increase of 44% ($1.20 \times 1.20 = 1.44$). If the disturbances were additive the combined increase would be a 40% increase in either case. For more than two disturbances, the departures from additivity can be somewhat greater. In general, multiple disturbances that have a combined effect of r on the response under a multiplicative model will result in a minimum increase of $\log(r)$ in the response under an additive model, where r is defined in the sense of r_{ij} above. (This results from a mathematical limit as the number of equal-magnitude disturbances contributing to the effect r becomes large.)

In the storm flow data, only the main-stem gaging stations received waters from multiple disturbances. The maximum observed increase in storm flow on any main stem gaging station was 118%, but 8 out of 10 increases were under 40% and the median increase was just 16%. Taking the logarithms of 2.18, 1.40, and 1.16, we find that multiple disturbances that could produce these increases in a multiplicative model would produce minimum increases of 78%, 34%, and 15%, respectively, under an additive model. Therefore, in the range of most of the data (increases less than 40%) the disturbance effect on storm flow is approximately additive.

Now we can evaluate the additivity of the disturbance effect on sediment load, since this is expressed mainly through Δq. For this evaluation we fit model {(25),(17),(18)}, but fixing the parameters involving road cuts and fills at zero. Under this model, analogously to equation (26) for the flow model, the expected value of the ratio between an observation and its expectation in an unlogged condition is given by

$$E(r_{ij}) = \exp\left[\beta_2 \Delta q_{ij}^{(2)}\right] = \exp\left[\beta_2 \log\left(\frac{y_{ij}}{y_{Cj}}\right)\right] = \left(\frac{y_{ij}}{y_{Cj}}\right)^{\beta_2} \tag{28}$$

The ratio of y_{ij} and y_{Cj}, the unit area flow volumes in storm j from the treated and control watersheds, is an expression of the increased flow related to tree removal. A plot of equation (28) using the maximum likelihood estimate of 1.514 for β_2 passes through (1,1) and is very nearly linear in the range $0.82 \le y_{ij}/y_{Cj} \le 1.92$, which includes 95% of the observations on the main-stem stations. It follows that the effect of flow on suspended sediment is approximately additive for stations which receive waters from multiple logging units. For example, a flow ratio of 1.40 corresponds to a 66% increase in sediment load, while a flow ratio of 1.80 corresponds to a 143% increase in sediment load. An additive flow effect would produce an increase of 66 + 66 = 132% in sediment load, not much less than 143%. Examples of smaller flow ratios deviate from additivity even less than this example.

So, in the range of data we observed, the effect of disturbance on flow is approximately additive, and the effect of flow on sediment loads is approximately additive. In summary, the mathematical approach indicates that the combined effect of multiple disturbances on sediment loads is very similar to the sum of the effects of the individual disturbances.

Question 2. Were downstream changes greater than would be expected from the proportion of area disturbed? This question was addressed by testing the coefficients of terms formed from the product of disturbance and watershed area. If the coefficient of this term were positive, it would imply that the effect of a given disturbance proportion increases with watershed size. The interactions of those disturbance measures that had explanatory utility in the sediment models were considered, including road cut and fill area and length of unbuffered stream channels. None of the product terms were found to have coefficients significantly greater than zero, indicating that suspended load increases were not disproportionately large in larger watersheds. To the contrary, the sum of the observed sediment loads at the four main-stem stations were all within 25% of the sum of the loads predicted for undisturbed watersheds (Table 7). Channel cross-section measurements indicate 1040 metric tons of net filling in the main stem during the post-logging period [Lisle and Napolitano, 1998]. Much of the logging-related sediment from the tributaries has apparently been deposited in the main stem, especially in reaches affected by blowdowns and in alluvial bars near tributary confluences, and therefore has not reached downstream gages.

There is, however, one subwatershed where this second type of cumulative effect may be occurring. Watershed DOL, only 36% cut, includes the 100% cut watershed EAG, yet the percentage sediment increases have been similar (269% at DOL versus 238% at EAG). Several mechanisms appear to be responsible for the unexpectedly high loads at DOL. In the incised lower reach, bank failures and channel widening have occurred. In addition, a major stream diversion caused by a windthrow resulted in the formation of a major gully eroding 87 m^3 directly into the stream. Sediment is also being released from behind decaying logs that were placed in the channel for skidding by oxen during historic logging. Finally, all these processes would have been augmented by the increased storm flows that followed modern logging.

Question 3. Were sediment loads in the lower watershed elevated to higher levels than in the tributaries? Regardless of the control watersheds used, suspended sediment transport per unit watershed area tended to increase downstream before logging (Figure 21). This tendency may reflect a greater availability of fine sediment downstream in lower gradient channels. If unit area sediment loads increase downstream and result in water quality levels of concern with a smaller proportion of watershed disturbance than upstream locations, then cumulative effects may be said to have occurred, in the sense that activities producing acceptable local impacts resulted in impacts that are unacceptable by the same standard downstream.

To the extent that larger watersheds reflect average disturbance rates and therefore have smaller proportions of disturbance than the smallest disturbed watersheds upstream, one might expect sediment loads downstream to increase by less than those in the logged tributaries. In addition, as mentioned before, some of the sediment may be temporarily stored before reaching the lower stations. Indeed, in this study the post-treatment regression lines were much more similar among watersheds than the pretreatment lines, and the main-stem stations no longer transported the highest unit area sediment loads. However, larger watersheds will not necessarily behave the same way. For example, in geographically similar Redwood Creek in northwestern California, two main-stem gaging stations (175 km^2 and 720 km^2) yield higher sediment loads per unit area than three intensively logged tributaries [Lewis, 1998].

Cumulative effects considered in this paper were limited to a few hypotheses about water quality that could be statistically evaluated. But cumulative effects can occur in many ways. For example, resources at risk are often quite different in downstream areas, so an activity that has acceptable local impacts might have unacceptable offsite impacts if critical or sensitive habitat is found downstream. Different physical processes also tend to dominate upstream and downstream reaches. Channel aggradation may be the biggest problem downstream, while channel scour may be of concern upstream.

Subwatersheds and KJE anomaly. Analyses of the 5 clear-cut tributaries in the North Fork drainage show suspended load increases at all gaging stations located immediately below clear-cut units except at KJE, where loads have decreased. KJE had the highest pre-logging (1986-1989) unit area sediment loads of any of the tributaries (Figure 22), but, after logging, loads were similar to the other logged tributaries (Figure 17).

Prior to logging, the stream channel above KJE was unique. The KJE channel was an active gully with an abundant supply of sediment and the lowest gradient of any of the tributaries. After logging, the number of small debris jams doubled in the buffered channel above KJE, and further upstream the channel contained a large amount of logging debris and dense vegetative regrowth. Thus, opportunities for temporary sediment storage increased, and net energy available for sediment transport may have decreased, despite moderately increased flows, because of the increased channel roughness. The other tributaries were stable, vegetated, steep channels with limited sediment supplies and relatively low unit area sediment loads prior to logging. In these tributaries the increased sediment introduced by logging was readily transported. While this explanation is speculative, response in sediment transport to a disturbance certainly will vary with channel morphology and the relative availability of sediment and energy.

CONCLUSIONS

The main conclusions from these analyses are:

- Models based upon the proportion of watershed area logged, an antecedent wetness index, time since logging, and the responses in unlogged control watersheds explained 95% of the variation in the logarithms of both storm discharge peaks and volumes. Goodness-of-fit is similar for pre-logging and post-logging data, and cross-validation indicates that the models were not overfit to the data.
- Storm discharge peaks and volumes after extended periods with little or no precipitation increased up to 300% and 400% respectively, but most increases were below 100%.
- The effect of logging on storm discharge peaks and volumes declines with increasing regional antecedent wetness, as indexed by a decay function of prior runoff at a control watershed. However, even under the wettest conditions of the study, increases in storm runoff from clear-cut watersheds averaged 23% for peaks and 27% for volumes.
- Relative increases in storm discharge peaks and volumes decline with storm size but were positive even in the largest storms of the study period.
- Average increases in annual storm runoff were 58% from 95-100% clear-cut watersheds and 23% from 30-50% clear-cut watersheds.
- Recovery rates in the first 4-7 years after logging are estimated to be 8% per year for peak flows and 9% per year for storm flow volumes.
- Effects of multiple disturbances on storm discharge peaks and volumes are approximately additive, and there is little evidence for magnification of effects downstream.
- Reduction in rainfall interception and transpiration by forest vegetation is the probable cause of increased storm discharge peaks and volumes following logging.
- Annual sediment loads increased 123-269% in the tributaries, but, at main-stem stations, increased loads were detected only in small storms and had little effect on annual sediment loads. At the North Fork weir, an increase of 89% was caused mainly by a landslide in an ungaged tributary that enters just above the weir.
- Much of the increased sediment load in North Fork tributaries was related to increased storm flow volumes. With flow volumes recovering as the forest grows back, flow-related increases in sediment load are expected to be short-lived.
- The effects of multiple disturbances on suspended loads in a watershed were approximately additive.
- In general, downstream suspended load increases were no greater than would be expected from the proportion of area disturbed. In one tributary, increased flows evidently impacted the channel in an uncut area downstream by mobilizing stored sediment and aggravating bank instabilities, but most of the increased sediment produced in the tributaries was apparently stored in the main stem and has not yet reached the main-stem stations.
- Before logging, sediment loads on the main stem were higher than on most tributaries. This was no longer the case after logging, apparently because sediment exported from tributaries was deposited at temporary storage sites, and smaller proportions of downstream watersheds were disturbed.
- Sediment increases in North Fork tributaries probably could have been reduced by avoiding activities that denude or reshape the banks of small drainage channels.
- Sediment loads are affected as much by channel conditions (e.g. organic debris, sediment storage sites, channel gradient, and width-to-depth ratio) as by sediment delivery from hillslopes.

APPENDIX A. Notation Used in the Text

a_i	Drainage area of watershed i
b_i	Estimate of parameter β_i
c_{ij}	Proportion of watershed i logged in water years prior to that of storm j, and
c'_{ij}	Proportion of watershed i logged prior to storm j but in the same water year
D_{ij}	Some measure of disturbance per unit area in watershed i at storm j
$d_{i_1 i_2}$	Distance between centroids of watersheds i_1 and i_2
K	Number of parameters estimated in a model
n	Number of observations used in an analysis
p_{ij}	True (unknown) percentage change in response of watershed i in storm j as a result of treatment
$\tilde{p}_{ij}$	"Observed" percentage change in response of watershed i in storm j based on a comparison of y_{ij} and $\hat{y}'_{ij}$
p_0	Percentage change in response, given an arbitrary vector $\mathbf{x}_0$
p_N	Significance level of a hypothesis test based on the normal distribution
$\Delta q_{ij}^{(1)}$	Residual from the flow model (3) containing only β_{0i} and β_{1i}
$\Delta q_{ij}^{(2)}$	Difference between the logarithms of flow in the treated and control watersheds
$\Delta q_{ij}^{(3)}$	Predicted change after logging in the logarithm of storm flow from eqn (10)
t_{ij}	Area-weighted mean cutting age (number of summers passed) in watershed i for areas logged in water years preceding that of storm j
w_j	Wetness index at start of storm j
$x_{ij}^{(1)}, x_{ij}^{(2)}$	Generic measures of unit area disturbance in watershed i at storm j
$\mathbf{x}_0$	Arbitrary vector of explanatory variables
y_{ij}	Unit area response at treated watershed i in storm j
y_{Cj}	Unit area response at control watershed in storm j
y'_{ij}	Unknown response at watershed i, if it had been left untreated, in storm j
$\hat{y}'_{ij}$	Estimate of y'_{ij}
β_{0i}, β_{1i}	Location parameters (slope and intercept) to be estimated for each watershed i
$\beta_0^{(1)}, \beta_0^{(2)}$	Parameters used to model β_{0i} as a function of a_i
$\rho_{i_1 i_2}$	Correlation between $\varepsilon_{i_1 j}$ and $\varepsilon_{i_2 j}$
$\sigma_{i_1}, \sigma_{i_2}$	Standard deviations of $\varepsilon_{i_1 j}$ and $\varepsilon_{i_2 j}$
ε_{ij}	Error or deviation of y_{ij} from model at treated watershed i in storm j
$\varepsilon_{i_1 j}, \varepsilon_{i_2 j}$	Errors for watersheds i_1 and i_2 in storm j
θ_i	Parameter in covariance model
$\hat{\theta}_i$	Estimate of parameter θ_i

APPENDIX B. Likelihood Function and Gradient

The model for the mean response can be written

$$\mathbf{u} = E(\mathbf{y}) = f(\boldsymbol{\beta}) \tag{29}$$

where $\mathbf{y}$ is an $n\times1$ response vector and $\boldsymbol{\beta}$ is a $p\times1$ vector of unknown parameters. The error, $\mathbf{e} = \mathbf{y} - \mathbf{u}$, is modelled as a multivariate normal variable depending on q parameters:

$$\begin{aligned} &\mathbf{e} \sim \mathrm{N}(0,\boldsymbol{\Sigma}) \\ &\boldsymbol{\Sigma} = \mathbf{G}(\boldsymbol{\theta}) \end{aligned} \tag{30}$$

where $\boldsymbol{\Sigma}$ is the $n\times n$ covariance matrix of $\mathbf{e}$ depending on $\boldsymbol{\theta}$, a $q\times1$ vector of unknown parameters. The elements of $\boldsymbol{\Sigma}$ are paramaterized by equations (15)-(18). The likelihood function and its logarithm are

$$\begin{aligned} &L = (2\pi)^{-n/2}|\boldsymbol{\Sigma}|^{-1/2}\exp\left[-\tfrac{1}{2}(\mathbf{y}-\mathbf{u})^T\boldsymbol{\Sigma}^{-1}(\mathbf{y}-\mathbf{u})\right] \quad \text{and} \\ &\ell = \log(L) = -\tfrac{n}{2}\log(2\pi) - \tfrac{1}{2}\log|\boldsymbol{\Sigma}| - \tfrac{1}{2}(\mathbf{y}-\mathbf{u})^T\boldsymbol{\Sigma}^{-1}(\mathbf{y}-\mathbf{u}) \end{aligned} \tag{31}$$

respectively, where $|\boldsymbol{\Sigma}|$ is the determinant of $\boldsymbol{\Sigma}$. The gradient consists of the partial derivatives of ℓ with respect to $\boldsymbol{\beta}$ and $\boldsymbol{\theta}$:

$$\begin{aligned} &\mathbf{grad} = \left(\frac{\partial\ell}{\partial\beta_1},\cdots,\frac{\partial\ell}{\partial\beta_p},\frac{\partial\ell}{\partial\theta_1},\cdots,\frac{\partial\ell}{\partial\theta_q}\right) \\ &\frac{\partial\ell}{\partial\beta_i} = \frac{\partial\mathbf{u}^T}{\partial\beta_i}\boldsymbol{\Sigma}^{-1}(\mathbf{y}-\mathbf{u}), \qquad i = 1,\cdots,p \\ &\frac{\partial\ell}{\partial\theta_j} = -\frac{1}{2}tr\left(\boldsymbol{\Sigma}^{-1}\frac{\partial\boldsymbol{\Sigma}}{\partial\theta_j}\right) + \frac{1}{2}(\mathbf{y}-\mathbf{u})^T\boldsymbol{\Sigma}^{-1}\frac{\partial\boldsymbol{\Sigma}}{\partial\theta_j}\boldsymbol{\Sigma}^{-1}(\mathbf{y}-\mathbf{u}), \qquad j = 1,\cdots,q \end{aligned} \tag{32}$$

in which $tr(\cdot)$ refers to the trace (sum of the diagonal elements) of the matrix. The partial derivatives, $\partial\mathbf{u}^T/\partial\beta_i$ and $\partial\boldsymbol{\Sigma}/\partial\theta_j$, are model-specific and can be derived from equations (10) and (14)-(18).

APPENDIX C. An Unbiased Estimator, and Confidence and Prediction Intervals for Percentage Change in Response

Let y_0 be the response given an arbitrary predictor vector $\mathbf{x}_0$ and let y_0' be the unknown response for the same storm assuming the watershed were undisturbed. A prediction interval is sought for $p_0 = 100[y_0/E(y_0') - 1]$, the percentage change in response, and an unbiased estimator and confidence interval are sought for its expectation, $E(p_0)$. It will be convenient to obtain the unbiased estimator and confidence interval first. Since $\log(y_0)$ and $\log(y_0')$ are assumed to be normally distributed,

$$\begin{aligned} &E(y_0) = \exp\left[E(\log(y_0)) + \tfrac{1}{2}\sigma^2\right] \qquad \text{and} \\ &E(y_0') = \exp\left[E(\log(y_0')) + \tfrac{1}{2}\sigma^2\right] \end{aligned} \tag{33}$$

Let us denote the ratio of the actual response to its expected undisturbed value by

$$r_0 = \frac{y_0}{E(y_0')} \tag{34}$$

Its expectation is

$$\begin{aligned} E(r_0) &= \frac{E(y_0)}{E(y_0')} \\ &= \frac{\exp\left[E(\log(y_0)) + \frac{1}{2}\sigma^2\right]}{\exp\left[E(\log(y_0')) + \frac{1}{2}\sigma^2\right]} \\ &= \exp\left[f_0(\beta)\right] \end{aligned} \tag{35}$$

where, for the runoff models (10),

$$f_0(\beta) = \left[(1-\beta_2(t_0-1))c_0 + \beta_3^{(k)}c_0'\right] \times \left[\ \beta_4 + \beta_5\log(y_{C0})\ + \beta_6\log(w_0)\ + \beta_7 a_0\right] \tag{36}$$

Since $\mathbf{b}$, the vector of estimates for $\boldsymbol{\beta}$, is asymptotically distributed normal, we have that $f_0(\mathbf{b})$ is asymptotically distributed normal with $E[f_0(\mathbf{b})] = f_0(\beta)$ and unknown variance σ_*^2 [Bishop et al., 1975]. In shorthand, $f_0(\mathbf{b}) \sim N\left(f_0(\beta), \sigma_*^2\right)$ for large samples. The variance σ_*^2 may be approximated using the delta method [Bishop et al., 1975]:

$$\tilde{\sigma}_*^2 = \sum_{i=1}^{p}\sum_{j=1}^{p} \frac{\partial f_0}{\partial b_i}\frac{\partial f_0}{\partial b_j} Cov\left[b_i, b_j\right] \tag{37}$$

The covariances are estimated by the elements of the inverted information matrix [McCullagh and Nelder, 1989]. The information matrix is the negative of the matrix of second derivatives (Hessian) of ℓ with respect to the parameters, $\boldsymbol{\beta}$ and $\boldsymbol{\theta}$.

Let us introduce an estimator $\hat{r}_0 = \exp\left[f_0(\mathbf{b}) - \frac{1}{2}\sigma_*^2\right]$. Its expected value is

$$\begin{aligned} E(\hat{r}_0) &= \exp\left(-\tfrac{1}{2}\sigma_*^2\right)E\left\{\exp\left[f_0(\mathbf{b})\right]\right\} \\ &= \exp\left(-\tfrac{1}{2}\sigma_*^2\right)\exp\left\{E\left[f_0(\mathbf{b})\right] + \tfrac{1}{2}\sigma_*^2\right\} \\ &= \exp\left\{E\left[f_0(\mathbf{b})\right]\right\} \\ &= \exp\left\{f_0(\boldsymbol{\beta})\right\} \\ &= E(r_0) \end{aligned} \tag{38}$$

Hence $\hat{r}_0$ is an asymptotically unbiased estimator for $E(r_0)$, and $100(\hat{r}_0 - 1)$ is an asymptotically unbiased estimator for $100(E(r_0) - 1) = E(p_0)$. In practice, because σ_* is unknown, we replace it with $\tilde{\sigma}_*$ in the expression for $\hat{r}_0$.

Next we will compute a confidence interval for $E(r_0)$, and convert it to a confidence interval for $E(p_0)$. A 100(1-α)% confidence interval for $f_0(\beta)$ is defined by the probability

$$\Pr\left[f_0(\mathbf{b}) - z_{\alpha/2}\sigma_* \le f_0(\boldsymbol{\beta}) \le f_0(\mathbf{b}) + z_{\alpha/2}\sigma_*\right] = 1 - \alpha \tag{39}$$

where $z_{\alpha/2}$ is the $\alpha/2$ cutoff point of the standard normal distribution. Applying the monotone transformation **exp** to all sides of the inequality yields a confidence interval for $E(r_0)$:

$$\Pr\left[\exp\left[f_0(\mathrm{b}) - z_{\alpha/2}\sigma_*\right] \le E(r_0) \le \exp\left[f_0(\mathbf{b}) + z_{\alpha/2}\sigma_*\right]\right] = 1 - \alpha \tag{40}$$

Noting that $E(p_0) = 100(E(r_0) - 1)$, the above confidence interval is readily transformed into a confidence interval for $E(p_0)$.

$$100(1-\alpha)C.I.\text{for } E(p_0)\text{: } 100\left[\exp(f_0(\mathbf{b}) \pm z_{\alpha/2}\sigma_*) - 1\right] \qquad (41)$$

Since σ_* is unknown, we replace it with $\tilde{\sigma}_*$.

Finally, we will compute a prediction interval for r_0, and convert it to a prediction interval for p_0. Using model (10) and (33), we find

$$\begin{aligned} r_0 &= \frac{y_0}{E(y_0')} \\ &= \frac{\exp\left[\beta_0 + \beta_1 \log(y_{C0}) + f_0(\beta) + \varepsilon_0\right]}{\exp\left[\beta_0 + \beta_1 \log(y_{C0}) + \frac{1}{2}\sigma^2\right]} \\ &= \exp\left[f_0(\beta) + \varepsilon_0 - \tfrac{1}{2}\sigma^2\right] \end{aligned} \qquad (42)$$

Since $\varepsilon_0 \sim N(0, \sigma^2)$ and, asymptotically, $f_0(\mathbf{b}) \sim N\left(f_0(\beta), \sigma_*^2\right)$, and they are independent random variables, it follows that $f_0(\mathbf{b}) - \varepsilon_0 \sim N\left(f_0(\beta), \sigma_*^2 + \sigma^2\right)$. Thus

$$\Pr\left[f_0(\mathbf{b}) - z_{\alpha/2}\left(\sigma_*^2 + \sigma^2\right)^{\frac{1}{2}} \le f_0(\beta) + \varepsilon_0 \le f_0(\mathbf{b}) - z_{\alpha/2}\left(\sigma_*^2 + \sigma^2\right)^{\frac{1}{2}}\right] = 1 - \alpha \qquad (43)$$

Subtracting $0.5\sigma^2$ and applying the monotone transformation **exp** to all parts of the inequality converts the middle term to r_0, yielding the following prediction interval:

$$100(1-\alpha)P.I.\text{for } r_0\text{: } \exp\left(f_0(\mathbf{b}) - \tfrac{1}{2}\sigma^2 \pm z_{\alpha/2}\left(\sigma_*^2 + \sigma^2\right)^{\frac{1}{2}}\right) \qquad (44)$$

which is readily transformed to a prediction interval for p_0:

$$100(1-\alpha)P.I.\text{for } p_0\text{: } 100\left[\exp\left(f_0(\mathbf{b}) - \tfrac{1}{2}\sigma^2 \pm z_{\alpha/2}\left(\sigma_*^2 + \sigma^2\right)^{\frac{1}{2}}\right) - 1\right] \qquad (45)$$

Since σ_* and σ are unknown, we replace them with $\tilde{\sigma}_*$ and $\hat{\sigma} = \hat{\theta}_3 a_0^{\hat{\theta}_4}$, where a_0 is the watershed area.

Confidence and prediction intervals for sediment models (24) and (25) are similar, but $f_0(\mathbf{b})$ is replaced by the linear functions $g_0(\mathbf{b})$ and $h_0(\mathbf{b})$, respectively, where

$$g_0(\mathbf{b}) = \beta_2 \Delta q_0^{(1)} + \beta_3 x_0^{(1)} + \beta_4 x_0^{(2)} + \beta_5 (x_0^{(1)} + x_0^{(2)}) \log(y_{(\mathrm{HI})0}) + \beta_6 (x_0^{(1)} + x_0^{(2)}) a_0 \qquad (46)$$

$$\text{and} \quad h_0(\mathbf{b}) = \beta_2 \Delta q_0^{(2)} + \beta_3 x_0 + \beta_4 x_0 a_0 \qquad (47)$$

Since these functions are linear, the delta method yields the exact variance; but, as before, the covariance matrix of **b** must be estimated from the observed information matrix, so σ_*^2 is still only known approximately.

Acknowledgments. This research was a result of a cooperative effort of the California Department of Forestry and Fire Protection and the USDA Forest Service, Pacific Southwest Research Station. The study design was a result primarily of the efforts of Raymond Rice, who was the Principal Investigator until his retirement in 1989. Robert Thomas designed the SALT sampling algorithm and Rand Eads designed the hardware/software interface used in the field implementation. In addition, the authors are grateful to Dave

Thornton and the many individuals, too numerous to mention here, who spent thousands of hours in the field (often during hazardous storm conditions), in the laboratory, and in the office to ensure the best possible data quality.

Detailed hydrologic and climatic data collected at Caspar Creek between 1963 and 1997 are available on compact disk from the authors.

REFERENCES

Bailey, E. H., W. P. Irwin, and D. L. Jones, Franciscan and related rocks, and their significance in the geology of western California, *Calif. Div. Mines Geol. Bull., 183*, 177 pp., 1964.

Baskerville, G. L., Use of logarithmic regression in the estimation of plant biomass, *Can. J. Forest Res., 2*, 49-53, 1972.

Beschta, R. L., M. R. Pyles, A. E. Skaugset, and C. G. Surfleet, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: An alternative analysis, unpublished report supplied by author, Department of Forest Engineering, Oregon State University, Corvallis, 1997.

Bishop, Y. M., S. E. Fienberg, and P. W. Holland, *Discrete Multivariate Analysis: Theory and Practice*, MIT Press, Cambridge, Mass., 557 pp., 1975.

Brown, G. W. and J. T. Krygier, Clear-cut logging and sediment production in the Oregon Coast Range, *Water Resour. Res. 7*(5):1189-1198, 1971.

Burnham, K. P. and D. R. Anderson, *Model Selection and Inference: A Practical Information-Theoretic Approach,* Springer, New York, 353 pp., 1998.

Chow, G. C., A test of equality between sets of observations in two linear regressions, *Econometrica, 28*, 591-605, 1960.

Cleveland, W. S., Robust locally weighted regression and smoothing scatterplots, *J. Amer. Stat. Assoc., 74*, 829-836, 1979.

Copas, J. B., Regression, prediction and shrinkage, *J. R. Statist. Soc. B, 45*(3): 311-354, 1983.

Efron, B. and R. J. Tibshirani, *An Introduction to the Bootstrap*, Chapman and Hall, New York, 436 pp., 1993.

Fredricksen, R. L., Sedimentation after logging road construction in a small western Oregon watershed, in *Proceedings of the Federal Inter-Agency Sedimentation Conference, 1963*, Agricultural Research Service Misc. Pub. No. 970, pp. 56-59, 1963.

Grant, G. E. and A. L. Wolff, Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA, *IAHS Publ. 203*, 31-40, 1991.

Hansen, M. H. and W. N. Hurwitz, On the theory of sampling from finite populations, *Ann. Math. Stat., 14*, 333-362, 1943.

Harr, R. D., Forest practices and streamflow in western Oregon, *Gen. Tech. Rep. PNW-49*, 18 pp., For. Serv., U.S. Dep. Of Agric., Portland, Oreg., 1976.

Harr, R. D., W. C. Harper, J. T. Krygier, and F. S. Hsieh, Changes in storm hydrographs after road building and clear-cutting in the Oregon Coast Range, *Water Resour. Res., 11*, 436-444, 1975.

Harr, R. D., R L. Fredriksen, and J. Rothacher, Changes in streamflow following timber harvest in southwestern Oregon, *Res. Paper PNW-249*, 22 pp., For. Serv., U.S. Dep. Of Agric., Portland, Oreg., 1979.

Harris, D. D., Hydrologic changes after logging in two small Oregon coastal watersheds, *U.S. Geol. Surv. Water Supply Paper 2037*, 31 pp., 1977.

Henry, N., Overview of the Caspar Creek watershed study, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168*, pp. 1-9, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

Hewlett, J. D. and A. R. Hibbert, Factors affecting the response of small watersheds to precipitation in humid areas, in *Forest Hydrology*, edited by W. E. Sopper and H. W. Lull, pp. 275-290, Pergamon, New York, 1967.

Jones, J. A. and G. E. Grant, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon, *Water Resour. Res., 32*, 959-974, 1996.

Keppeler, E. T., R. R. Ziemer, and P. H. Cafferata, Changes in soil moisture and pore pressure after harvesting a forested hillslope in northern California, in *Effects of Human-induced Changes on Hydrologic Systems*, edited by R. A. Marston, and V. R. Hasfurther, pp. 205-214, American Water Resources Association, Herndon, Virginia, 1994.

Keppeler, E. T. and D. Brown, Subsurface drainage processes and management impacts, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168*, pp. 25-34, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

Keppeler, E. T. and R. R. Ziemer, Logging effects on streamflow: water yields and summer flows at Caspar Creek in northwestern California. *Water Resour. Res., 26*(7), 1669-1679, 1990.

Leaf, C. F., Sediment yields from central Colorado snow zone, *J. Hydraulics Division, ASCE Proc. 96*(HY1): 87-93, 1970.

Lewis, J., Turbidity-controlled suspended sediment sampling for runoff-event load estimation, *Water Resour. Res., 32*(7), 2299-2310, 1996.

Lewis, J., Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168,* pp. 55-69, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

Lisle, T. E. and M. B. Napolitano, Effects of recent logging on the main channel of North Fork Caspar Creek, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168,* pp. 81-85, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

McCullagh, P. and J. A. Nelder, *Generalized Linear Models,* 2nd edn., Chapman & Hall, London, 1989.

Megahan, W. F., J. G. King, and K. A. Seyedbagheri, Hydrologic and erosional responses of a granitic watershed to helicopter logging and broadcast burning, *Forest Science, 41*(4), 777-795, 1995.

Miller, R. G., *Simultaneous Statistical Inference,* 2nd edn., Springer-Verlag, New York, 299 pp., 1981.

Miller, E. L., Sediment yield and storm flow response to clear-cut harvest and site preparation in the Ouachita Mountains, *Water Resour. Res. 20*(4): 471-475, 1984.

Mood, A. M., F. A. Graybill, and D. C. Boes, *Introduction to the Theory of Statistics,* 3rd edn., McGraw-Hill, New York, 564 pp., 1974.

Napolitano, M. B., Persistence of historical logging impacts on channel form in mainstem North Fork Caspar Creek, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168,* pp. 97-101, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

Norick, N. X., SALT (selection at list time) sampling: a new method and its application in forestry. M.A. Thesis, 50 pp., Univ. of California, Berkeley, 1969.

Olive, L. J. and W. A. Rieger, Assessing the impact of land use change on stream sediment transport in a variable environment, *IAHS Publ. 203,* 73-81, 1991.

O'Loughlin, C. L., L. K. Rowe, and A. J. Pearce, Sediment yield and water quality responses to clearfelling of evergreen mixed forests in western New Zealand, *IAHS Publ. 130,* 285-292, 1980.

Plamondon, A. P., Logging and suspended sediments input in small streams: concentration, origin, and duration, presented at *XVII IUFRO World Congress, Kyoto, Japan,* Sept. 1981.

Rao, C. R. *Linear Statistical Inference and its Applications,* 2nd edn., Wiley and Sons, New York, 625 pp., 1973.

Reid, L. M. and S. Hilton, Buffering the buffer, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168,* pp. 71-80, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

Rice, R. M., F. B. Tilley, and P. A. Datzman, A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. *Res. Pap. PSW-146,* 12 pp., For. Serv., U.S. Dep. Of Agric., Berkeley, Calif.,1979.

Rice, R. M., Sediment delivery in the North Fork of Caspar Creek, unpublished final report, Agreement CA94077, Calif. Dep. of For. and Fire Prot., Sacramento, 1996.

Rothacher, J., Net precipitation under a Douglas-fir forest. *Forest Science, 4,* 423-429, 1963.

Rothacher, J., Regimes of streamflow and their modification by logging, in *Proceedings of the Symposium on Forest Land Use and Stream Environment,* edited by J. T. Krygier and J. D. Hall, pp. 55-63, Oregon State Univ., Corvallis, 1971.

Rothacher, J., Does harvest in west slope Douglas-fir increase peak flow in small streams? Pacific Northwest Forest and Range Experiment Station, *Res. Pap. PNW-163,* 13 pp., For. Serv., U.S. Dep. of Agric., Portland, Oreg., 1973.

Shumway, R. H., *Applied Statistical Time Series Analysis,* Prentice Hall, Englewood Cliffs, N. J., 379 pp., 1988.

Statistical Sciences, S-Plus Version 3.3 for Unix, StatSci, a division of MathSoft, Inc., Seattle, 1995.

Thomas, R. B., Estimating total suspended sediment yield with probability sampling, *Water Resour. Res., 21*(9), 1381-1388, 1985.

Thomas, R. B., Piecewise SALT sampling for estimating suspended sediment yields, *Gen. Tech. Rep., PSW-114,* 11 pp., For. Serv., U.S. Dep. Of Agric., Berkeley, Calif., 1989.

Thomas, R. B. and J. Lewis, A comparison of selection at list time and time-stratified sampling for estimating suspended sediment load, *Water Resour. Res. 29*(4), 1247-1256, 1993.

Thomas, R. B. and J. Lewis, An evaluation of flow-stratified sampling for estimating suspended sediment loads, *J. Hydrol.*, *170*, 27-45, 1995.

Thomas, R. B. and W. F. Megahan., Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion, *Water Resour. Res.*, *34*(12):3393-3403, 1998.

Wilson, A. L., When is the chow test UMP? *The American Statistician, 32*(2), 66-68, 1978.

Wright, K. A., K. H. Sendek, R. M. Rice, and R. B. Thomas, Logging effects on streamflow: storm runoff at Caspar Creek in northwestern California, *Water Resour. Res., 26*(7), 1657-1667, 1990.

Ziemer, R. R., Soil moisture depletion patterns around scattered trees, *Res. Note PSW-166*, 13 pp., For. Serv., U.S. Dep. of Agric., Berkeley, Calif., 1968.

Ziemer, R. R., Stormflow response to roadbuilding and partial cutting in small streams of northern California, *Water Resour. Res.*, *17*(4), 907-917, 1981.

Ziemer, R. R., Effect of logging on subsurface pipeflow and erosion: coastal northern California, USA., *IAHS Publ. 209*, 187-197, 1992.

Ziemer, R. R., Flooding and stormflows, in Proceedings, Conference on Coastal Watersheds: The Caspar Creek Story, *Gen. Tech. Rep. PSW-168*, pp. 15-24, For. Serv., U.S. Dep. Of Agric., Albany, Calif., 1998.

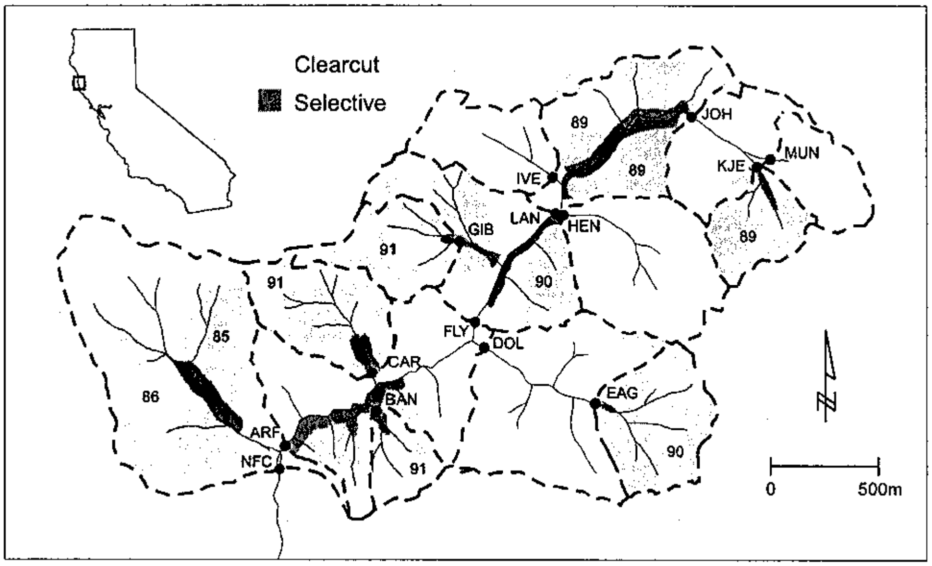

Figure 1. North Fork Caspar Creek. Gaging stations are identified by 3-letter abbreviations and dots, subwatershed boundaries by dashed lines, and logged areas by shading. Inset locates Caspar Creek within California.

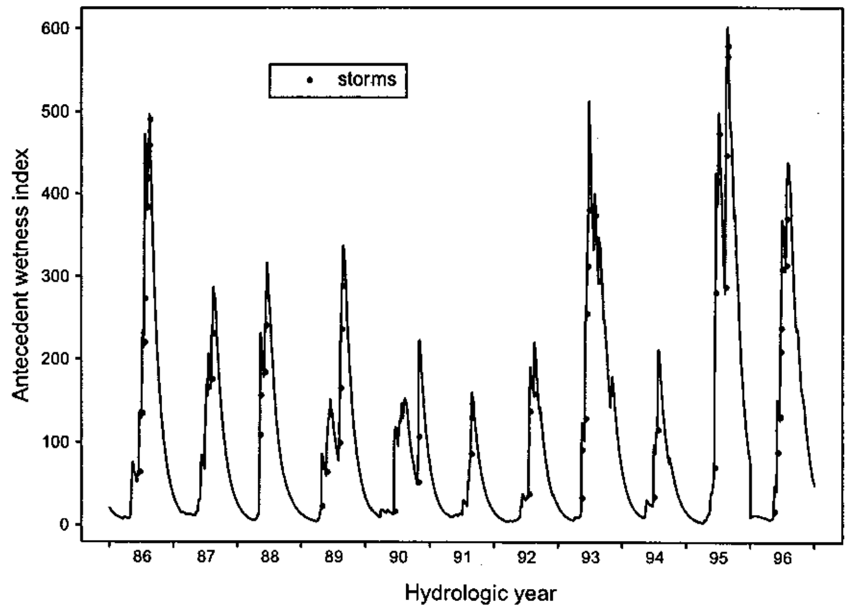

Figure 2. Antecedent wetness index (equation (2)) and temporal distribution of storms for the period of study (1986-1996). Solid circles indicate the wetness level at the start of each storm.

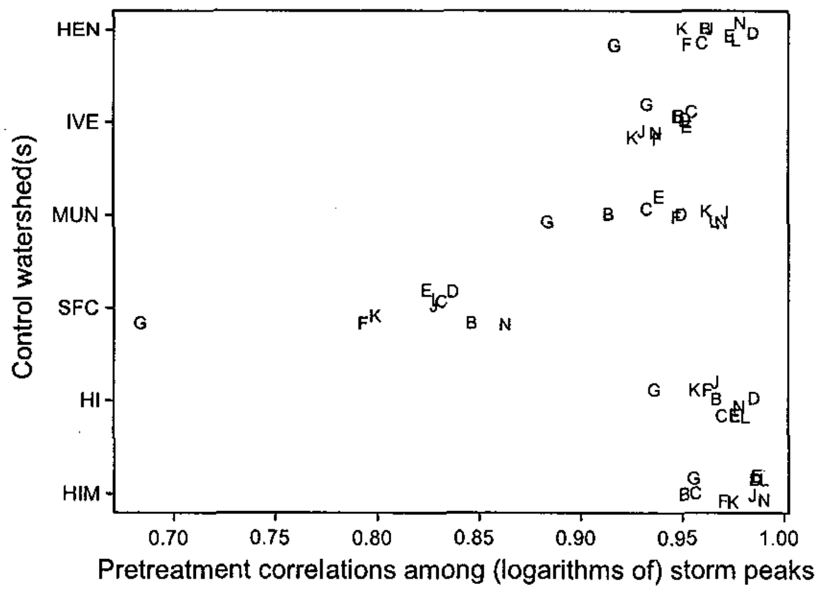

Figure 3. Pretreatment correlations between logarithms of storm peak at treated watersheds and alternative control watersheds. Letters designate watersheds (e.g. G is watershed GIB). Random noise has been added to the vertical plotting positions to improve readability.

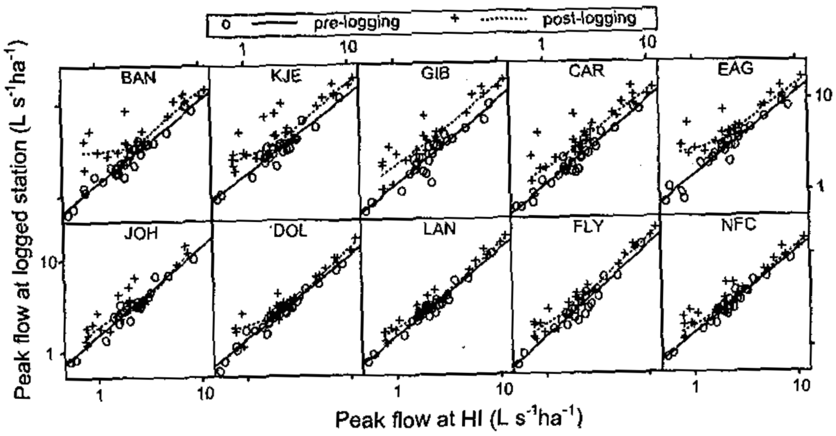

Figure 4. Relation between peak streamflow in the 10 treated tributaries in the North Fork of Caspar Creek, and that of the HI control. Post-logging relations were fitted by locally weighted regression [Cleveland, 1979]. The top row represents 95-100% clear-cut watersheds.

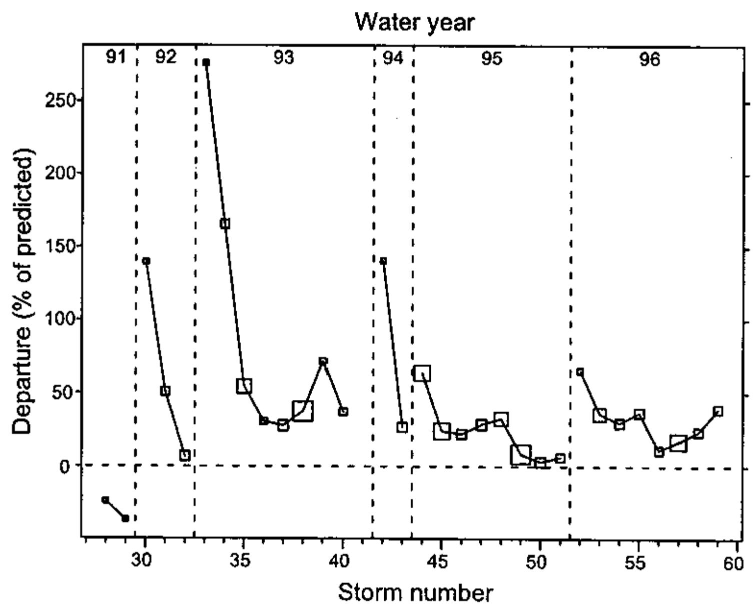

Figure 5. Post-logging departures of storm peaks (as percentage of predicted) at watershed EAG from those predicted from pretreatment regression on HI control. Axes are logarithmic. Symbol sizes indicate relative size of storm peak at HI control. Vertical dotted lines separate water years. About half the watershed was winter-logged before storm 28 and logging was completed by storm 30.

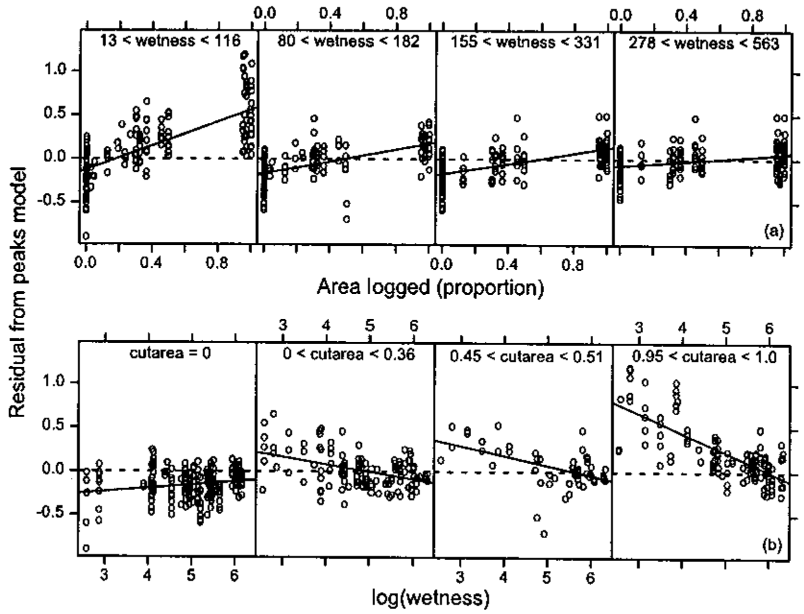

Figure 6. Conditioning plots of residual from storm peaks model (3) and interaction between area logged and antecedent wetness index with (a) wetness index fixed in each frame, and (b) proportion of area logged fixed in each frame.

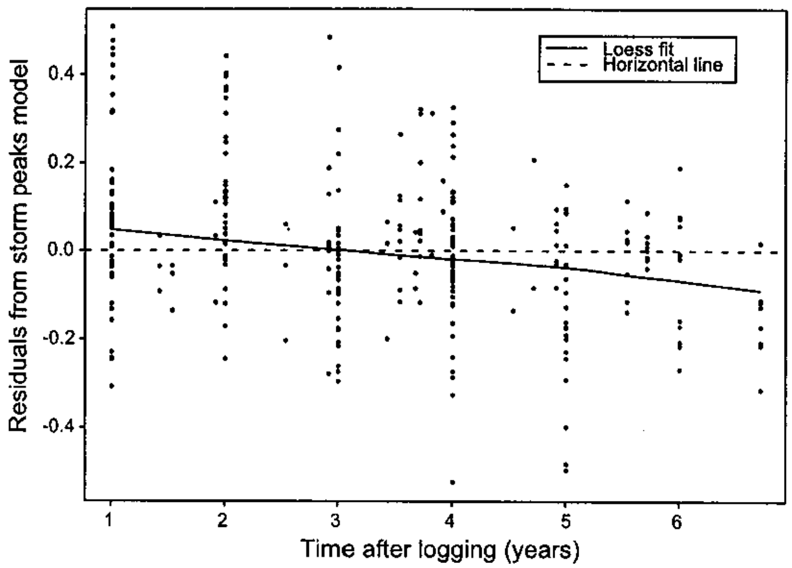

Figure 7. Relation between storm peak residuals and time after logging. Curve is fit by loess method [Cleveland, 1979]. Residuals are from least squares fit to the model $\log(y_{ij}) = \beta_{0i} + \beta_{1i}\log(y_{Cj}) + \beta_4 D_{ij} + \beta_6 D_{ij}\log(w_j) + \varepsilon_{ij}$.

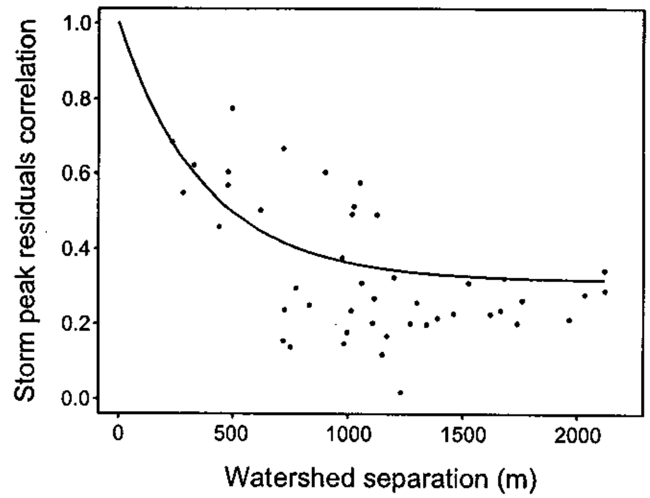

Figure 8. Relation between storm peak residuals correlation and distance between watershed centroids. Residuals are from maximum likelihood fit to storm peak model {(10),(16),(18)}. Curve depicts equation (16), with estimated parameters $\hat{\theta}_1$ and $\hat{\theta}_2$.

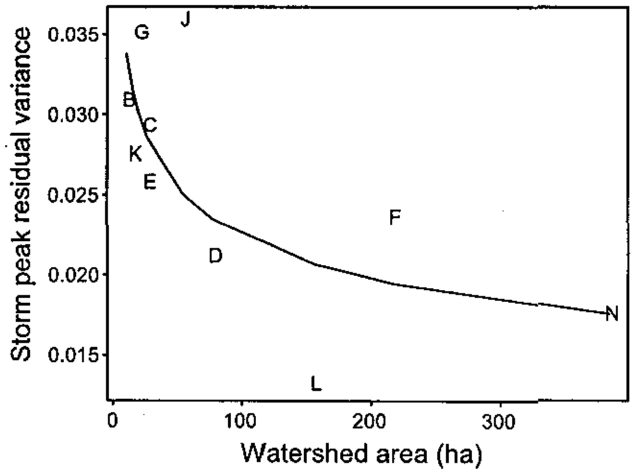

Figure 9. Relation between variance of storm peak residuals and watershed area. Residuals are from maximum likelihood fit to storm peak model {(10),(16),(18)}. Curve depicts equation (18) with estimated parameters $\hat{\theta}_3$ and $\hat{\theta}_4$. Letters designate watersheds (e.g. G is watershed GIB).

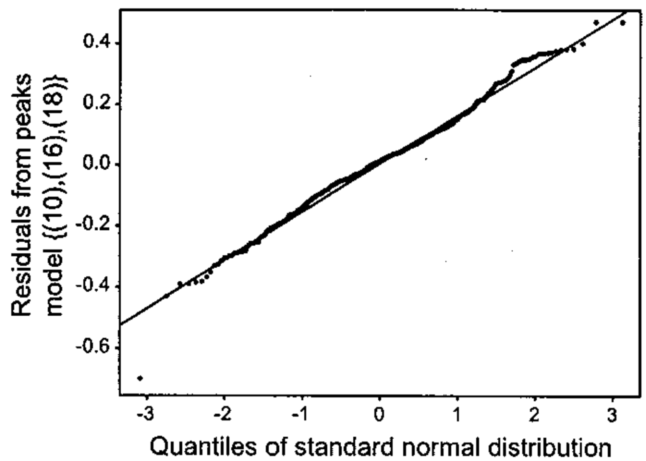

Figure 10. Normal quantile plot of residuals from storm peak model {(10),(16),(18)}. Line is least squares fit.

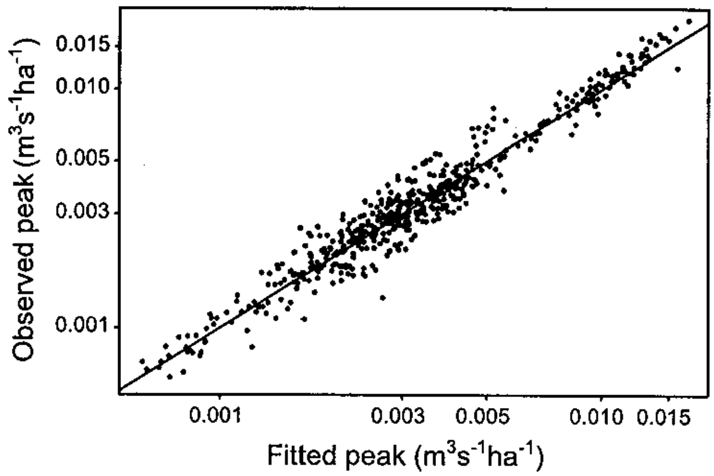

Figure 11. Observed storm peaks versus fitted values from model {(10),(16),(18)}. Line is $y = x$.

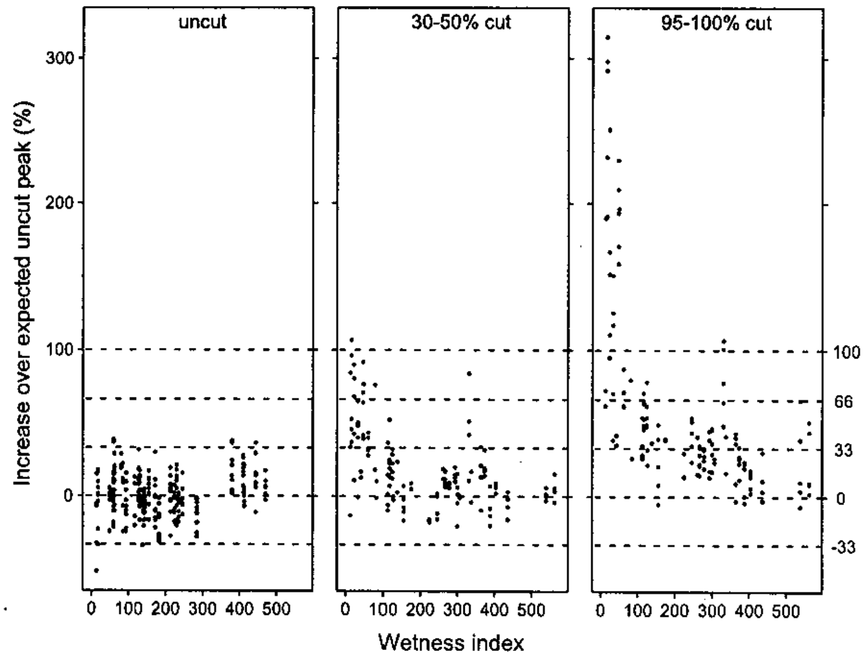

Figure 12. Percentage increase over expected uncut storm peak as related to antecedent wetness index for uncut (before treatment), partly (30-50%) clear-cut, and (95-100%) clear-cut watersheds. Bias-corrected predictions are from model {(10),(16),(18)} with disturbance set to zero.

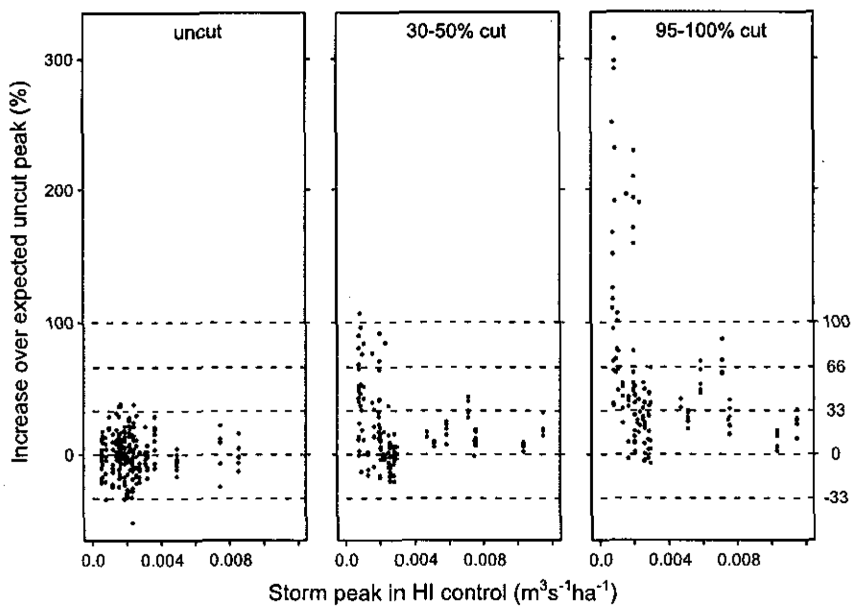

Figure 13. Percentage increase over expected uncut storm peak as related to peak size in the HI control for uncut (before treatment), partly (30-50%) clear-cut, and (95-100%) clear-cut watersheds. Bias-corrected predictions are from model {(10),(16),(18)} with disturbance set to zero.

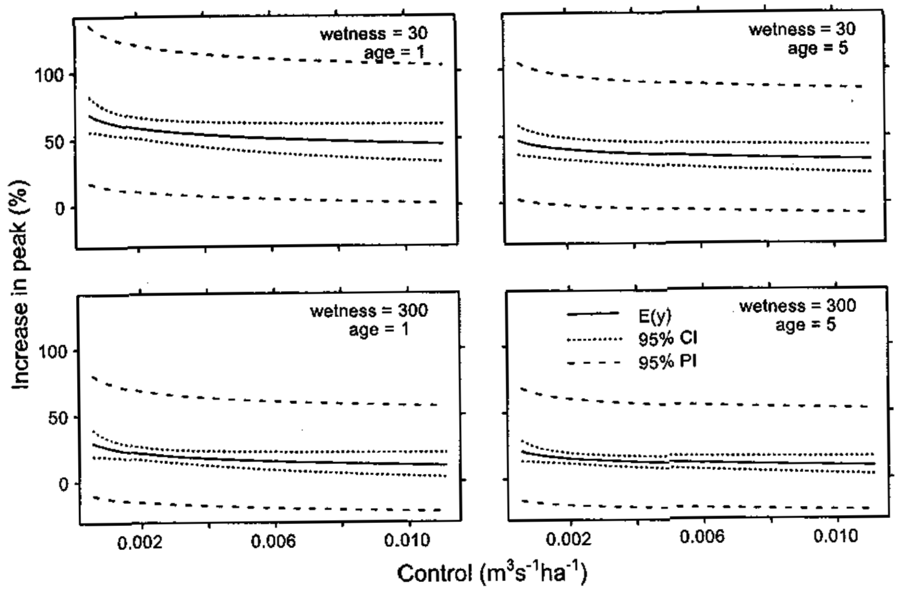

Figure 14. The effect of wetness and age after cutting on predictions from storm peak model {(10),(16),(18)} after clear-cutting 50% of a 20 ha watershed. Expected increases and 95% confidence (CI) and prediction (PI) intervals are shown for two levels of antecedent wetness 1 and 5 years after cutting.

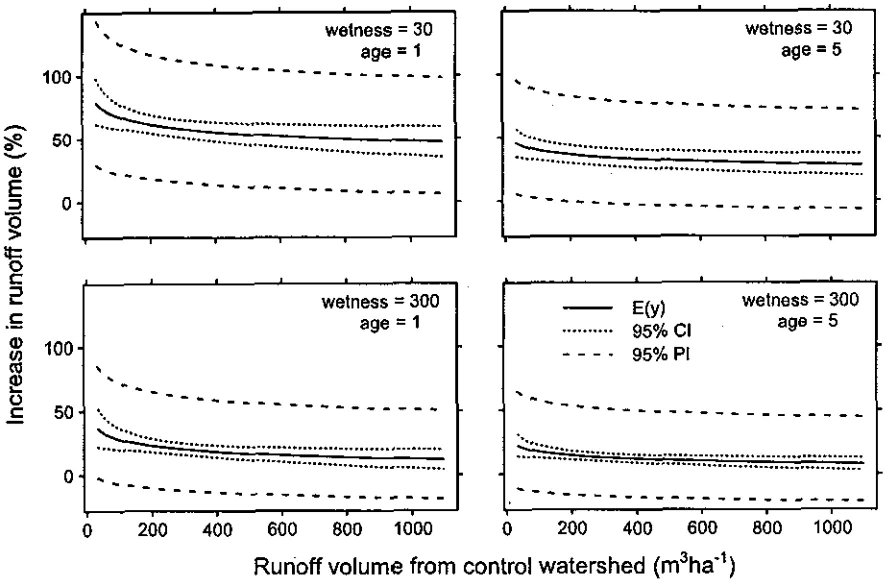

Figure 15. The effect of wetness and age after cutting on predictions from storm runoff volume model {(10),(17),(18)}, after clear-cutting 50% of a 20 ha watershed. Expected increases and 95% confidence (CI) and prediction (PI) intervals are shown for two levels of antecedent wetness 1 and 5 years after cutting.

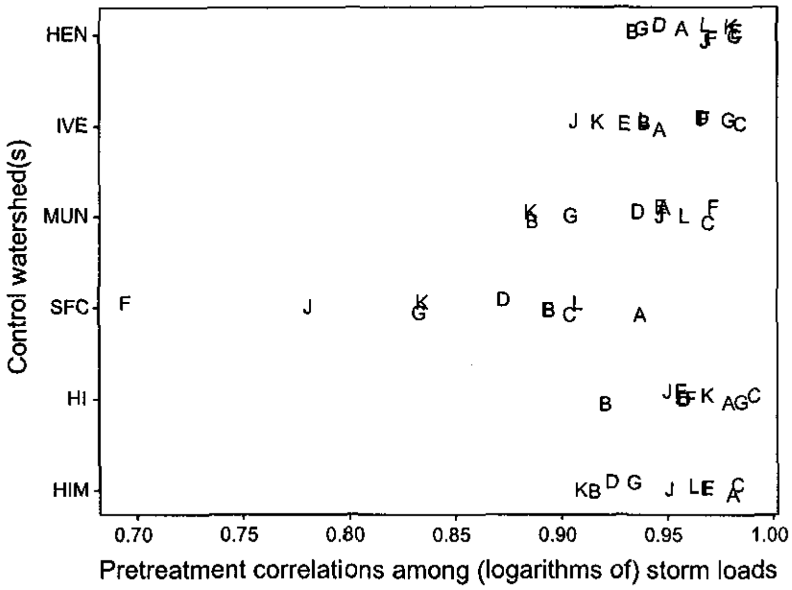

Figure 16. Pretreatment correlations between logarithms of storm sediment load at treated watersheds and alternative control watersheds. Letters designate watersheds (e.g. G is watershed GIB). Random noise has been added to the vertical plotting positions to improve readability.

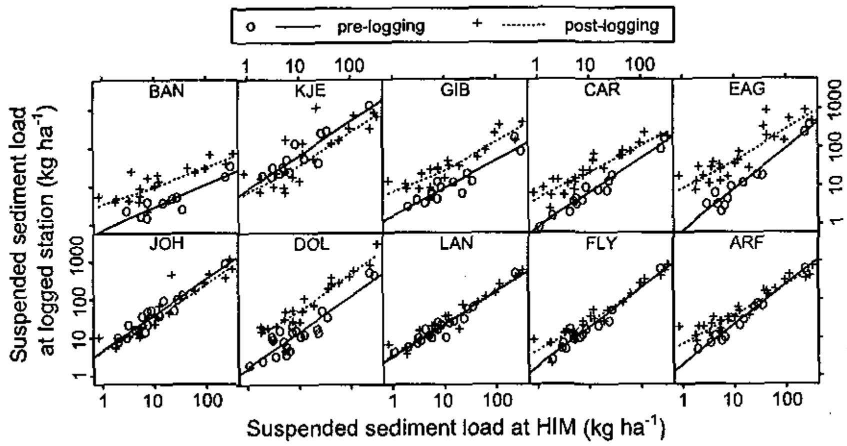

Figure 17. Relations between storm suspended sediment loads at logged subwatersheds in the North Fork and the the HIM control from 1986 to 1995. Post-logging relations were fitted by loess method [Cleveland, 1979]. The top row represents 95-100% clear-cut watersheds.

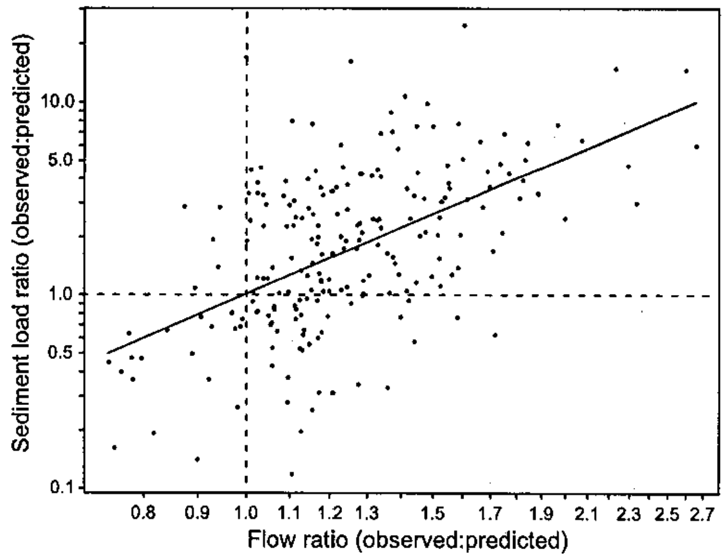

Figure 18. Relation between post-treatment sediment load departures from pretreatment relationship (3) and flow departures $\Delta q_{ij}^{(1)}$. Departures are expressed as the ratio of observed to predicted response.

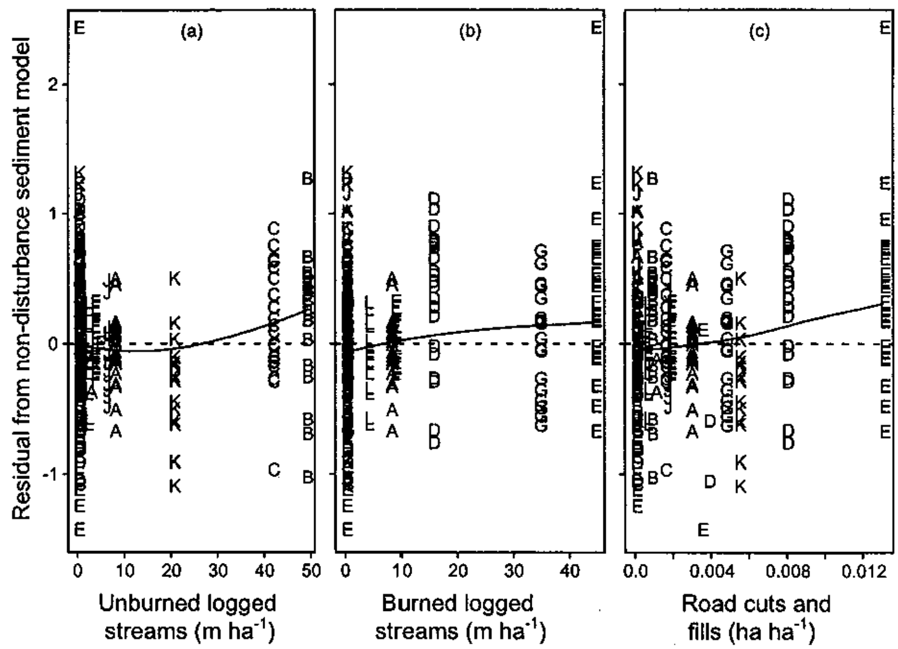

Figure 19. Relation between sediment load residuals and disturbance per unit watershed area. Curves are fit by loess method [Cleveland, 1979] to least squares residuals from the model: $\log(y_{ij}) = \beta_{0i} + \beta_{1i}\log(y_{(\mathrm{HI})j}) + \beta_2 \Delta q_{ij}^{(1)} + \varepsilon_{ij}$. Disturbance variables shown are (a) length of stream in burned clear-cut areas, (b) length of stream in unburned clear-cut areas, and (c) road cut and fill area. Letters designate watersheds (e.g. G is watershed GIB).

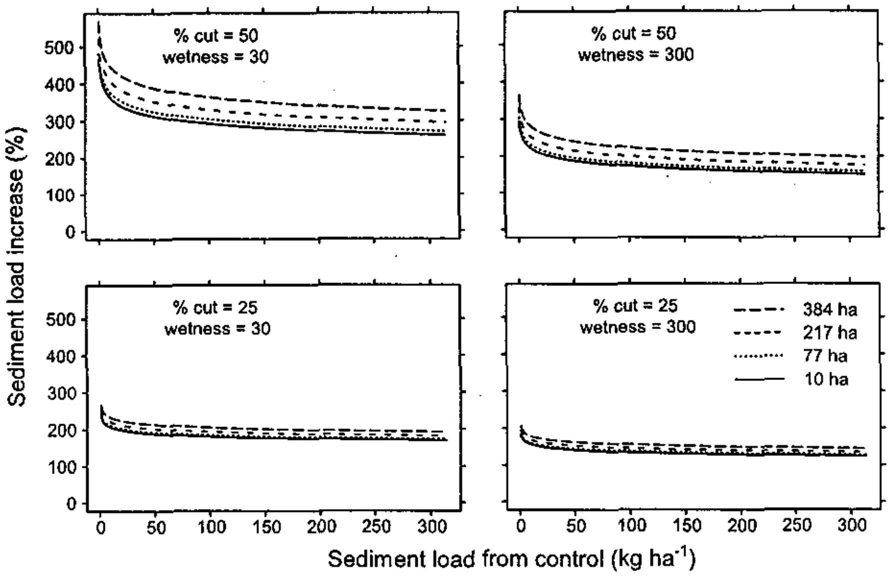

Figure 20. Effect of watershed area on predictions from sediment model {(24),(17),(18)} for two levels of cutting and two levels of antecedent wetness. Watershed areas are those of ARF, FLY, DOL, and BAN (Table 1). Predictions are for first year after cutting with $x_{ij}^{(1)} = x_{ij}^{(2)} = 12 \text{ m ha}^{-1}$.

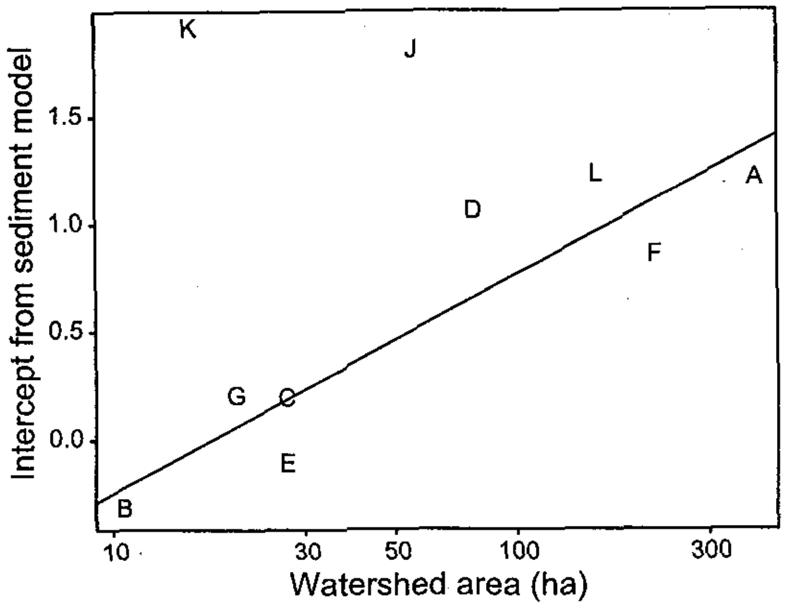

Figure 21. Relation between watershed area and fitted intercepts b_{0i} from model {(24),(17),(18)}, with β_6 fixed at zero. Watersheds JOH (J) and KJE (K) are omitted from regression. Letters designate watersheds (e.g. G is watershed GIB).

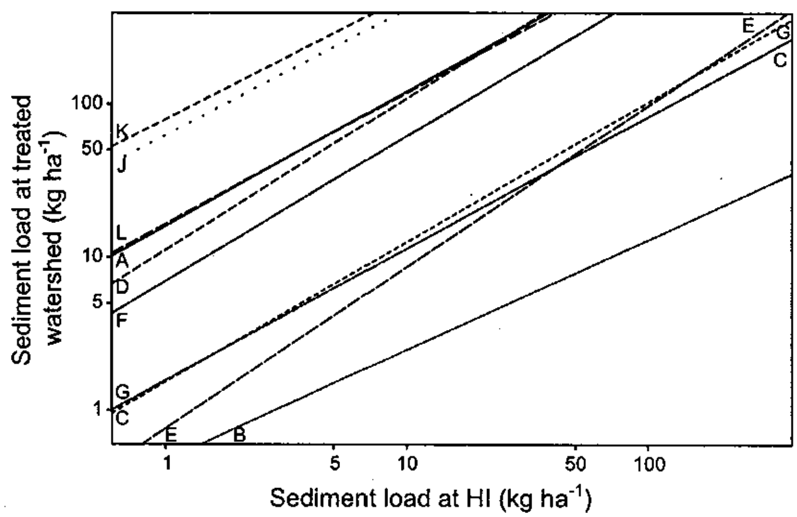

Figure 22. Regression lines for each watershed based on intercepts b_{0i} and slopes b_{1i} of sediment model {(24),(17),(18)}, with β_6 fixed at zero. Letters designate watersheds (e.g. G is watershed GIB).

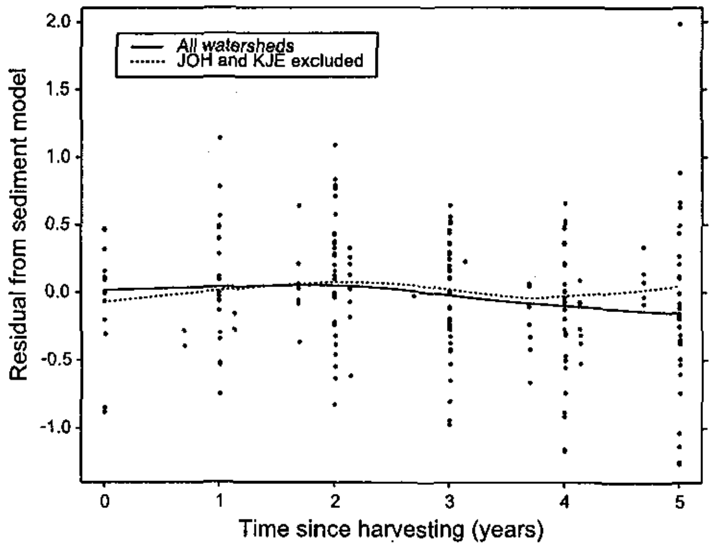

Figure 23. Relation between residuals from sediment model {(24),(17),(18)} and time after logging. Curves are fit by loess method [Cleveland, 1979], with and without the anomalous watersheds JOH and KJE.

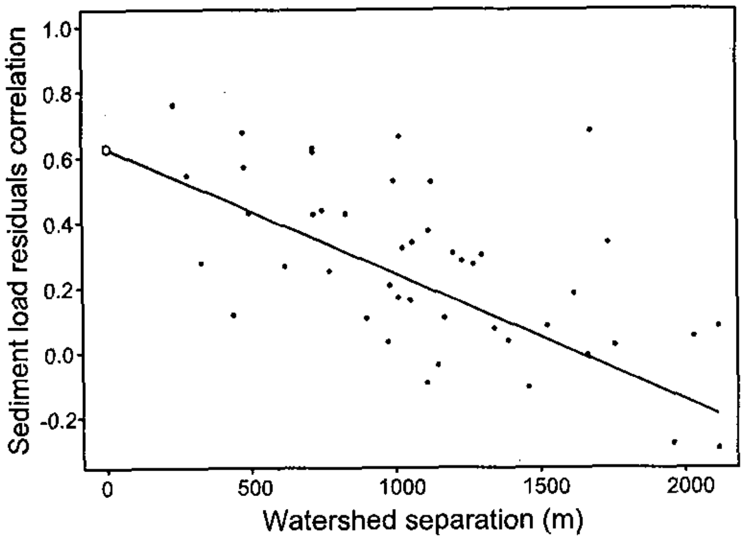

Figure 24. Relation between sediment residuals correlation and distance between watershed centroids. Residuals are from maximum likelihood fit to sediment model {(24),(17),(18)}. Curve depicts equation (17), with estimated parameters $\hat{\theta}_1$ and $\hat{\theta}_2$.

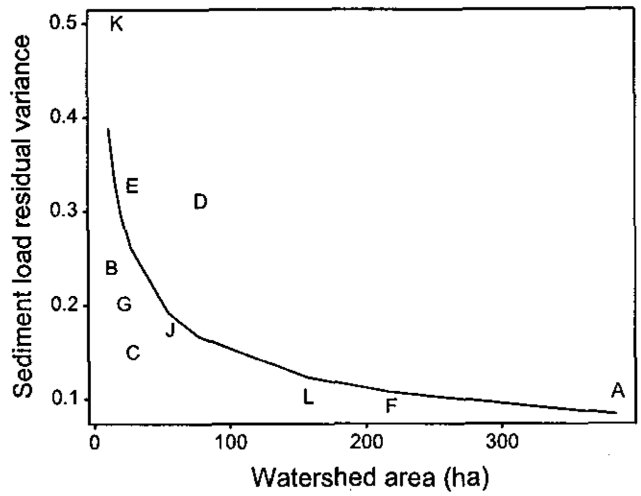

Figure 25. Relation between variance of sediment residuals and watershed area. Residuals are from maximum likelihood fit to model {(24),(17),(18)}. Curve depicts equation (18) with estimated parameters $\hat{\theta}_3$ and $\hat{\theta}_4$. Letters designate watersheds (e.g. G is watershed GIB).

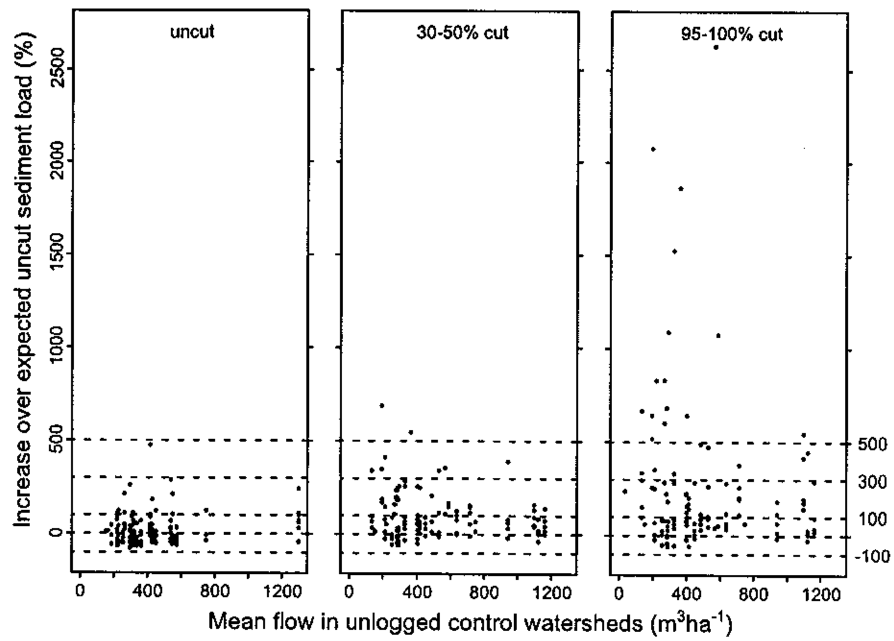

Figure 26. Percentage increase over expected uncut storm sediment load as related to mean of storm runoff volume in HIM control watersheds for uncut (before treatment), partly (30-50%) clear-cut, and (95-100%) clear-cut watersheds. Bias-corrected predictions are from model {(25),(17),(18)} with disturbance set to zero.

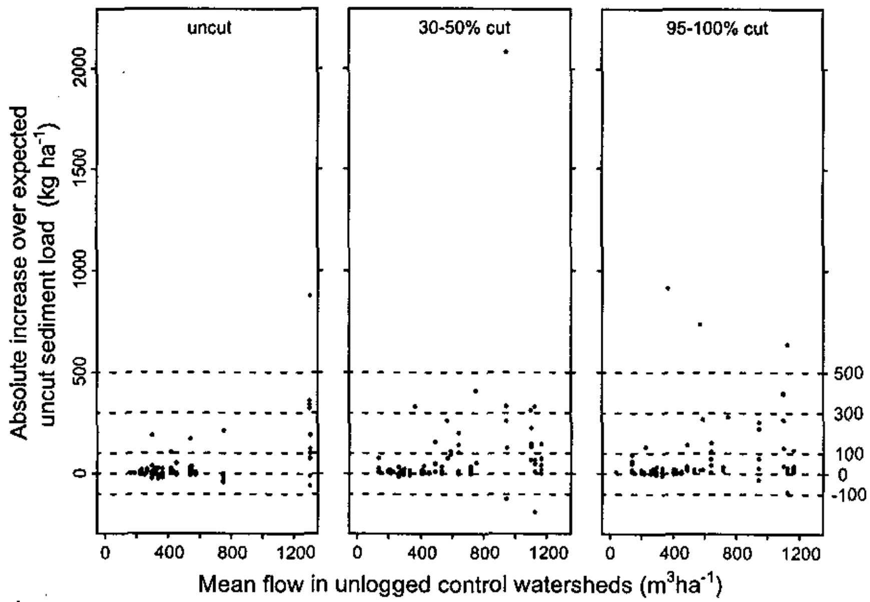

Figure 27. Absolute increase over expected uncut storm sediment load as related to mean of storm runoff volume in HIM control watersheds for uncut (before treatment), partly (30-50%) clear-cut, and (95-100%) clear-cut watersheds. Bias-corrected predictions are from model {(25),(17),(18)} with disturbance set to zero.

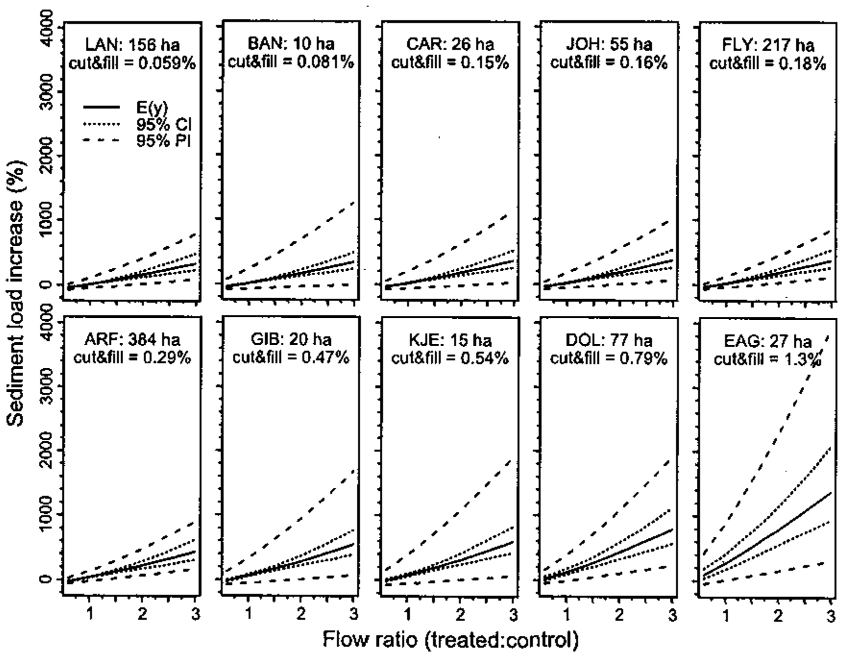

Figure 28. Predictions of sediment load as a function of flow ratio ($\Delta q_{ij}^{(2)}$) based on sediment load model {(25),(17),(18)}, with area interaction term for cumulative impacts (β_4) fixed at zero. Expected increases and 95% confidence (CI) and prediction (PI) intervals are shown for each treated watershed, ordered by proportion of the watershed occupied by road cuts and fills.

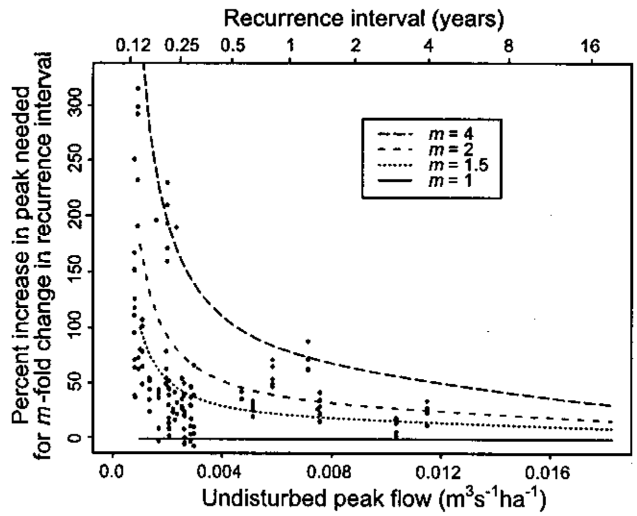

Figure 29. The curve shows the percentage increase in peak flow necessary to reach a size that formerly had 1 to 4 times the recurrence interval. The data points are from Figure 13 (third frame), representing the observed percentage increases in storm peak flow (based on the HI control, plotted on the abscissa) in 95-100% clear-cut watersheds.

Table 1. Basic watershed data and percentage in various conditions. Cut area includes portions of stream buffer zones corresponding to the proportion of timber volume removed.

Water-shed	Area (ha)	Cut area	Cable	Trac-tor	Road+ Lndg	Total Bare	Total Burnt	Dates logged
ARF	384	45.5	35.1	7.1	1.8	2.9	24.0	Spr89-Win92
BAN	10	95.0	77.3	13.4	2.6	3.2	0.0	Fall91
CAR	26	95.7	2.1	9.2	2.8	4.4	0.0	Fall91-Win91
DOL	77	36.4	27.4	5.9	2.5	3.7	33.9	Fall90-Fall91
EAG	27	99.9	79.0	15.4	4.9	8.5	97.8	Fall90-Fall91
FLY	217	45.4	34.6	7.6	1.6	3.0	30.4	Spr89-Sum91
GIB	20	99.6	54.9	39.4	4.2	7.9	98.2	Spr91-Sum91
HEN	39	0.0	0.0	0.0	0.0	0.0	0.0	
IVE	21	0.0	0.0	0.0	0.0	0.0	0.0	
JOH	55	30.2	26.4	1.3	2.0	2.1	0.1	Spr89-Fall89
KJE	15	97.1	85.2	3.9	6.5	6.9	0.0	Spr89-Fall89
LAN	156	32.2	27.8	1.9	1.0	1.9	20.3	Spr89-Spr90
MUN	16	0.0	0.0	0.0	0.0	0.0	0.0	
NFC	473	12.7	38.6[a]	7.6[a]	2.0[a]	3.2[a]	19.5[a]	Spr85-Spr86
		+36.9	38.6	7.6	2.0	3.2	19.5	Spr89-Win92

[a] not measured; assumed equal to Spr89-Win92 disturbance proportions

Table 2. Comparison of suspended sediment load estimation by time interpolation, stage interpolation, and SALT algorithms. The load was estimated for 5000 simulated SALT samples from each storm event.

				Percent RMSE			Percent Bias		
Station	Start of Storm	Load (kg/ha)	$\bar{n}$	Time Interp	Stage Interp	SALT	Time Interp	Stage Interp	SALT
ARF	950109	178.6	21.2	6.0	6.7	12.2	-2.3	-2.8	0.1
ARF	950113	123.6	22.9	2.8	3.4	8.2	-1.6	-2.0	0.1
ARF	950308	122.4	32.6	4.1	4.1	7.6	-0.3	-0.5	0.0
ARF	950108	99.2	8.6	14.2	14.6	19.8	-6.0	-7.2	-0.0
ARF	940216	33.6	16.5	7.0	6.7	10.0	-3.7	-3.5	-0.2
Mad	821214	846.3	41.8	2.1	1.8	10.0	0.0	-0.3	-0.1
Mad	830209	527.2	36.0	4.2	4.1	13.8	0.4	-1.3	0.1
Mad	830117	198.0	40.8	2.2	2.6	7.2	-0.4	-0.9	0.1
Mad	830225	134.4	22.9	7.8	7.6	19.3	-1.6	-2.6	0.3
Mad	831223	42.8	18.1	5.8	5.4	13.6	-2.7	-2.7	0.0
Mad	830221	33.2	15.7	7.5	8.1	16.1	-4.0	-4.9	-0.3
Mad	830212	27.2	14.0	8.1	7.4	16.2	-3.2	-3.9	0.0
Mad	830218	25.4	14.1	14.7	15.1	22.3	-3.4	-4.2	0.0

Table 3. Maximum likelihood parameter estimates for storm peaks model {(10),(16),(18)}, excluding β_{0i} and β_{1i}. p_N is normal probability value for H_0: $\beta = 0$.

Parameter	Effect	Estimate	Standard Error	p_N
β_2	Recovery	0.0771	0.0183	<0.0001
$\beta_3^{(1)}$	Fall logging	0.5939	0.0996	<0.0001
$\beta_3^{(2)}$	Winter logging	0.0000	0.2843	1.0000
β_4	Amount logged	1.1030	0.3409	0.0012
β_5	Storm size interaction	-0.0963	0.0484	0.0468
β_6	Wetness interaction	-0.2343	0.0251	<0.0001
β_7	Watershed area interaction	3.553E-4	2.861E-4	0.2142
θ_1	Correlation shape parameter	2.809E-3	6.188E-4	<0.0001
θ_2	Correlation limit parameter	0.4698	0.1564	0.0027
θ_3	Variance magnitude	0.2285	0.0242	<0.0001
θ_4	Variance shape	-0.0937	0.0238	0.0001

Table 4. Maximum likelihood parameter estimates for storm runoff model {(10),(17),(18)}, excluding β_0, and β_1. p_N is normal probability value for H_0: $\beta = 0$.

Parameter	Effect	Estimate	Standard Error	p_N
β_2	Recovery	0.0912	0.0143	<0.0001
$\beta_3^{(1)}$	Fall logging	0.8117	0.0910	<0.0001
$\beta_3^{(2)}$	Winter logging	-0.196	0.225	0.3843
β_4	Amount logged	2.3054	0.2646	<0.0001
β_5	Storm size interaction	-0.1103	0.0467	0.0181
β_6	Wetness interaction	-0.2362	0.0236	<0.0001
β_7	Watershed area interaction	6.481E-4	2.578E-4	0.0119
θ_1	Correlation intercept	0.6697	0.0587	<0.0001
θ_2	Correlation slope	-1.898E-4	4.962E-5	0.0001
θ_3	Variance magnitude	0.1987	0.0190	<0.0001
θ_4	Variance shape	-0.0873	0.0209	<0.0001

Table 5. Percentage and absolute departures from predicted annual storm runoff volume (sum of storms).

	Uncut	30-50% Clearcut	95-100% Clearcut
Mean (%)	2	23	58
Median (%)	2	19	51
Mean (m^3 ha^{-1} yr^{-1})	54	415	1119
Median (m^3 ha^{-1} yr^{-1})	29	387	1050

Table 6. Chow test [Chow, 1960; Wilson, 1978] significance levels for hypothesis of no change in suspended sediment load after logging.

Watershed	HI control	HIM control
ARF	0.1649	0.0215
BAN	0.0128	0.0292
CAR	0.0000*	0.0001*
DOL	0.0198	0.0093
EAG	0.0056	0.0013*
FLY	0.3528	0.0955
GIB	0.0002*	0.0096
JOH	0.0983	0.0476
KJE	0.0026*	0.0384
LAN	0.8018	0.2453

* significant at nominal $\alpha = 0.005$ (experimentwise error rate = 0.05)

Table 7. Summary of changes in suspended sediment load (summed over storms) after logging in North Fork subwatersheds. Predicted loads are computed from pre-treatment linear regressions between the logarithms of the storm sediment load in the treated watershed and control HIM, the mean of the storm sediment loads at watersheds HEN, IVE, and MUN. Predictions were corrected for bias when back-transforming from logarithmic units. The number of years in the post-logging period varies from 4 to 6, depending upon when the watershed was logged and whether or not monitoring was discontinued in water year 1996.

Treated watershed	Number of years	Observed ($kg\ ha^{-1}yr^{-1}$)	Predicted ($kg\ ha^{-1}yr^{-1}$)	Change ($kg\ ha^{-1}yr^{-1}$)	Change (%)
ARF	4	505	591	-86	-15
BAN	4	85	28	57	203
CAR	5	240	108	132	123
DOL	5	1130	306	824	269
EAG	5	710	210	500	238
FLY	5	536	555	-19	-3
GIB	4	358	119	239	200
JOH	5	667	865	-198	-23
KJE	5	821	1371	-551	-40
LAN	5	420	400	20	5
NFC	6	465	246	219	89

Table 8. Increase in residual sum of squares after dropping variables from least squares fit to model (24).

Coefficient	Variable	SS Reduction
β_2	Change in flow	25.33
β_3	Burned stream channel	10.21
β_4	Unburned stream channel	3.51
β_5	Storm size interaction	1.62
β_6	Watershed area interaction	0.62

Table 9. Maximum likelihood parameter estimates for suspended sediment load model {(24),(17), (18)}, excluding β_0, and β_1. p_N is normal probability value for H_0: $\beta = 0$. Control is HI, the mean sediment load from watersheds HEN and IVE.

Parameter	Effect	Estimate	Standard Error	p_N
β_2	Change in flow	1.3276	0.1609	<0.0001
β_3	Stream length, burned	0.0376	0.0057	<0.0001
β_4	Stream length, unburned	0.0204	0.0053	0.0001
β_5	Storm size interaction	-0.0051	0.0017	0.0031
β_6	Watershed area interaction	-3.316E-5	1.649E-5	0.0443
θ_1	Correlation intercept	0.6222	0.0846	<0.0001
θ_2	Correlation slope	-3.802E-4	9.218E-5	<0.0001
θ_3	Variance magnitude	1.0841	0.1565	<0.0001
θ_4	Variance shape	-0.2286	0.0338	<0.0001

Table 10. Maximum likelihood parameter for suspended sediment load model {(25),(17),(18)}, excluding β_{0i} and β_{1i}. p_N is normal probability value for H_0: $\beta = 0$. Control is HIM, the mean sediment load from watersheds HEN, IVE, and MUN.

Parameter	Effect	Estimate	Standard Error	p_N
β_2	Flow increase (log ratio)	1.3564	0.1414	0.0000
β_3	Road cut and fill area	107.11	13.071	0.0000
β_4	Watershed area interaction	-0.1822	0.0872	0.0367
θ_1	Correlation intercept	0.6848	0.0643	0.0000
θ_2	Correlation slope	-3.949E-4	7.618E-5	0.0000
θ_3	Variance magnitude	1.1839	0.1473	0.0000
θ_4	Variance shape	-0.2330	0.0290	0.0000

Table 11. Percentage and absolute departures from annual (sum of storms) sediment load predicted from HIM control. Parenthesized values omit outlier in middle frame of Figure 27.

	Uncut	30-50% Clearcut	95-100% Clearcut
Mean (%)	35	73 (67)	212
Median (%)	15	52	109
Mean (kg ha^{-1} yr^{-1})	65	263 (180)	262
Median (kg ha^{-1} yr^{-1})	1	46	59

Table 12. Apparent and cross-validated RMSE for model predictions.

Data Omitted	Data Predicted	Model			
		Peaks[a]	Volume[b]	Sed (HI)[c]	Sed (HIM)[d]
None	All	0.1589	0.1426	0.4584	0.5046
10% at random	All	0.1633	0.1483	0.4900	0.5238
None	Post-treatment	0.1654	0.1560	0.4644	0.5094
10% at random	Post-treatment	0.1692	0.1623	0.4948	0.5291
Systematic by station	Post-treatment	0.1739	0.1676	0.6966	0.6724

[a] model {(10),(16),(18)}, HI control, $\beta_7 = 0$

[b] model {(10),(17),(18)}, HI control, $\beta_3^{(2)} = 0$

[c] model {(24),(17),(18)}, HI control

[d] model {(25),(17),(18)}, HIM control

Table 13. Regression slope of observed versus predicted response.

Data Omitted	Data Predicted	Model			
		Peaks[a]	Volume[b]	Sed (HI)[c]	Sed (HIM)[d]
None	All	1.0039	1.0103	1.0012	0.9986
10% at random	All	1.0028	1.0047	0.9920	0.9947
None	Post-treatment	1.0077	1.0103	0.9921	0.9651*
10% at random	Post-treatment	1.0085	1.0020	0.9825	0.9611*
Systematic by station	Post-treatment	1.0014	0.9998	0.8601**	0.8775**

[a] model {(10),(16),(18)}, HI control, $\beta_7 = 0$

[b] model {(10),(17),(18)}, HI control, $\beta_3^{(2)} = 0$

[c] model {(24),(17),(18)}, HI control

[d] model {(25),(17),(18)}, HIM control

* $0.01 < p < 0.05$ for one-sided test of H_0: slope=1 (with H_A: slope<1)

** $p < 10^{-6}$ for one-sided test of H_0: slope=1 (with H_A: slope<1)

Reference (3) of

MONITORING STUDY GROUP
CALIFORNIA STATE BOARD OF FORESTRY AND FIRE PROTECTION

HILLSLOPE MONITORING PROGRAM

MONITORING RESULTS FROM 1996 THROUGH 2001

Andrea E. Tuttle
Director
Department of Forestry and Fire Protection

Mary D. Nichols
Secretary for Resources
The Resources Agency

Gray Davis
Governor
State of California

DECEMBER 2002
SACRAMENTO, CALIFORNIA
BOARD OF FORESTRY AND FIRE PROTECTION

HILLSLOPE MONITORING PROGRAM: MONITORING RESULTS FROM 1996 THROUGH 2001

December 2002

by Peter H. Cafferata and John R. Munn
California Department of Forestry and Fire Protection

MONITORING STUDY GROUP

Tharon O'Dell, Chair	California State Board of Forestry and Fire Protection
Dr. Marty Berbach, Brad Valentine	California Department of Fish and Game
Pete Cafferata, John Munn, Clay Brandow	California Department of Forestry and Fire Protection
Dr. Rich Walker, Dr. Russ Henly	California Department of Forestry and Fire Protection—Fire and Resource Assessment Program
Syd Brown	California Department of Parks and Recreation
Mark Rentz	California Forestry Association
Tom Spittler, Trinda Bedrossian	California Geological Survey
Joe Blum	National Marine Fisheries Service
Nathan Quarles	North Coast Regional Water Quality Control Board
Gaylon Lee	State Water Resources Control Board
Doug Eberhardt	U.S. Environmental Protection Agency
Dr. Richard Harris	University of California Cooperative Extension
Richard Gienger, SSRC/HWC	Member of the Public
Rob DiPerna, EPIC	Member of the Public
Roger Poff, R.J. Poff and Associates	Member of the Public
Mike Anderson, Anderson Logging Company	Member of the Public
Peter Ribar, Campbell Timberland Management	Industrial Timberland Owner
Bernie Bush, Simpson Resource Company	Industrial Timberland Owner
Tom Shorey, Fruit Growers Supply Company	Industrial Timberland Owner
Robert Darby, Pacific Lumber Company	Industrial Timberland Owner

The Monitoring Study Group (MSG) is made up of members of the public, resource agencies (both state and federal), and the timber industry. The agencies listed above make up the MSG; the names listed above are the primary representatives for these agencies at MSG meetings. The MSG chair is appointed by the Board of Forestry and Fire Protection (BOF) and the group is staffed by CDF. Each agency and organization is responsible for determining the appropriate person to serve as a representative on the MSG (i.e., the BOF does not make formal appointments to the MSG).

Executive Summary

The Hillslope Monitoring Program has been evaluating the implementation and effectiveness of California forest practices since 1996. This project began with field inspection of 50 timber harvesting plans (THPs) in Humboldt and Mendocino Counties in 1996, and has continued with a statewide random sample of 50 plans in subsequent years. Non-industrial timber management plans (NTMPs) were added in 2001.

As part of the Program, detailed information has been collected during summer months on THPs that have gone through one to four winters after harvesting was completed. Site characteristics, erosion problems, and Forest Practice Rule (FPR) implementation were recorded for randomly located landings, watercourse crossings and for randomly selected road, skid trail, and watercourse protection zone segments. Data was also collected at the site of large erosion events that were identified in the THP or located while conducting the field work. Some information was recorded on non-standard practices and additional mitigation measures when they were applied at the study sites and transects. Observations of fine sediment transport during winter storms were not included in this program because of logistic and safety concerns. Additionally, evaluation of the THP review and inspection process was not included as part of the Hillslope Monitoring Program.

This report is based on the 295 THPs and 5 NTMPs sampled through 2001. About 63 percent of these plans were on large ownerships and 37 percent were classified as smaller ownerships (non-industrial timberlands and other types of ownerships). The Coast Forest Practice District contained 61 percent of the plans, while the Northern and Southern Districts had 26 and 13 percent, respectively. The monitoring data was collected and entered into an extensive database by experienced independent contractors who acted as third party auditors. An interim report of study findings was prepared for the California State Board of Forestry and Fire Protection in June 1999. This report updates the interim findings and offers several recommendations. Analysis completed on the data set to date has primarily been composed of frequency counts and has been limited by time and access to database analysts. Additional data analysis will be conducted in the future.

Implementation and effectiveness of the Forest Practice Rules were rated by the field team as conditions requiring application of the Rules were encountered on the study sites and transects, and as part of an overall evaluation following completion of the inspection. In both cases, implementation of the Rules applicable to a given subject area was rated as either exceeding the requirements of the Forest Practice Rules, meeting the requirements, minor departure from requirements, major departure from requirements, not applicable, could not determine, or could not evaluate (with a description of why). At erosion problem points, the source and cause of the feature was recorded, along with whether sediment had been transported to a watercourse.

Results to date show that implementation rates of the Forest Practice Rules related to water quality are high and that individual practices required by the Rules are effective in preventing hillslope erosion features when properly implemented. Overall implementation ratings were greater than 90 percent for landings and for road, skid trail, and watercourse protection zone transects. Watercourse crossings had the lowest overall implementation ratings at 86 percent. Implementation of applicable Rules at problem points was nearly always found to be less than that required by the FPRs. These results, however, do not allow us to draw conclusions about whether the existing Rules are providing properly functioning habitat for aquatic species, since evaluating the biological significance of the current Rules was not part of the project.

To focus on areas where improvement in Rule implementation would provide the greatest benefit to water quality and where educational efforts are required, a list of 20 FPR requirements with the highest percentage of major departures is provided in the report. Three of these Rule requirements relate to roads, three to both roads and crossings, one to both roads and landings, one to skid trails, one to landings, ten to watercourse crossings, and one to watercourse protection zones.

Watercourse crossing problems are caused by a number of factors, including inherent uncertainties in determining and implementing site specific construction and abandonment needs, improper maintenance, the finite expected life of culverts, and high risk location for sediment delivery when stream discharge exceeds design discharge. The majority of the evaluated crossings were existing structures that were in place prior to the development of the THP, and frequent problems related to adequate design, construction, and maintenance were found. Crossings with culverts installed as part of the plan evaluated had a significantly lower rate of problem points per crossing, when compared to existing culverted crossings. Common problems included culvert plugging, stream diversion potential, fill slope erosion, scour at the outlet, and ineffective road surface cutoff waterbreaks.

The other main problem area identified by this program is erosion from roads caused by improper design, construction, and maintenance of drainage structures. Nearly half the road transects had one or more rills present and approximately 25 percent had at least one gully. Evidence of sediment transport to at least the high flow channel of a watercourse was found on 12.6 percent and 24.5 percent of the rill and gully features, respectively, with high percentages of delivery to Class III watercourses. These erosion features were usually caused by a drainage feature deficiency, and the FPRs rated at these problem sites were nearly always found to be out of compliance. Most of the identified road problems were related to inadequate size, number, and location of drainage structures; inadequate waterbreak spacing; and lack of cover at waterbreak discharge points. About six percent of the drainage structures evaluated along the road transects were found to have problems.

In contrast, watercourse protection zones were found to retain high levels of post-harvest canopy and surface cover, and to prevent harvesting related erosion. Mean total canopy exceeded FPR requirements in all three Forest Practice Districts and was approximately 80 percent in the Coast Forest Practice District for both Class I and II watercourses. Surface cover exceeded 75 percent for all watercourse types in the three districts. WLPZ width requirements were generally met, with major Rule departures recorded only about one percent of the time. The frequency of erosion events related to current operations in watercourse protection zones was very low for Class I, II, and III watercourses. Similarly, landings and skid trails were not found to be producing substantial impacts to water quality. Erosion problems on landing surfaces, cut slopes, and fill slopes were relatively rare. Rill and gully erosion features on skid trails were much less frequent than found on road transects, and sediment delivery to watercourses was also considerably lower.

Preliminary results on the use of non-standard practices and additional mitigation measures indicate the need for more thorough THP inspection to ensure proper implementation. A more focused monitoring approach, however, is needed to adequately examine the implementation and effectiveness of these practices. To date, the emphasis of the Hillslope Monitoring Program has been on evaluating the adequacy of standard Forest Practice Rules, and relatively little data has been collected for non-standard practices.

Ten recommendations are provided based on study findings to date. Six of these relate to training needs for CDF Forest Practice Inspectors, RPFs, Licensed Timber Operators, and personnel from other reviewing agencies (e.g., CDFG, CGS, and the Regional Water Quality Control Boards). Since watercourse crossings were found to be a significant problem area, voluntary, cooperative road management plans are recommended to effectively locate, prioritize, and schedule improvement work for high risk crossing structures. The results of this study also indicate a need to revise the Hillslope Monitoring Program to adequately sample additional mitigation measures and non-standard practices that are frequently added to THPs. Study revisions are also needed to monitor changes in the Forest Practice Rules that have occurred since July 1, 2000. Finally, it is recommended that the BOF and CDF continue to support the implementation and funding of instream monitoring projects designed to monitor compliance with Regional Water Quality Control Board Basin Plan standards.

Acknowledgements

We would like to thank all the landowners that granted access for the Hillslope Monitoring Program from 1996 through 2001. Large landowners participating were: Barnum Timber Company, Coombs Tree Farms, Congaree River Limited Partnership, Crane Mills, Eel River Sawmills, Fruit Growers Supply Company, Georgia-Pacific Corporation, Gualala Redwoods Company, Hawthorne Timber Company, J.H. Baxter Company, LaTour Demonstration State Forest, Louisiana Pacific Corporation, Mountain Home Demonstration State Forest, Miller-Rellim Company, Mendocino Redwood Company, Pacific Lumber Company, Pacific Gas and Electric Company, Red River Forest (managed by W.M. Beaty and Associates), Richard Padula, Roseburg Resources Company, Shasta Forest (managed by W.M. Beaty and Associates), Sierra Pacific Industries, Siller Brothers, Inc., Simpson Resource Company, Soper-Wheeler Company, Stimson Lumber Company, Strategic Timber Trust, Timber Products Company, and Wetsel-Oviatt Lumber Company. Small landowners who participated are too numerous to thank individually, but their cooperation is deeply appreciated. In addition to providing access to their properties, many of these landowners (both small and large) assisted our field teams by providing maps, gate combinations, keys, and other help in locating the sites.

Roger Poff, Cliff Kennedy, and Joe Hiss collected data on more than 90 percent of the THPs and NTMPs monitored and provided helpful comments and suggestions throughout the project. Natural Resources Management Corporation (NRM) collected field data in Humboldt County on 25 THPs in 1996.

Clay Brandow of CDF assisted in many aspects of the project, including the laborious task of screening THPs and NTMPs in Santa Rosa, Redding, and Fresno.

CDF's State Forests Research Coordinator Tim Robards provided very valuable assistance with database queries for the current report and his efforts are greatly appreciated. We would also like to thank Dr. Don Warner, California State University, Sacramento, for his valuable assistance with the Hillslope Monitoring Program database over the entire six year period. Don developed the database, modified it as requested, maintained it, and queried it for report generation. CDF's Forest Practice Database Coordinator Shana Jones queried the Forest Practice Database for the basic pool of THPs and NTMPs to randomly sample.

CDF Deputy Director for Resource Management Ross Johnson recognized the importance of the Hillslope Monitoring Program and provided the funding for individual contracts to collect the field data and enter the data in the database from 1996 through 2001. Individuals representing the various state and federal agencies making up the Monitoring Study Group helped design the study and supplied valuable guidance and oversight for the Hillslope Monitoring Program throughout the six year period. CDF Secretaries and Office Technicians in Santa Rosa, Redding, and Fresno provided assistance with screening potential THPs and NTMPs and copying the appropriate sections of the THP/NTMP files for field work.

Table of Contents

List of Figures

List of Tables

Appendix Tables

List of Abbreviations

ACL	Associated California Loggers
BMPs	Best management practices
BOF	California State Board of Forestry and Fire Protection
CDF	California Department of Forestry and Fire Protection
CDFG	California Department of Fish and Game
CDPR	California Department of Parks and Recreation
CFA	California Forestry Association
CGS	California Geological Survey
CLFA	California Licensed Foresters Association
CPSS	Certified Professional Soil Scientist
CSES	Critical Sites Erosion Study
EEZ	Equipment exclusion zone
EHR	Erosion hazard rating
ELZ	Equipment limitation zone
ESU	Evolutionarily significant unit
FLOC	Forest Landowners of California
FPA	Forest Practice Act
FPRs	Forest Practice Rules
HMP	Hillslope Monitoring Program
LTMP	Long-Term Monitoring Program
LTO	Licensed Timber Operator
LWD	Large woody debris
MAA	Management Agency Agreement
MCR	Modified Completion Report
MSG	Monitoring Study Group
NMFS	National Marine Fisheries Service
NTMP	Nonindustrial Timber Management Plan
NCRWQCB	North Coast Regional Water Quality Control Board
NTO	NTMP Notice of Timber Operations
PHI	Pre-Harvest Inspection
PMP	Pilot Monitoring Program
QA/QC	quality assurance/ quality control
RCD	Resource Conservation District
RG	Registered Geologist
RPF	Registered Professional Forester
Rules	Forest Practice Rules
RWQCB	California Regional Water Quality Control Board
SWRCB	State Water Resources Control Board
TMDL	Total Maximum Daily Load
THP	Timber Harvesting Plan
UCCE	University of California Cooperative Extension
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Department of Agriculture, Forest Service
WLPZ	Watercourse and lake protection zone

Introduction

Monitoring the impacts of forestry related activities on water quality is an important issue for California. Aquatic species continue to be listed as threatened or impaired by state and federal agencies, such as the state listing of coho salmon in August 2002. The Regional Water Quality Control Boards are considering how to address a legislatively mandated expiration of waivers on January 1, 2003, for silvicultural activities under the Clean Water Act. The listing of numerous North Coast watersheds as impaired waterbodies under Section 303(d) of the Clean Water Act and the implementation of Total Maximum Daily Load (TMDL) requirements are significant issues to numerous landowners. Additionally, debate continues on the appropriate protection measures needed along small headwater streams for adequate water quality protection. Scientifically credible monitoring data is needed to help resolve these issues and to reach sound conclusions regarding the impacts of current timber operations on water quality.

The purpose of the Hillslope Monitoring Program is to determine if California's Forest Practice Rules are adequately protecting beneficial uses of water associated with commercial timber operations on nonfederal lands in California. In June 1999, the California State Board of Forestry and Fire Protection's Monitoring Study Group presented an interim report documenting preliminary findings from its Hillslope Monitoring Program (CSBOF 1999). Additional data collected over the past three years is now sufficient for the preparation of a second report on the project. Hillslope monitoring will continue in the future, with refined protocols for improved tests of individual practice effectiveness. Continued monitoring is also needed to evaluate changes in the California Forest Practice Rules, the issues raised above, and the changing expectations of resource agencies and California's citizens.

The Hillslope Monitoring Program is not the only approach used in California to determine impacts of timber operations to water quality. Other efforts to evaluate how well California's Forest Practice Rules are implemented and how effective they are in protecting water quality include: 1) extensive inspection, enforcement, and monitoring by California Department of Forestry and Fire Protection Forest Practice Inspectors, and 2) research conducted as part of detailed watershed studies, such as the Caspar Creek watershed study. Each approach has its advantages and disadvantages. The Hillslope Monitoring Program described in this report complements these efforts, and when combined with the results from other monitoring efforts, conclusions can be reached regarding Rule implementation and effectiveness (Ice et al. 2002).

Specific objectives of the Hillslope Monitoring Program are: 1) implementation monitoring to determine if the Forest Practice Rules (FPRs) related to water quality are properly implemented, and 2) effectiveness monitoring to determine if the FPRs affecting water quality are effective in meeting their intent when properly implemented. Both implementation and effectiveness monitoring are necessary to differentiate between water quality problems created by non-compliance with a FPR, versus problems with the practice itself. The goal of effectiveness monitoring is to provide information on where, when, and in what situations problems occur under proper implementation (Tuttle 1995). Determining which Rules have the poorest implementation and effectiveness and the highest frequency of violations both provides input to the BOF on needed Rule changes and identifies training needs for: (1) CDF's Forest Practice Inspectors; (2) Registered Professional Foresters (RPFs) submitting THPs; and (3) Licensed Timber Operators (LTOs).

Background Information

California's modern Forest Practice Act (FPA) was adopted in 1973, with full field implementation occurring in 1975, and many monitoring efforts have taken place over the past two decades to learn more about the implementation and effectiveness of California's Forest Practice Rules in protecting water quality. These monitoring efforts complement the California Department of Forestry and Fire Protection (CDF) Forest Practice compliance inspection program that has been in place for over 25 years.

Under the FPA, Timber Harvesting Plans (THPs) must be submitted to CDF and approved for commercial timber harvesting on all non-federal timberlands. THPs are reviewed for compliance with the FPA and the Forest Practice Rules adopted by the Board of Forestry and Fire Protection (BOF), as well as other state and federal regulations protecting watersheds and wildlife. CDF, along with the Department of Fish and Game, Regional Water Quality Control Boards, and the California Geological Survey, conducts Pre-Harvest Inspections (PHIs) of proposed harvest areas to determine if plans are in compliance with the Act and FPRs. During PHIs, additional mitigation measures beyond the standard rules are often recommended based upon site-specific conditions. This report focuses on water quality issues, but the added THP mitigation also relates to habitat protection, public safety, and numerous other public trust resources. CDF also conducts inspections during active timber operations and the post-harvest period when logging is completed to assess compliance with the Act, the FPRs, and the specific provisions of the THP.

The State Water Resources Control Board (SWRCB) certified the Forest Practice Rules and review process as Best Management Practices under Section 208 of the Federal Clean Water Act in 1984, with a condition that a monitoring and assessment program be implemented. Initially, a one-year qualitative assessment of forest practices was undertaken in 1986 by a team of four resource professionals (Johnson 1993) that audited 100 THPs distributed across the state and produced the final "208 Report" (CSWRCB 1987). The team found that the Rules generally were effective when properly implemented on terrain that was not overly sensitive, and that poor Rule implementation was the most common cause of observed water quality impacts. They recommended several changes to the FPRs based on their observations.

Additional water quality monitoring projects in the 1980's related to the Forest Practice Rules include the Critical Sites Erosion Study (CSES), conducted within watersheds throughout northern California, and the North Fork phase of the Caspar Creek watershed study, located near Fort Bragg. Objectives of the CSES project were to determine site characteristics on THPs that could be used to identify potential large erosion features, and to identify management factors which may have been responsible for erosion events. This project collected data during 1985 and 1986 on management and site factors associated with existing mass wasting events on a random sample of 314 THPs covering over 60,000 acres (Durgin et al. 1989; Lewis and Rice 1989, Rice and Lewis 1991). A brief summary of the Caspar Creek watershed study findings is included in the following section under Summary of Related Studies.

In 1988, the Board of Forestry, CDF, and the SWRCB entered into a Management Agency Agreement (MAA) that required the BOF to improve forest practice regulations for protection of water quality based on needs described in the "208 Report." At this point, the SWRCB approved final certification of the FPRs as Best Management Practices. The U.S. EPA, however, withheld certification until the conditions of the MAA were satisfied, one of which was to develop a long-term monitoring program (LTMP).

In response to the MAA conditions, the BOF formed an interagency task force, later known as the Monitoring Study Group (MSG), in 1989 to develop this long-term monitoring program that could test the implementation and effectiveness of FPRs in protecting water quality. With public input, the MSG developed a LTMP with both implementation and effectiveness monitoring components, and conducted a pilot project to develop appropriate techniques for both hillslope and instream monitoring (CSBOF 1993). CDF has funded this monitoring program since 1990.

From 1989 to 1999, the MSG was an "ad hoc" committee which met periodically to: 1) develop the long-term monitoring program, and 2) provide guidance to CDF in implementing the program. The MSG was designated as an Advisory Committee to the Board of Forestry and Fire Protection in January 2000. The MSG continues to refine the long-term monitoring program testing the effectiveness of California's Forest Practice Rules and provide oversight to CDF in implementing the program.

The primary goal of the MSG's monitoring program has been to provide timely information on the implementation and effectiveness of forest practices related to water quality for use by forest managers, agencies, and the public. CDF and BOF chose to place more initial emphasis on hillslope monitoring for the Long-Term Monitoring Program because it can provide a more immediate, cost effective and direct feedback loop to resource managers on impacts from current timber operations when compared to instream monitoring (particularly channel monitoring which involves coarse sediment parameters) (Reid and Furniss 1999). As stated in Robben and Dent (2002), it is usually easier to identify a sediment source and quantify the volume of sediment it produced, when compared to measuring sediment in the watercourse and tracing it to the source.

The components of the Long-Term Monitoring Program are described in the MSG's Strategic Plan (CSBOF 2000) adopted by the BOF in 2000. This program is robust—utilizing a combination of approaches to generate information on Forest Practice Rule implementation and effectiveness related to water quality. The major components of the program include: 1) continuation of the Hillslope Monitoring Program, 2) use of CDF Forest Practice Inspectors to collect hillslope monitoring data on a random sample of completed THPs as part of a Modified Completion Report (MCR), 3) development of scientifically credible monitoring plans for cooperative watershed monitoring projects in selected basins to provide instream monitoring data, and 4) development and/or funding of selected monitoring projects that can answer key questions about forest practice implementation and effectiveness.

To date, considerable information has been collected by projects conducted as part of each of these components of the Long-Term Monitoring Program. A summary of what has been learned so far as part of the Modified Completion Report monitoring process is included in the following section of this report. One cooperative instream monitoring project has been started in the Garcia River watershed. The first phase of the project provided a watershed assessment and instream monitoring plan (Euphrat et al. 1998). The second phase was implementation of the instream monitoring plan to document baseline habitat conditions, which will allow examination of long-term trends to determine if instream conditions are improving. A final report documenting baseline measurements made in 1998 and 1999 for parameters such as water temperature, canopy and shading, gravel composition and permeability, large wood loading, sediment source areas, fish surveys, channel cross sections, and thalweg profiles was produced in 2001 (Maahs and Barber 2001). In 2002/2003, smaller scale cooperative instream monitoring projects are planned in Mendocino County with Campbell Timberland Management/ Hawthorne Timber Company, and in the Sierra Nevada/Cascade province with Sierra Pacific Industries.

Additionally, numerous monitoring projects have been supported, or are currently being supported, by CDF that provide critical information related to monitoring techniques and/or answer key questions regarding forest practice implementation and effectiveness. Examples of these projects include:

- Testing Indices of Cold Water Fish Habitat—Knoop (1993)
- V-Star Tests in Varying Geology— Lisle (1993), Lisle and Hilton (1999)
- Erodible Watershed Index--McKittrick (1994)
- Evaluation of Road Stream Crossings (Flanagan et al. 1998)
- Sediment Storage and Transport in the South Fork Noyo River Watershed, Jackson Demonstration State Forest (Koehler et al. 2001)
- Sediment Composition as an Indicator of Stream Health (Dr. Mary Ann Madej, USGS, and Dr. Peggy Wilzbach, HSU; in progress)
- Central Sierra Nevada Sediment Study (Dr. Lee MacDonald, CSU; in progress)
- Caspar Creek Watershed Study—Ziemer 1998, Lewis et al. 2001 (Dr. Robert Ziemer, USFS-PSW (retired), Dr. Thomas Lisle, USFS-PSW, in progress)

Final reports for completed projects, as well as other earlier monitoring reports and papers, detailed information on the Modified Completion Report monitoring process, the MSG Strategic Plan, and agendas for upcoming MSG meetings are available online at: **http://www.fire.ca.gov/bof/board/msg_geninfo.html**

Over 100 papers and reports documenting findings from the Caspar Creek Watershed Study are available online at:
http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Summary of Other Related Studies

Several recently completed and ongoing monitoring efforts are related to the hillslope monitoring work reported on in this document. Many of the findings in these studies are similar to and support results described in this Hillslope Monitoring Program report.

Colorado State University, Department of Earth Resources— Central Sierra Nevada Sediment Study. Dr. Lee MacDonald and Drew Coe, Colorado State University, Fort Collins, CO (MacDonald and Coe 2001; Coe and MacDonald 2001; Coe and MacDonald 2002)

The objective of this research is to quantify natural and anthropogenic hillslope erosion rates for use in a spatially-explicit cumulative watershed effects model. Study sites are on the Eldorado National Forest and Sierra Pacific Industries land in the Central Sierra Nevada. Approximately 150 sediment fences were installed in the summers of 1999 and 2000 to measure sediment production and sediment delivery to the stream network (Figure 1). Silt fences were installed in areas subjected to different management activities, including undisturbed sites, across three geologic types (volcanic, granitic, and metamorphic) and different elevation zones. Sediment production rates were measured for three winter periods (hydrologic years 2000 through 2002). The first winter was the wettest of the three years, while the second winter was drier and colder. The third winter was intermediate in terms of total precipitation and the duration of snow cover.

Data analysis is currently nearing completion, although several progress reports and presentations have described some of the initial key findings. The results have shown that native surface roads are the primary anthropogenic source of sediment. High rates of sediment production have also been documented for high severity wildfires and areas used for off-highway vehicles. Most harvest units and areas burned at low severity produced relatively little sediment. Overall, there was a large degree of variability between sites within a given management category as well as between years. For example, sediment production rates in the first year were 3 to 11 times higher than the sediment production rates for the second winter, and this is due in large part to the lower amounts of precipitation and more consistent snow cover.

Data from the first winter showed that, on average, native-surface roads generated approximately seven times as much sediment as harvest units and landings. These results led to a greater focus on sediment production from native surface roads. Data from the next two winters indicated that recently-graded native surface roads produced twice as much sediment as comparable segments that had not been graded. Road surface area, slope, annual precipitation, elevation, and grading (i.e., recently graded vs. ungraded) were the primary controls on road sediment production. The product of road surface area and road gradient was the single best predictor of road surface erosion, and this explained from 40 to 65% of the variability within a given year. Rocked roads produced only 2-4% as much sediment as comparable native surface roads. Relative to the other factors, soil type was not an important control on sediment production from the native surface roads. However, the limited data suggest that erosion rates from harvest units on granitic soils can be as much as an order of magnitude larger than the erosion rates from harvest units on volcanic soils.

A survey of 285 road segments as defined by specific drainage outlets (e.g., waterbar, rolling dip, or culvert) indicated that approximately 18% of the segments (20% of the total surveyed length) had gullies or sediment plumes that reached to within 10 m (33 ft) of a stream channel. Road crossings accounted for 58% of the road segments that were connected to the stream network.

Overall, the highest sediment production rates were often associated with insloped road segments located downslope of areas with shallow, impermeable bedrock. Because the product of area and slope was a dominant control on road segment sediment production, the older roads with inadequate drainage produced much more sediment per unit area than roads that followed current drainage specifications. Hence the best means to reduce erosion rates from native surface roads is to alter the road surface by rocking, decreasing the product of area and slope by improving and maintaining road drainage, and avoiding areas with shallow bedrock that increase sideslope drainage and increase ditch runoff. Areas with shallow bedrock also appear to facilitate the generation of extended gullies that can link roads to the stream network. These segments, together with road crossings, account for nearly all of the road-derived sediment that is being delivered to the stream network.

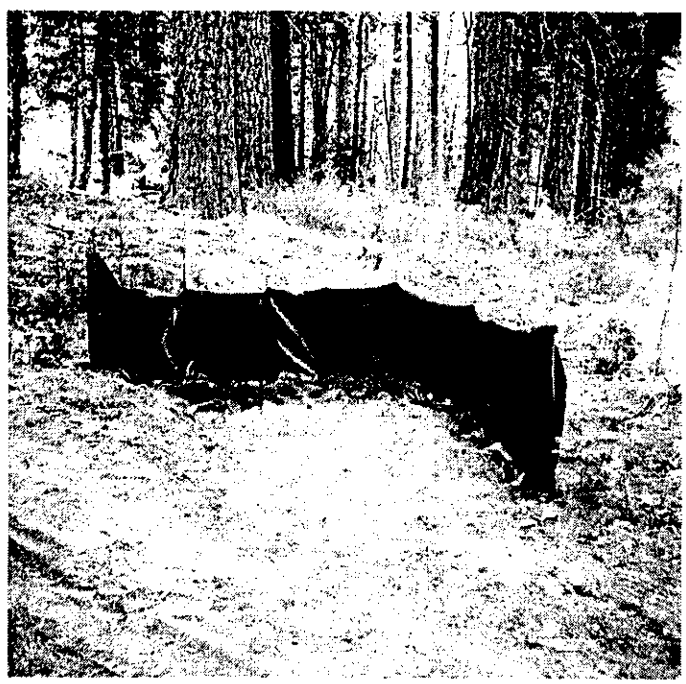

Figure 1. Example of one of 147 sediment fences installed to measure sediment production rates in the central Sierra Nevada Mountains (photo by Drew Coe used with permission).

US Forest Service—Pacific Southwest Region—Best Management Practice Evaluation Program. Brian Staab, USFS, Vallejo, CA (Staab 2002)

The U.S. Forest Service's (USFS) Best Management Practices (BMP) Evaluation Program in California is focused on hillslope monitoring of BMP implementation and effectiveness. Preliminary results indicate that USFS silvicultural BMPs are generally implemented and effective. Statewide, average implementation and effectiveness rates from 1992-2001 were both approximately 87% (n=2900 random evaluations). Yearly rates of BMP implementation and effectiveness ranged from 83% to 91% and 78% to 92%, respectively. Effectiveness rates were above 85% every year except 1997. Implementation and effectiveness rates, respectively, for specific silvicultural BMPs were as follows: streamside management zones: 82%/79% (n=248); skid trails: 84%/91% (n=276); suspended yarding 97%/90% (n=87); landings: 90%/95% (n=373); timber sale administration (n=62): 95%/98%; special erosion control and revegetation: 84%/96% (n=57); meadow protection: 93%/95% (n=121); road surface, drainage and slope protection: 87%/84% (n=238); stream crossings: 86%/80% (n=259); control of sidecast: 81%/89% (n=185); servicing and refueling: 95%/97% (n=38); in-channel construction practices: 92%/61% (n=115); temporary roads: 91%/88% (n=120); rip rap composition: 91%/82% (n=22); snow removal: 85%/87% (n=163); pioneer road construction: 96%/56% (n=25); management of roads during wet periods: 92%/85% (n=61); prescribed fire: 77%/95% (n=231); vegetation manipulation: 89%/96% (n=93); and revegetation of surface disturbed areas: 84%/76% (n=85).

Oregon Department of Forestry—Best Management Practices Compliance Monitoring Project: Final Report. Joshua Robben and Liz Dent, ODF, Salem, OR (Robben and Dent 2002)

The ODF Forest Practice Monitoring Program implemented the BMP Compliance Monitoring Project to evaluate compliance with BMPs on non-federal forestlands in Oregon. This was a three year statewide project, with the first year (1998) being a pilot study to develop and test protocols. A total of 189 harvest operations were randomly selected, using criteria that favored selection of units with fish-bearing waters. At the selected units, harvesting practices, roads, skid trails, stream crossings, riparian management areas, wetlands, etc. were evaluated for compliance with 150 Forest Practice Rules designed to protect water quality and fish habitat. Monitoring was completed by a former Forest Practices Forester who rated individual BMP applications as compliant or noncompliant. The type and magnitude of resulting riparian and channel impacts were recorded for noncompliant practices.

A total of approximately 13,500 BMP applications were evaluated and the overall compliance rate was 96.3%. Specific practices that were found to have the poorest compliance (less than 96% compliance and five or more noncompliance practices) are: slash piling within waters of the state (89.6%), removal of petroleum-related waste from the unit (82.0%), stream crossing fill stability (84.3%), road surface drainage design (86.5%), road surface drainage maintenance (94.2%), restrictions on felling of trees into small streams (83.1%), skid trails not located within 35 feet of Type F streams (91.5%), skid trails located so that stream water will not flow onto the skid trail (92.5%), removal of temporary crossings (47.8%), protection of other wetlands (69.8%), prior approval requirements (90.4%), and written plan requirements (77.1%).

Approximately 500 noncompliant practices were recorded and 185 of these were administrative requirements not directly affecting water quality. About 65% of the noncompliant practices either had impacted water quality or had the potential to impact riparian and channel conditions in the future. The greatest source areas of sediment delivery were from 36 noncompliant road construction and maintenance practices. To improve BMP compliance, the results of this monitoring work are being presented to landowner groups, operator workshops, and Oregon Department of Forestry conferences. Additionally, the results are being used to clarify guidance language, develop additional implementation tools, and guide future monitoring work.

California Department of Forestry and Fire Protection—Modified Completion Report Monitoring Progress Report. Clay Brandow, CDF, Sacramento, CA (Brandow 2002)

As part of the CDF's Forest Practice Program, the Department's Forest Practice Inspectors collect hillslope monitoring data for areas of the landscape that have been found in previous monitoring work to be either particularly sensitive to disturbance or having significant impacts to water quality. For each THP evaluated, a randomly selected road segment (1000 feet), a randomly selected WLPZ segment (200 feet), and two randomly located watercourse crossings are rated for FPR implementation at the time logging is completed. Effectiveness of erosion control facilities and crossing design/construction are rated a second time for the same road segment and crossings during an Erosion Control Maintenance inspection after one to three overwintering periods. Rating implementation immediately following logging and effectiveness after stressing winter storms follows the guidelines suggested by Lewis and Baldwin (1997) in a statistical review of the Hillslope Monitoring Program. Sample size is a random selection of 12.5% of THPs undergoing Work Completion Report field inspections. As of September 2002, 132 THPs have been sampled, with 101 having a Class I or II WLPZ. Class I WLPZ total canopy has averaged 83% in the Coast District and 68% in the inland (Northern and Southern) districts. Class II total canopy has been similar, with 83% and 69% in the Coast and inland districts, respectively. For the road segments to date, 15% of evaluated stretches have had at least one departure from the FPRs. Most of the departures have related to waterbreak spacing, waterbreak discharge into cover, and waterbreak construction. Additionally, 145 crossings have been sampled, and FPR departure rates have been found to be low (contrary to Hillslope Monitoring Program results). This may be due to: 1) fewer overwintering periods; 2) differences in monitoring forms, rating categories, and reviewer opinions; and 3) requirement for major problems to be fixed prior to plan completion report approval.

US Forest Service—Pacific Southwest Research Station—Caspar Creek Watershed Study. Dr. Robert Ziemer, Chief Research Hydrologist (retired), Redwood Sciences Laboratory, Arcata, CA; Dr. Thomas Lisle, Research Hydrologist, Redwood Sciences Laboratory, Arcata, CA. (Ziemer 1998, Lewis 1998, Cafferata and Spittler 1998, Lewis et al. 2001, Lewis 2002)

Results from the Caspar Creek watershed study located near Fort Bragg, California show that improved forestry practices after 1974 have significantly reduced sediment yields in the past two decades. Selection logging conducted prior to the implementation of the modern Rules in the South Fork of Caspar Creek produced from 2.4 to 3.7 times more suspended sediment compared to that produced by clearcutting in the North Fork under the modern Rules. Suspended sediment monitoring in the North Fork of Caspar Creek following clearcut harvesting of almost half the watershed in three years under the modern Forest Practice Rules showed that annual sediment loads increased 123-269% in the tributaries. At main-stem stations, however, increased loads were detected only in small storms and there was little effect on annual sediment loads. Most of the suspended sediment generated at the North Fork weir resulted from one large landslide that occurred in January 1995.

The overall conclusion from the Caspar Creek watershed study is that logging operations conducted under the modern Forest Practice Rules produce much less sediment than logging in the early 1970's prior to the implementation of these Rules. Unit area sediment loads from four storm events in hydrologic year 2001 show that sediment yields are higher in several South Fork tributary watersheds, without disturbance for almost 30 years, than was found in clearcut tributary basins in the North Fork that were logged approximately 10 years ago. Much of this difference is attributed to poor design, construction, and maintenance of pre-modern Forest Practice Rule roads, landings, and skid trails.

Road rehabilitation work was conducted during the summer of 1998 on three miles of old road constructed along the South Fork in 1967. A total of 33 watercourse crossings were abandoned, removing a total of approximately 28,500 cubic yards of fill material. Surveys of the abandoned crossings have shown that downcutting following large winter storm events, including a 40-year recurrence interval event the first winter following excavation, has resulted in 854 cubic yards of sediment, or three percent of the total amount of sediment removed, being washed downstream. Most of this material came from three crossings. Approximately 500 cubic yards were lost from one abandoned crossing on the mainstem of the South Fork, primarily from upstream residual deposits of sediment above an old splash dam built in the 1860s. The other two problem crossings each lost 50 to 70 cubic yards of sediment due to downcutting at the crossing site. Little additional downcutting has occurred after the first winter following excavation (W. Baxter, CDF—Jackson Demonstration State Forest, Fort Bragg, CA, personal communication).

Study Design

Overview

The Hillslope Monitoring Program began in 1993 with a pilot project designed to develop and test monitoring procedures. Dr. Andrea Tuttle and CDF began the process by modifying previously developed U.S.D.A. Forest Service hillslope monitoring forms developed for the Pacific Southwest Region (USFS 1992). Modifications were made to allow detailed information to be recorded for locations within Timber Harvesting Plans (THPs) that were felt to present the greatest risk to water quality--roads, skid trails, landings, watercourse crossings and watercourse and lake protection zones (Tuttle 1995). The forms developed for the U.S. Forest Service monitoring program did not adequately identify the specific requirements of the Forest Practice Rules. As a result, these initial forms were either substantially modified (i.e., watercourse crossings and landings) or completely re-written (i.e., transect evaluations were developed for roads, skid trails, and watercourse and lake protection zones). Dr. Tuttle and CDF prepared new forms for practices that are unique in the FPRs, and developed methods for measuring and identifying features related to Rule implementation and effectiveness. Harvest units were not included because few of the Rules apply to these areas and previous studies had shown that most of the erosion features were associated with the more disturbed sites (Durgin et al. 1989).

As part of the hillslope component of the Pilot Monitoring Project, Monitoring Study Group members identified all of the separate Forest Practice Rule requirements that could be related to protection of water quality. This resulted in a list of over 1300 separate items, including plan development, the review process, and field application requirements. This list was then pared down to 191 Rule requirements that are implemented during the conduct of a Timber Harvesting Plan and can be evaluated by subsequent field review. Many of the Rule sections with multiple requirements were broken down into their separate components for field evaluations.[1] FPRs related to cumulative watershed effects and the THP review process were not included because they could not be evaluated using an on-the-ground inspection of the THP area. The overall goal of the Hillslope Monitoring Program has been to collect data that can, over time, provide information on: 1) how well the Rules are being implemented in the field, and 2) where, when, and to what degree problems occur—and don't occur—under proper implementation (Tuttle 1995).

The California Division of Mines and Geology (now known as the California Geological Survey) assisted with the hillslope pilot program and provided detailed geomorphic mapping for two of the watersheds used for the pilot work (Spittler 1995). The California Department of Fish and Game completed the pilot project work for the instream monitoring component of the program (Rae 1995). The Pilot Monitoring Program was completed during 1993 and 1994, and final reports were prepared in 1995. Pilot

[1] The Forest Practice Rules referred to in this report, including all the tables, are based on the Rules in effect in 1994. Changes to the FPRs since that time have affected the letters and numbers assigned to some individual Rules, but the listed Rules remain in effect in the same Rule Section.

Monitoring Program Manager Gaylon Lee of the SWRCB prepared a summary document that included a detailed description of what had been learned about hillslope monitoring and made recommendations for the long-term program (Lee 1997).

Site Selection

Data collection for the BOF/CDF Hillslope Monitoring Program began in 1996 with a stratified random sample of 25 THPs in both Humboldt and Mendocino Counties to collect information from watersheds with coho salmon habitat, due to the proposed federal listing of that species.[2] Contracts were developed with the Resource Conservation Districts (RCDs) in each county, and the RCDs hired Registered Professional Foresters (RPFs) to collect the required field data on THPs that had over-wintered for a period of one to four years. Natural Resources Management Corporation (NRM) was the contractor hired by the Humboldt County RCD, while R.J. Poff and Associates was hired by the Mendocino County RCD. Stratified random sampling was utilized to select the THPs for work completed in 1996. Using erodibility ratings developed as part of a study completed by the California Division of Mines and Geology (now the California Geological Survey) (McKittrick 1994), approximately 50 percent of the THPs evaluated were included in the areas designated as having high overall erosion hazard, 35 percent were included in the moderate category, and 15 percent were included in the low erosion hazard rating.[3]

From 1997 through 2001, field data was collected from a statewide random sample of 50 THPs each year. These THPs were not stratified based on the CGS erodible watershed categories utilized in 1996. While only a fraction of all completed THPs were evaluated, the random sample design ensured that the results were representative of all the THPs harvested during the same period. Beginning in 2001, Nonindustrial Timberland Management Plan (NTMP) Notices of Timber Operations (NTOs) (or NTMP projects) were included as part of the sample because of the growing number of NTMPs statewide, and a lack of information regarding rule implementation and effectiveness on these projects. NTMPs are long-term management plans for small nonindustrial timberland owners. When a portion of the area covered by the NTMP is to be harvested, an NTO is submitted to CDF for review and is valid for one year following approval.

CDF's RBASE Forest Practice Database was queried from 1996 through 1998 in Santa Rosa, Redding, and Fresno to produce a combined list of potential THPs meeting the completion and acceptance dates (approximately 2,500 THPs were in the population).

---

[2] Coho salmon were listed by the NMFS as threatened for the Southern Oregon/Northern California Coasts Coho ESU in 1997.

[3] This project rated large (e.g., 50,000 acre) watersheds on their inherent erodibility, excluding land use impacts. Variables input into a GIS model included precipitation, slope, and geology. A low, moderate or high rating was assigned to each factor. Numbers were summed to create an ordinal display of relative susceptibility of watersheds to erosion.

Beginning in 1999, CDF's new Oracle Forest Practice Database system was queried in Sacramento to generate the list of potential THPs and, in 2001, NTMP NTOs, with appropriate completion and acceptance dates.

These queries produced a preliminary, randomized list of THPs and NTMP NTOs to evaluate. Individual THP and NTMP files were then reviewed at CDF's regional offices in Santa Rosa, Redding, and Fresno to determine whether the individual plans met the criteria for when the logging was completed, the length and types of watercourses present, yarding system(s) utilized, plan or project size, and wildland classification described below. THPs eliminated from the preliminary list were replaced with the next THP meeting the above criteria, keeping the original percentages for each CDF Forest Practice District (i.e., Coast, Northern and Southern) established in the random sort.[4] The statewide sample, therefore, is very similar to the distribution of THPs CDF receives at each of its three Forest Practice District offices.

Specifically, THPs and NTMP NTOs were included in the study if they met the following criteria:

1. The THP had been filed and completed under the Forest Practice Rules adopted by the BOF after October 1991 (when the most recent WLPZ rules were implemented prior to adoption of the Threatened and Impaired Watersheds Rule Package in July 2000).

2. The THP was not accepted by CDF after the adoption of the July 2000 Threatened and Impaired Watersheds Rule Package.

3. The plans had been through at least one, but not more than four winters, since logging was completed. To ensure that plans met this requirement, the CDF Work Completion Report for the entire THP must have been signed by a CDF Forest Practice Inspector, and the date used to determine the one to four over-wintering periods was the date supplied by the RPF that indicated when all the logging was completed on the THP. This length of over-wintering provided the opportunity for erosion control measures to be tested by wet-weather prior to the field evaluation of effectiveness.

4. The THP or NTMP NTO was primarily composed of wildlands (e.g., it was not a campground or golf course). Also, the THP or NTMP NTO could not be a road-right-of-way-only plan.

5. The THP or NTMP NTO was not entirely helicopter logged and had significant components of either ground based tractor logging and/or cable yarding systems.

[4] If this were not done, a much higher percentage of THPs would have been selected from the Coast Forest Practice District, since many more of these plans have the required watercourse length.

6. The THP or NTMP NTO had at least 500 continuous feet of a Class I or II watercourse present, or the project boundary was a distance from the Class I or II watercourse that would correspond to what the Forest Practice Rules would prescribe for a WLPZ for that watercourse type and slope.

7. The THP was at least 5 acres in size.

8. The THP was not previously sampled.

Permission for THP access was first requested in a letter written by CDF and then with follow-up telephone calls made by the contractor for those plans where a response was not received. CDF stressed that there was no possibility of legal actions as a consequence of the field inspection, since no citations or violations could be issued by our contractor. Where permission was not granted, the next THP on the list was used. Permission was received from large industrial owners for all but one THP. In contrast, more than 50 percent of the selected THPs on small, nonindustrial timberlands were excluded from the study because of either an inability to locate the landowner, sale of the parcel, or denial of access. This resulted in the study being weighted toward the industrial timberlands.

Starting in 2000, to prevent additional bias in the sample towards large industrial forest landowners, large forest landowner THPs that were rejected due to a lack of access were replaced with other large landowner plans, and small landowner plans were replaced with other small landowner THPs. Large landowners were arbitrarily defined as having combined ownership in California of at least 6,000 acres based on a list of landowners and their ownership size developed by CDF Forest Practice Program staff. This practice was largely successful, but a few large industrial plans were still needed at the last moment when small non-industrial landowners changed their mind about access.

When permission for access was received for 50 THPs and NTMP NTOs, a final list of projects was developed and copies of the THPs and NTMPs were made by the CDF Regional Offices for the contractor. The contractor was supplied with copies of the Pre-Harvest Inspection reports, Amendments, Notices of Violations, and Final Work Completion Reports (including maps). Alternate THPs were supplied for each Forest Practice District in 1999, 2000, and 2001 in addition to the 50 THPs and NTMP NTOs. This was necessary to provide alternate plans for situations where field inspection revealed that the THP would not be acceptable for monitoring (e.g., all the roads had their drainage structures removed for more recent logging activities).

Data Collection

The monitoring work was conducted by independent contractors who acted as third party auditors (Figure 2). CDF developed the bid package, advertised the bid package, accepted bids from qualified contractors, and hired the qualified contractor with the lowest bid for each year from 1997 through 2001. To qualify, bidders must have met the following requirements:

1. The Contractor must have been a Registered Professional Forester (RPF) in the state of California. The Contractor could employ assistants who were not Registered Professional Foresters who worked under the supervision of the RPF and the on-site team conducting each THP or NTMP NTO must have included at least one RPF and one earth scientist (note that one person meeting both requirements could fill this role).

2. The Contractor must have had experience in the development, implementation, and evaluation of THPs on private timberlands within the state of California.

3. The Contractor must have had a working knowledge of the California Forest Practice Rules and experience with tractor and cable logging operations.

4. The Contractor's team must have had experience evaluating hillslope erosion problems, and must have had at least one member who was an earth sciences specialist with soil science or geology expertise and who had experience working with forested environments. To meet this criteria, one of the team members must have been either a **Certified Professional Soil Scientist** (CPSS) (as designated by the American Registry of Certified Professionals in Agronomy, Crops, and Soils) or a **California Registered Geologist** (RG) (as designated by the Board for Registration of Geologists and Geophysicists).[5]

5. The Contractor must have had an extensive background in monitoring, including experience with on-site monitoring to evaluate the impacts of timber operations on water quality.

The contractor for each of these contracts from 1997 to 2001 was R.J. Poff and Associates. Mr. Roger Poff was the U.S.D.A. Forest Service North Sierra Zone Soil Scientist and was stationed on the Tahoe National Forest from 1980 to 1993. He is both a Certified Professional Soil Scientist and a Registered Professional Forester (RPF) in California. Assisting Mr. Poff were Mr. Cliff Kennedy, an RPF in California, and Mr. Joe Hiss, the principles of High Country Forestry.[6]

Field work was conducted during the spring, summer, and fall months. During the site inspections, data was recorded by the contractor on paper field forms supplied by CDF. Detailed information was collected on: 1) randomly located road, skid trail, and watercourse protection zone segments; randomly located landings and watercourse crossings; 2) large erosion events (e.g., mass wasting features) where they were encountered, and 3) non-standard practices and additional mitigation measures when they were utilized at the randomly sampled locations. A set of forms was provided for each of these subject areas, with sub-sections for site information, non-standard practices and additional mitigation measures, rule implementation, and rule

---

[5] From 1997 to 1999, the bid package specified that the one of the members of the field team must be either a RG, CPSS, or a Certified Professional Erosion and Sediment Control Specialist (CPESC).

[6] Mr. Chris Hipkin, RPF, assisted R.J. Poff and Associates in 1996 in Mendocino County.

Figure 2. Field data was collected by highly qualified independent contractors who acted as third party auditors. Cliff Kennedy and Roger Poff are shown collecting field data in Mendocino County.

effectiveness. Direct observation of fine sediment delivery to stream channels during storm events was not attempted with this dry season program.

A Hillslope Monitoring Program database was developed in Microsoft Access for Windows (Microsoft Office 97) and runs on a personal computer. It is a relational database, approximately 30 megabytes in size without data. The data collected in 1996 was entered into the database by CDF. From 1997 to 2001, data was entered into the database by CDF's contractor. A preliminary set of queries were developed for the interim report prepared in 1999 (CSBOF 1999). These queries and additional, new queries were utilized for the current report.

Quality Assurance/Quality Control (QA/QC)

Quality assurance consists of actions to ensure quality data collection and analysis, while quality control is associated with actions to maintain data collection and analysis quality consistent with study goals through checks of accuracy and precision. The quality assurance program was composed of three components: 1) minimum qualifications for the contractor (see above), 2) a detailed training program, and 3) protocols provided in a field instruction package. New contractors were trained in the field by CDF Forest Practice personnel who developed the field sampling procedures and a detailed set of instructions on the Hillslope Monitoring Program procedures was provided.

The quality control program was composed of the following components: 1) self-evaluation, 2) CDF review, and 3) independent review. Under self-evaluation, it was stressed that the contractor ensure that the forms were completed satisfactorily and that the features were mapped prior to leaving the field site. CDF field inspections were "front-loaded", meaning that more field inspections were completed early on in the program compared to later years. CDF remeasured selected transects for canopy measurements in made in 1996 and found that the canopy measurements reported by the contractors were approximately seven percent higher than the internal estimate. The CDF average for three transects in Humboldt County and three transects in Mendocino County was 77.4 percent (measured with a spherical densiometer). The contractor's measurement for these transects was 84.8 percent.

For independent review, a random sample of 10 THPs were chosen in 1997 for quality control work. Dr. Stephen Daus and Mr. Michael Parenti were hired by CDF to complete the field work for these THPs a second time to test the repeatability of the process. Three plans were located in the Coast Forest Practice District, three in the Northern District, and four in the Southern District. Eighteen WLPZ transects were evaluated (14 Class II watercourses and four Class I watercourses). The average canopy cover measured with a spherical densiometer by the Daus/Parenti team for the WLPZ transects was 70.7 percent. The corresponding average canopy measurement for the same 10 THPs by the R.J. Poff and Associates team was 64.4 percent. A paired T Test revealed that these means of these two groups are significantly different at alpha <0.05.

Site Characteristics

Of the 300 plans evaluated, 295 were THPs and five were NTMP NTOs. Most of the THPs in the sample were accepted by CDF in the early to mid-1990's and the harvesting was completed by the mid to late 1990's (Figure 3). None of the THPs evaluated were approved under the new July 2000 Threatened and Impaired Watersheds Rule Package.

The THPs and NTMP NTOs sampled from 1996 through 2001 are displayed by Forest Practice District in Table 1. About 60 percent of the plans were from the Coast Forest Practice District. The distribution of large and small landowners is displayed in Table 2, and approximately 60 percent were on timberlands owned by large landowners. Figure 4 shows the general location of the projects which were monitored. Table 3 displays the distribution of THPs and NTMP NTOs by county. Slightly more than half the plans were located in Humboldt and Mendocino Counties. The average size of the THPs classified as being filed by large landowners was 441 acres, while the average size of the THP filed by small landowners was 169 acres. Considering both categories, the overall average size was 341 acres. In total, the 300 projects covered 102,260 acres.

Table 1. Distribution of THPs and NTMP NTOs by Forest Practice District.

Forest Practice District	THPs/NTMP NTOs	Percent
Coast	183	61
Northern	78	26
Southern	39	13

Table 2. Distribution of THPs and NTMP NTOs by landowner category.

Landowner Category	Number of THPs/ NTMP NTOs	Percent of THPs/ NTMP NTOs
Large landowner	189	63
Small landowner	111	37

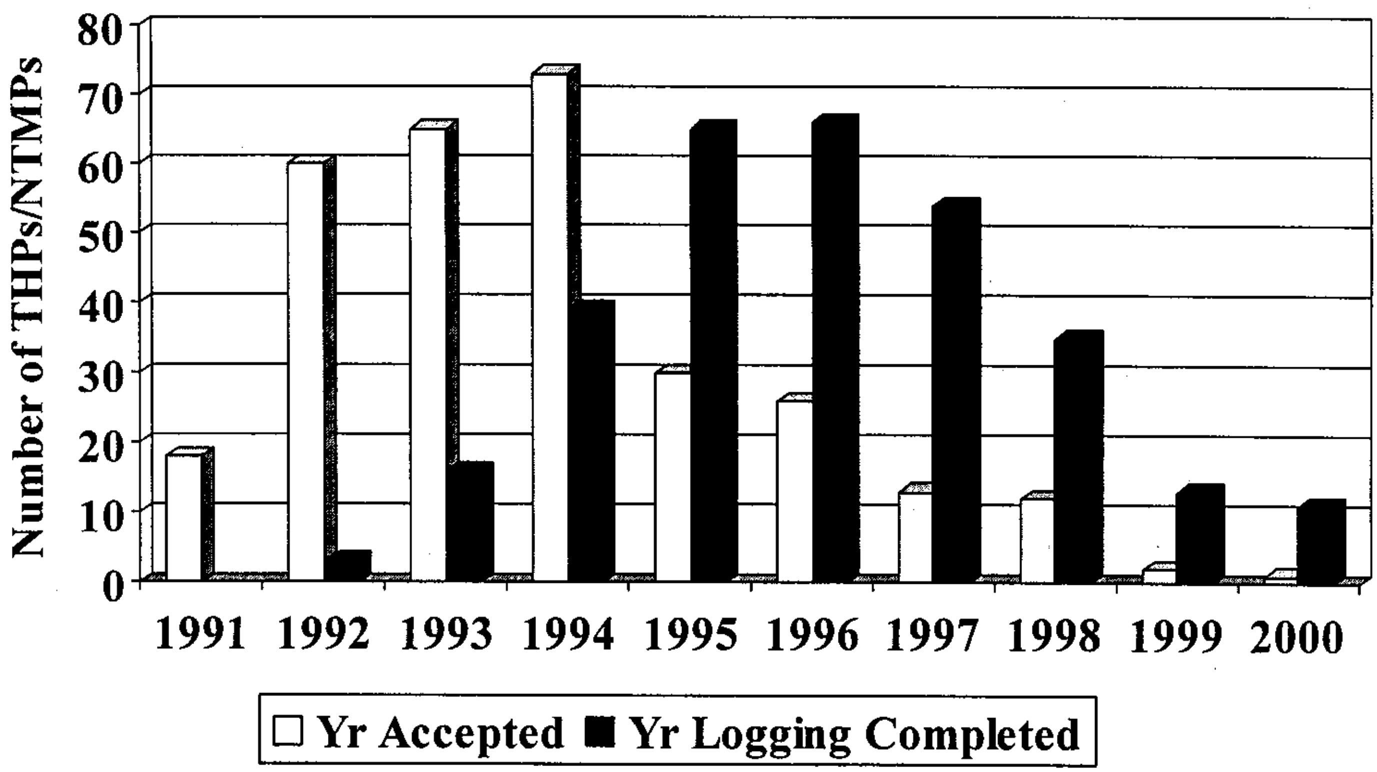

Figure 3. Distribution of when THPs and NTMP NTOs were accepted by CDF and when the logging was completed.

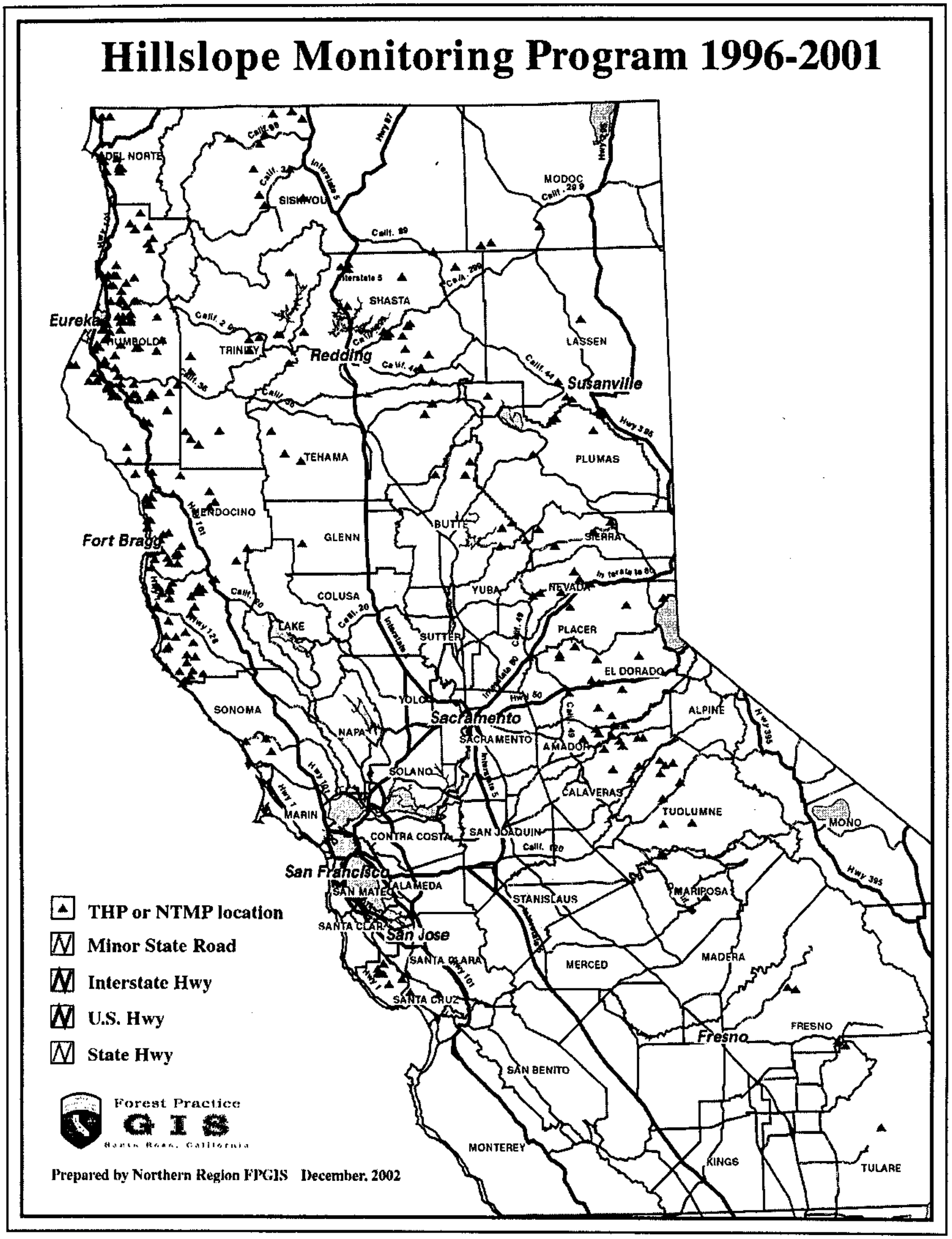

Figure 4. General location of THPs and NTMPs monitored from 1996 through 2001.

Table 3. Distribution of THPs and NTMP NTOs monitored from 1996 through 2001 by county.

County	North Coast THPs: 1996	Statewide THPs: 1997- 2001	Statewide NTMPs: 2001	Total Number of Projects
Coast Forest Practice District				
Del Norte		11		11
Humboldt	25	52	4	81
Mendocino	25	48	1	74
Santa Clara		2		2
Santa Cruz		7		7
Sonoma		4		4
Trinity		4		4
District Total	50	128	5	183
Northern Forest Practice District				
Butte		6		6
Glenn		1		1
Lassen		7		7
Modoc		3		3
Nevada		5		5
Placer		4		4
Plumas		4		4
Shasta		18		18
Sierra		3		3
Siskiyou		12		12
Tehama		5		5
Trinity		9		9
Yuba		1		1
District Total	0	78	0	78
Southern Forest Practice District				
Amador		6		6
Calaveras		8		8
El Dorado		10		10
Fresno		3		3
Mariposa		2		2
Tulare		2		2
Tuolumne		8		8
District Total	0	39	0	39
Totals	**50**	**245**	**5**	**300**

Methods

GENERAL INFORMATION

Five sample features were evaluated within each THP or NTMP NTO: roads, skid trails, landings, watercourse crossings, watercourse protection zones (i.e., WLPZs, ELZs, and EEZs). Two samples of each of these features were evaluated within each selected THP or NTMP NTO if possible. Large erosion events were inventoried where they were encountered on the THP or NTMP project. Additionally, non-standard practices and additional mitigation measures were evaluated when they applied to randomly located sample features.

Conducting the evaluations involved both office and field activity. Office work needed to prepare for the field evaluations included:

- Determining the plan location and access routes.
- Reading the THP or NTMP/NTMP NTO to identify and become familiar with Review Team requirements, alternatives, in-lieu practices, additional mitigations, and addenda in the approved plan.

The following items were completed either in the office or in the field:

- Filling out "Site Information" sheets for each sample site with information that could be obtained from the THP or NTMP NTO document.
- Laying out the road transect grid and WLPZ transect grid for selection of sample transects, as described under "Site Selection" below.

SITE SELECTION

Selection of specific sample areas began with marking approximate 500 foot road segments on all roads on the THP or NTMP NTO map. Each of these segments was assigned a number.. A random number table or generator was then used to identify one of the segments. From this point, a coin was flipped to determine direction of travel along the road until a landing was encountered. This randomly selected landing was used for the landing sample. Where more than one road entered or exited the landing, coin flips were used to identify a road transect that began where the selected road left the landing. Coin flips were also used to determine the direction of travel to the first available skid trail transect. Watercourse crossing sites were selected as either the first crossing encountered during the road transect or, if no crossing was encountered, the first crossing along a road selected by a coin flip. Finally, the point on a Class I or Class II watercourse closest to the landing was used as the starting point for the WLPZ transect, and direction of travel along the WLPZ was determined by a coin flip. Either

GPS readings or topographic maps were used to record site locations with UTM coordinates.

FIELD ACTIVITIES COMMON TO ALL SAMPLE AREAS

The first step in the field work was to finish filling out Site Information sheets. This was followed by an effectiveness evaluation of pertinent features that presented an erosion or water-quality problem to permit calculation of the relative proportion of problem to non-problem areas.

Sample area field evaluations were designed to provide a database "sketch" of the sites and transects that were inspected. The resulting detailed information was used to estimate the proportion of Rule or water quality problems in the whole population of similar features. This also allowed evaluation of Forest Practice Rule implementation and effectiveness for protection of water quality and identification of problems requiring revisions or additions to the Forest Practice Rules.

At "problem" sites (such as cut bank failures, gullies, excessive grades, and Rule violations), the problem type, erosion, and sediment delivery codes were recorded and a Rule implementation evaluation was conducted. Any rills, gullies, mass failures, or sloughing features that were encountered as part of the transect and site inspections were followed to determine whether sediment from these erosional features reached a watercourse protection zone or stream channel.[7] The presence of rills, gullies or deposited sediment at the edge of the high flow channel was sufficient to class the sediment as having entered that portion of the stream.

After the field review had been completed, an evaluation of all the Rules was conducted based upon the overall frequency of problem sites and Rule violations found along the transect as a whole. Implementation of the Forest Practice Rules applicable to a given subject area was rated as either exceeding the requirements of the Forest Practice Rules, meeting the requirements, minor departure from requirements, major departure from requirements, not applicable, could not determine (evidence is masked), or could not evaluate (with description of why).

Major departures were assigned when there was a substantial departure from Rule requirements (e.g., no or few waterbars installed for entire transect), or where sediment was delivered to a watercourse. Minor departures were assigned for slight Rule departures (e.g., WLPZ width slightly less than that specified by the Rule).[8]

---

[7] Rills, gullies, mass failures, and cutbank/sidecast sloughing are defined in the glossary.

[8] Minor and major departures from Forest Practice Rule have similar impact to water quality for watercourse crossings since sediment is assumed to enter the watercourse for both categories.

ROAD AND SKID TRAIL TRANSECT METHODS

Transects

The location of road and skid trail transects on the THP or NTMP NTO were determined using procedures described under Site Selection. Roads or skid trails that were not used as part of the THP or NTMP project being evaluated were not included. The starting point for the transect was the point at which the road or skid trail narrowed to its "normal width" and was outside of the influence of operations on the landing. Where a road forked, the transect followed the road that was of the same general type of construction and level of use. Where a skid trail forked, the branch that continued in the same basic direction (up-hill or down-hill) as the transect to that point was followed. If there were no clear differences, a coin flip was used to determine direction. The direction that was chosen was described in the comments section of the data form to provide a record for follow-up inspections or re-measurement, if required.

At the start of a transect, a measurement string was tied to a secure object, the string box counter was set to zero, and the location of the starting point was described in the comments for future reference. The road or skid trail was walked in the pre-determined transect direction for a distance of 1000 feet or to the end, whichever occurred first.[9]

If the total road distance was less than 800 feet, another transect on a different road segment was started from the landing without resetting the string box counter, and measurements were continued to obtain a total transect length of 1000 feet.

The minimum skid trail transect length was 500 feet. If needed, this distance could be made up of several segments. Skid trails were randomly selected from those entering the landing, where possible. If a skid trail was not available at this location, the nearest trail that brought logs to the measured road segment was used. Skid trail transects were no shorter than the length of trail requiring two waterbars. If the total skid trail distance was less than 300 feet, the transect was continued from the most recently passed trail intersection. Where there was no intersection, the transect was continued from the landing without resetting the string box counter, and the transect was continued in this fashion up to a maximum distance of 1000 feet. If there was less than 500 feet of skid trail, the available trail length was sampled and an explanatory comment was included. If there were no skid trials (i.e., the plan was entirely cable or cable/helicopter yarded), this was noted at the start of one of the skid trail forms.

Data Recording

The general procedure for linear transects was to record the starting and ending distance to each feature as it was encountered. On roads, for example, the beginning and ending point of all features (e.g., inside ditches, cut banks, location of waterbreaks,

[9] Note that main-line logging roads were not sampled if drainage structures had been removed to facilitate log hauling from more recent timber operations. This type of road (i.e., native surfaced primary road with waterbars) was probably under sampled as a result of these more recent operations.

cross drains, etc.) were recorded, regardless of whether or not they presented a water quality problem. Consecutive numbers were assigned to each feature, which, in combination with the THP and transect numbers, became a unique database identifier for that feature. Then codes were entered to indicate the type of feature and any associated drainage problems, erosion source area, erosion causes, and sediment production, plus information about road or trail gradient, sideslope steepness, and dimensions of erosion features. A feature date code was included for all erosion features, features with drainage problems, and other features related to Rule requirements to indicate if the feature was created by the current THP or NTMP project.[10]

LANDING METHODS

Site Identification

The landing to be evaluated was located as previously described under Site Selection. Landing selection was important because it became the basis for locating random sites for the other sample features.

Landing Surface

The entire landing surface was inspected for rills and gullies. Gullies were defined as being six inches or greater in depth and of any length. The total length of all gullies and their average width and depth were recorded on the data forms. Sample points for rills were located along a single transect that bisected the landing into two roughly equal parts perpendicular to the general direction of surface runoff in 1996. The percentage of the landing surface drained by rills was estimated for 1997 through 2001. To be counted, rills had to be a least one inch deep and 10 feet long. Both rills and gullies were inspected to determine whether they continued for more than 20 feet past the toe of the landing fill slope, and gullies were followed to determine if sediment had been delivered to the nearest WLPZ and channel.

Cut Slopes (if present)

The face of the cut slope was inspected for evidence of slope failures, rilling, and gullying. The path of any transported sediment was traced to determine the quantity and whether material was transported to a drainage structure(s) on the landing.

---

[10] Number codes that were used to indicate erosion and problem feature date were: 1-feature created by current THP; 2-feature predates and was affected by current THP; 3-feature predates and was not affected by current THP; 4-cannot determine feature date; and 5-feature created after THP but was not affected by THP. For example, 1-R indicated that a rill was created by the current THP or NTMP project.

Fill Slopes (if present)

The toe of the fill slope was inspected for evidence of slope failures, rilling, and gullying. Rills or gullies that were not caused by drainage from the landing surface were traced to determine whether they extended to a downslope channel. All slope failures were evaluated to determine the total amount of material moved and whether it reached a watercourse channel.

WATERCOURSE CROSSING METHODS

Site Identification

A watercourse crossing site was established at the first crossing encountered on the road or skid trail transects, which was also noted as a feature on the transect. If no crossing was encountered as part of the transects, the first crossing beyond the end of the road transect was used for this evaluation.

Once the crossing had been identified, the next step was to determine the length of road to be included in the drainage evaluation. This was done by walking in both directions from the crossing and identifying the points where runoff from the road surface, cuts, and fills no longer carried toward the stream crossing. The road length for evaluation also included the cut-off waterbar that should route water away from the crossing.

Fill Slopes

The crossing fill slope was evaluated to determine whether it had vigorous dense cover or if at least 50 percent of its surface was protected by vegetation, mulch, rock, or other stable material. The presence and frequency of rills, gullies, and cracks or other indicators of slope failure were noted, and the size of rills and slope failures was recorded.

Road Surface

The type and condition of road surfacing was assessed and was evaluated for ruts from vehicles and, if ruts were present, whether they impaired road drainage. The presence, frequency and length of rills and gullies on the road surface were also determined along with average gully size and surface drainage conditions. The presence, condition, and effectiveness of cutoff waterbars and inside ditches were evaluated, along with evidence of ponding or other water accumulation on the road.

Culverts

The stream channel at both the culvert inlet and outlet was examined for evidence of scouring. The current degree of plugging at the upstream inlet was assessed along with the diversion potential in case the culvert eventually becomes plugged. Alignment of the culvert, crushing of the inlet and outlet, and degree of corrosion were also evaluated. Pipe length and gradient were determined and evidence of piping around the culvert was identified.

Non-Culvert Crossings (e.g., Rocked Class III crossings)

The crossing was examined to determine the type and condition of armoring and whether downcutting or scouring at the outlet was occurring. Crossing approaches were evaluated to determine if they had been maintained to prevent diversion of stream overflow down the road should the drainage structure become plugged.

Removed or Abandoned Crossings (where applicable)

Removed crossings were examined to determine whether the restored channel configuration was wider than the natural channel and as close as feasible to the natural watercourse grade and orientation. The location of excavated material and any resulting cut bank was assessed to determine if they were sloped back from the channel and stabilized to prevent slumping and minimize erosion. The crossing was also evaluated for the following conditions:

- Permanent, maintenance free drainage.
- Minimizing concentration of runoff, soil erosion and slope instability.
- Stabilization of exposed soil on cuts, fills or sidecast that prevents transport of deleterious quantities of eroded surface soils to a watercourse.
- Grading or shaping of road surfaces to provide dispersal of water flow.
- Pulling or shaping of fills or sidecast to prevent discharge of materials into watercourses due to failures of cuts, fills or sidecast.

WATERCOURSE PROTECTION ZONE (WLPZ, ELZ, EEZ) TRANSECT METHODS

Transects

Two Class I or II WLPZs were sampled on each THP or NTMP project, when available (transects may have been shorter than 1000 feet, but must have been at least 500 feet to be included). These WLPZ segments were located along the nearest, accessible Class I or II watercourse relative to the selected landing sites. When WLPZs were present near only one of the selected landings, both segments were selected from this location. And where there was only one WLPZ on the THP, both segments could have been located along the same watercourse but, where possible, should have represented different conditions (e.g., different stream classes, stream gradients, sideslope gradients, adjacent logging methods, etc.).

For Class I waters, two 1000 foot long transects were sampled parallel to the stream within the WLPZ. One of these was a "mid-zone" transect located between the watercourse bank and the up-slope boundary of the WLPZ. The other was a "streambank" transect located immediately along the stream bank and parallel to the mid-zone transect. For Class II watercourses, only the mid-zone transect was used.

Beginning in 2000, Class III watercourses were included in the Hillslope Monitoring Program. Two Class III watercourses were sampled on each THP or NTMP project, when available. One 300 foot long transect parallel to the watercourse was established for each Class III evaluated. These segments were located along the nearest, accessible Class III watercourse relative to the selected landing sites. The transect was located either: 1) approximately 25 feet from the watercourse where no WLPZ had been established, or 2) where there was a designated protection zone (i.e., WLPZ, ELZ, or EEZ), along the "mid-point" of the designated zone. Class III monitoring protocols were developed in 1999 during a pilot project involving the THPs sampled as part of the 1999 Hillslope Monitoring Program work (Poff and Kennedy 1999).

Data Recording

Within the transects, groundcover and canopy cover were evaluated at regular intervals and at disturbed sites where timber operations had exposed more than 800 continuous square feet of mineral soil. Several other factors were also evaluated wherever they occurred, such as sediment delivery to the channel, streambank disturbance, and channel conditions.

Parameters measured or estimated in the mid-zone transect for Class I and II watercourses included groundcover at every 100 feet, canopy cover at every 200 feet with a spherical densiometer (from 1996 to 1998),[11] WLPZ width at every 200 feet (concurrent with canopy measurement and whenever there was a change in sideslope class), and sediment to the channel wherever it occurred. Measurements in the Class I watercourse streambank transect included canopy cover at 200 foot intervals, disturbance to streambanks wherever it occurred, and other stream related features. In addition, Rule implementation was evaluated continuously along both transects, and any Rule requirements or discrepancies were noted as a feature and were included in the implementation evaluation.

From 1999 to 2001, the canopy sampling method for Class I and II watercourses was changed from use of the spherical densiometer (Figure 5) to use of the sighting tube (Figures 6 and 7). This change was based on findings from a recent study that the sighting tube provides unbiased estimates of true canopy cover, while the densiometer does not (Robards et al. 2000). The procedure for estimating canopy was as follows:

[11] In 1996, the spherical densiometer was used as suggested by Lemmon (1956). The Strickler (1959) modification, which requires counting only 17 grid intersections, was used in 1997 and 1998 to reduce bias.

- Estimate the length of the WLPZ segment to be evaluated to the nearest 100 feet (maximum length was 1000 feet and minimum length was 500 feet). A 200 foot segment was randomly selected from the number of feet in this estimate.

- Canopy was estimated at 44 to 56 systematically located points throughout the 200 foot transect, where the number of points was based on the WLPZ width at the site. Sighting tube lines were run by "zig-zagging" back and forth across the WLPZ (i.e., up and down the hillslope) (see Figure 8).

- A random starting point for the first canopy point was used to reduce sampling bias.

- After leveling the sighting tube in both horizontal and vertical directions, a "hit" or a "miss" was recorded for that point depending on whether the small dot in the center of viewing area appeared to be touching or not touching some form of vegetation.

- The percent canopy for the transect was determined by the total number of "hits" for the transect divided by the total number possible (44 to 56).

The general procedure for recording watercourse protection zone transect data and the use of codes was similar in format to the methods used for roads and skid trails, but with features that were specific to watercourse protection zone conditions and Rule requirements. As with roads, the starting and ending distance to each feature was recorded along with a unique identification number and information about feature type, erosion causes, dimensions of erosion features, and sediment deposition. Additionally, a feature date code was included for all erosion features and other features related to Rule requirements to indicate if the feature was created by the current THP or NTMP project (see footnote number 10).

Groundcover was estimated in an area with a diameter of approximately one foot located directly in front of the observer's boot toe, where adequate cover was defined as "living plants, stumps, slash, litter, humus, and surface gravel (minimum diameter of 3/4 inch) in amounts sufficient to break the impact of raindrops and serve as a filter media for overland flow."

Features did not need to intersect the transect line to be included. This was necessary because dense vegetation and other obstructions in watercourse protection zones make following a straight line transect impractical, so the location of the transect line will be biased by access within the zone and some extensive watercourse protection zone features might not intersect the transect. An example of this situation would be a road running parallel to, but not on, the transect.

The Class I and II WLPZ measurements began at one end of the mid-zone transect and included a continuous record of the beginning and end points of features encountered along the transect for a distance perpendicular to the end of the mid-zone transect and proceeded in the opposite direction toward the starting point of the mid-zone transect.

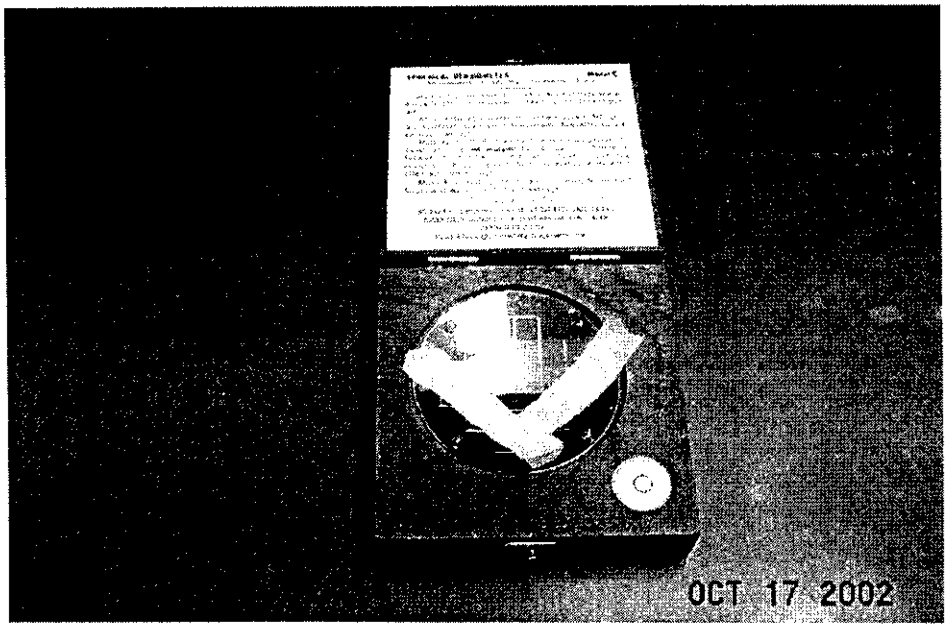

Figure 5. Concave spherical densiometer used for canopy measurements from 1996 to 1998 (the Strickler (1959) modification was utilized in 1997 and 1998 to reduce bias).

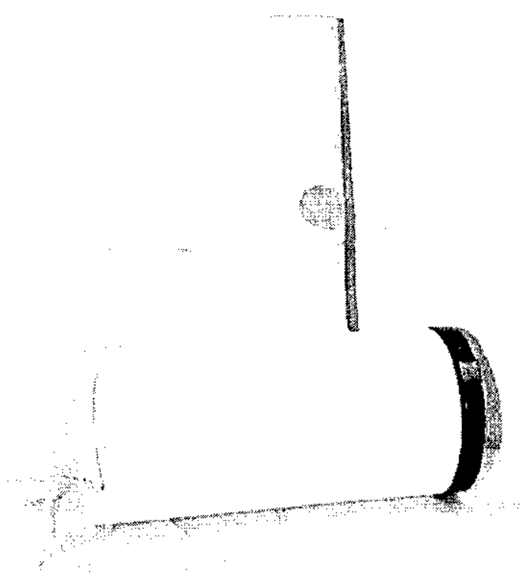

Figure 6. Close-up view of the sighting tube.

Figure 7. The sighting tube in use in the field. This instrument was utilized for obtaining an unbiased estimate of canopy cover from 1999 through 2001.

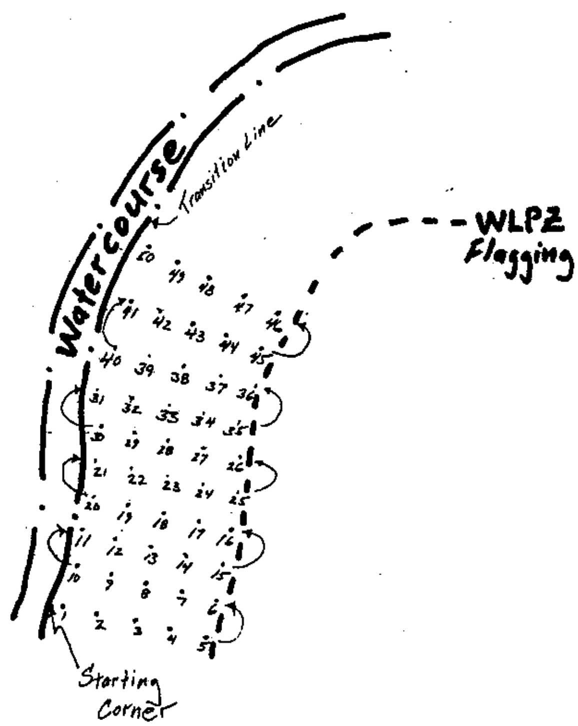

Figure 8. Example of the systematic grid used for a 125-foot WLPZ to determine canopy cover with a sighting tube for a randomly selected 200 foot reach of Class I or II watercourse (total number of sighting tube points varied from 44 to 56 depending on WLPZ width). Diagram drawn by Mr. Clay Brandow, CDF, Sacramento.

For Class III watercourses, ground cover was evaluated every 100 feet, including end points, and at the mid-points of disturbed sites. ELZ, EEZ, or WLPZ widths were determined every 100 feet, including end points. Erosion features were recorded and sediment delivery to channels was documented where it occurred. Canopy was not measured, but where canopy was retained, it was noted with the appropriate code.

LARGE EROSION EVENT EVALUATION METHODS

Erosion events that created voids larger than 100 cubic yards were assessed whenever they were encountered on the THP on NTMP project. For watercourse crossings that had failed, a large erosion event was defined as greater than 10 cubic yards. These sites were identified during the standard site evaluations, while traveling within the THP, or as a result of information provided in the THP or by landowners or managers. Data collected included the location, size, and type of feature; site conditions; and an evaluation of the causal connections between the feature and specific timber operations, along with any applicable Forest Practice Rules. Features were classified as gullies, shallow debris slides, debris torrents, deep seated rotational failures, streambank failures, or catastrophic crossing failures. This process was modified significantly in 1997 based on information provided by the Hillslope Monitoring Program contractors who completed the field work in Mendocino and Humboldt Counties during 1996.

If more than five large erosion events were discovered on a THP or NTMP, only the first five were required to be completely evaluated by the field team. For additional events, only the location, type, and estimate of the cause were briefly noted.

NON-STANDARD PRACTICES AND ADDITIONAL MITIGATION MEASURE METHODS

In addition to completing the site information, implementation, and effectiveness sections of the field forms, the field teams also filled out a form for non-standard practices and additional mitigation measures, for each of the five subject areas.[12] Non-standard practices include in-lieu and alternative practices. These site specific practices and/or additional mitigation measures often did not apply at the randomly selected transects and features, so the totals reported are a relatively small sample that does not include all of the types of practices that were included in the THPs and NTMP projects.

For each of the five evaluation areas (roads, skid trails, landings, watercourse crossings, and watercourse protection zones), four questions were asked:

1. Was an alternative, non-standard, or in-lieu practice approved on the THP or NTMP NTO?

[12] Non-standard practices, alternatives, in-lieu, and exception practices are defined in the Glossary.

2. Were additional mitigation measures beyond the standard Rules included in the approved THP or NTMP NTO?

3. Where present on the sample transect or feature, have the alternative measures been implemented as described in the THP or NTMP NTO?

4. Provide comments on the implementation and effectiveness of the alternative practices.

The field team provided brief qualitative answers to these questions where they were applicable to the randomly located sites being evaluated.

TOTAL SAMPLE SIZE FOR THE PERIOD FROM 1996 TO 2001

If qualifying features had been found for all the THPs and NTMP projects sampled (and all the plans had been tractor yarded), the total sample size would have equaled the "maximum possible" number illustrated in Table 4. The actual sample size, however, is lower (as shown in Table 4) because numerous smaller plans did not have two of each feature to sample and many of the plans were entirely yarded with aerial systems (i.e., cable or cable/helicopter).

Table 4. Potential and actual sample sizes for the Hillslope Monitoring Program from 1996 through 2001.

	Road Segments	**Skid Trail Segments**	**Landings**	**Watercourse Crossings**	**Class I and II WLPZs**[13]	**Class III ELZs, EEZs, WLPZs**
Maximum Possible	600	600	600	600	600	200
Actual Number Sampled	568	480	569	491	501	182

[13] This column includes three Class IV watercourses.

Results

The results of the Hillslope Monitoring Program reported here are organized using the following major categories: roads, skid trails, landings, watercourse crossings, watercourse protection zones, large erosion events, and non-standard practices/additional mitigation measures. The results are generally displayed in a manner similar to that used in the earlier interim Hillslope Monitoring Program Report (CSBOF 1999).

Roads

From 1996 through 2001, 568 randomly located road transects were evaluated, covering a total of approximately 550,200 feet or 104.2 miles. Over 80 percent of the road transects were classified as seasonal roads (Table 5). About 23.4 percent of the road length surveyed had been surfaced with rock. Approximately 81 percent of the road transects monitored were existing roads built prior to the current plan; 19 percent of the transects were classified as new roads.

As part of the road transects, the field team rated the implementation and effectiveness of applicable Forest Practice Rules as they were encountered and as part of an overall evaluation following completion of the transect. In the overall evaluation of road transects, a total of 59 questions were answered in the field based on 46 Forest Practice Rule sections, since some FPRs were broken down into separate components. The majority of the Rules had high percentages (i.e., greater than 90 percent) of cases where implementation ratings either met or exceeded the standard Rule requirements. When considering all the Forest Practice Rules related to roads, the implementation rate where the Rules were met or exceeded was **93.2** percent. For the Forest Practice Rules where the sample size was adequate[14], 23 Rule requirements were found to have combined minor and major departures greater than five percent (Table 6).

Table 5. Percentages of road segment type.

Road Segment Type	Percent
Permanent	10
Seasonal	84
Temporary	4
Combination	2

[14] The results reported here are based on at least **30** observations where the field team assigned an implementation rating of exceeded rule requirement, met requirement, minor departure from requirement, or major departure from requirement. Thirty observations represents five percent or more of the implementation ratings available for each major category (i.e., roads, skid trails, landings, watercourse crossings, and watercourse protection zones).

Table 6. Road related Forest Practice Rule requirements with more than five percent departures based on at least 30 observations from the overall transect evaluation where implementation could be rated (note that some Rule sections are divided into components and the table is ordered by the percentage of total departures).

Forest Practice Rule	Description	Total Number	% Total Departure	% Minor Departure	% Major Departure
923.4(c)	waterbreaks maintained to minimize erosion	458	24.2	22.1	2.2
914.6(f)	where waterbreaks do not work—other erosion controls installed	214	19.2	15.0	4.2
923.1(f)	adequate numbers of drainage structures to minimize erosion	567	18.3	13.6	4.8
923.2(h)	size, number, and location of structures sufficient to carry runoff water	564	17.6	12.2	5.3
914.6(c)	waterbreak spacing according to standards in 914.6(c)	452	17.5	14.8	2.7
914.6(g)	waterbreaks have embankment of at least 6 inches	438	17.4	14.6	2.7
923.1(a)	landings on roads greater than ¼ acre or requiring substantial excavation must be shown on the THP map	243	15.2	3.7	11.5
923.2(h)	size, number, and location of structures sufficient to minimize erosion	565	15.2	11.2	4.1
914.6(g)	waterbreaks cut to depths of at least 6 inches	443	15.1	12.6	2.5
923.2(b)	sidecast minimized for slopes greater than 65% and distances greater than 100 feet	66	13.6	13.6	0.0
923.2(o)	discharge onto erodible fill prevented	510	13.1	9.2	3.9
923.2(d) Coast District	fills constructed with insloping approaches, berms, rock armoring, etc.	192	13.0	8.3	4.7
923.2(m)	sidecast extending greater than 20 feet treated to avoid erosion	202	11.9	4.5	7.4
914.6(f)	waterbreaks built to discharge into cover	464	11.4	9.3	2.2
923.2(d) Northern/ Southern	breaks in grade for drainage are located above and below through-fill, or other measures provided to protect the fill	222	11.3	8.6	2.7
923.6	wet spots rocked or otherwise treated	318	10.4	9.7	0.6
923.2(l)	trash racks, etc. installed where appropriate	173	9.2	6.4	2.9
923.2(p)	waterbars installed according to 914.6	401	8.7	6.5	2.2
923.4(j)	drainage ditches maintained to allow flow of water	306	8.5	8.2	0.3
923.1(d)	slopes greater than 65%, 50% within 100 feet of WLPZ--treat soil	93	7.5	5.4	2.2
923.4(c)	erosion controls maintained during the maintenance period	177	5.6	4.5	1.1
923.1(g)(3)	insloped roads-adequate number of ditch drains installed	237	5.5	4.6	0.8
923.4(e)	roadside berms removed or breached	513	5.5	5.3	0.2

The Rules with the highest percentages of total departures were related to waterbreak maintenance; use of other erosion control measures when waterbreaks are not effective; use of adequate numbers of drainage structures to minimize erosion; sufficient size, number, and location of drainage structures to carry runoff water; and waterbreak spacing. All the Rules evaluated had major departure percentages of less than five percent except for three: 1) if the landing on road was greater than ¼ acre or had substantial excavation, it must be shown on THP map; 2) sidecast extending greater than 20 feet must be treated to avoid erosion, and 3) the size, number, and location of drainage structures must be sufficient to carry runoff water.

A total of 1,132 erosion features were noted on the road transects. These features included rilling, gullying, mass failures, cutbank/sidecast sloughing, and other erosion types. Gullies were defined as erosion channels deeper than six inches, while rills were defined as small surface erosion channels that: 1) were greater than two inches deep at the upslope end when found singly or greater than one inch deep where there were two or more, and 2) were longer than 20 feet if located on a road surface or of any length when located on a cut bank, fill slope, cross drain ditch, or cross drain outlet. Mass failures were defined as downslope movement of soil and subsurface material that occurs when its internal strength is exceeded by the combination of gravitational and other forces. Mass erosion processes include slow moving, deep-seated earthflows and rotational failures and rapid, shallow failures on hillslopes (debris slides) and in downstream channels (debris torrents). Sloughing was defined as shallow, surficial sliding associated with either the cutbank or fill material along a forest road or skid trail, with smaller dimensions than would be associated with mass failures.

The distribution of erosion features is displayed in Table 7. Total erosion volumes from cutbank/sidecast sloughing, mass failure, and gullying is estimated to be roughly 3,600; 76,200; and 2,500 cubic yards, respectively.[15] This equates to approximately 790 cubic yards per mile.[16] Of the mass failures, one feature (450 feet x 270 feet x 15 feet) accounted for 88.6 percent of the total mass failure volume.[17] Without including this large feature, the average erosion volume is reduced to 142 cubic yards per mile. These estimates are based on the volumes of voids remaining at the hillslope locations, not the amount of sediment delivered to watercourse channels. Table 7 also shows the

---

[15] Note that rilling volumes were not determined. Erosion from rilling is generally a much smaller component of total hillslope erosion when compared to that from mass wasting and gullying. For example, Rice et al. (1979) found that rilling accounted for only three percent of the total hillslope erosion following tractor logging in the South Fork Caspar Creek watershed. Rice and Datzman (1981) reported rill erosion to be eight percent of the total erosion measured in northwestern California.

[16] Measuring only erosion voids of 13 cubic yards or more, Rice and Lewis (1991) reported that the average road erosion rate measured in the Critical Sites Erosion Study was 524 cubic yards/mile for their North Coast analysis unit (rain-dominated portions of the North Coast with redwood and Douglas-fir).

[17] This mass wasting feature was classified as a deep seated rotational failure on 70 percent slopes and located in the Northern Forest Practice District. Management related factors included waterbar discharge onto erodible material and subsurface water concentration.

number of erosion features recorded in the first three year period (1996 through 1998) and the second three year period (1999 through 2001). For all types of erosion features, the numbers are lower for the 1999 through 2001 period. Possible reasons for this difference are presented in the Discussion and Conclusions section of this report.

Table 8 shows the percentage of road transects with one or more erosion features of a given erosion type. Almost half the road transects had at least one rill, roughly a quarter of the transects had one or more gullies, and about four percent had at least one mass failure.

When an erosion problem feature or other type of problem (such as inadequate waterbar construction, tension cracks in the road surface, etc.) was discovered, implementation of the applicable Forest Practice Rule(s) was also rated for that problem point. A total of 40 Rule requirements were rated for implementation at problem sites along the road transects. Of these, 21 Rules were associated with approximately 95 percent of the problem points (Table 9). The most commonly cited Rules were: 1) sufficient size, number, and location of drainage structures to carry runoff water, 2) adequate numbers of drainage structures to minimize erosion, and 3) sufficient size, number, location of drainage structures to minimize erosion. As was reported in the interim Hillslope Monitoring Program report (CSBOF 1999), the vast majority of problem

Table 7. Road transect erosion features related to the current THP or NTMP project.

Erosion Feature	**Number of Features 1996-1998**	**Number of Features 1999-2001**	**Total Number of Features 1996-2001**
Cutbank/sidecast Sloughing	80	48	128
Mass Failure	18	12	30
Gullying	148	120	268
Rilling	478	225	703
Other Erosion Features	3	0	3
Totals	727	405	1,132

Table 8. Percent of road transects with one or more erosion features associated with the current plan for selected types of erosion features.

Erosion Feature	**Percent of Transects with One or More Features**
Sloughing	12.2
Mass Failures	3.9
Gullying	25.5
Rilling	48.9

points recorded along the road transects were judged to be due to either minor or major departures from specific Rule requirements. When considering all the implementation ratings assigned at problem points, only about two percent were associated with situations where the Rule requirements were judged to have been met or exceeded and 98 percent were associated with departures from Rule requirements.

Table 9. Problem point implementation ratings that account for approximately 95 percent of all the Forest Practice Rule requirements rated along road transects.

Forest Practice Rule	Description of Rules Rated for Implementation at Problem Points	Number of Times FPR Cited	Meets/ Exceeds Rule (%)	Minor Departure (%)	Major Departure (%)
923.2(h)	size, number, and location of structures sufficient to carry runoff water	452	0.2	80.8	19.0
923.1(f)	adequate numbers of drainage structures to minimize erosion	438	2.7	78.8	18.5
923.2(h)	size, number, and location of structures sufficient to minimize erosion	401	4.7	78.3	17.0
914.6(f)	waterbreaks built to discharge into cover	236	0.0	87.3	12.7
914.6(c)	waterbreak spacing according to standards in 914.6(c)	234	5.1	78.6	16.2
923.2(o)	discharge onto erodible fill prevented	217	0.0	85.7	14.3
914.6(g)	waterbreaks have embankment of at least 6 inches	186	0.0	86.6	13.4
923.4(c)	waterbreaks maintained to minimize erosion	186	0.0	75.3	24.7
914.6(g)	waterbreaks cut to depths of at least 6 inches	166	0.0	84.3	15.7
923.2(p)	waterbars installed according to 914.6	89	6.7	74.2	19.1
914.6(f)	where waterbreaks do not work--other erosion controls installed	67	0.0	73.1	26.9
923.4(l)	soil stabilization on cuts, fills, sidecast	59	1.7	83.1	15.3
923.4(m)	inlet/outlet structures/additional structures have been maintained	38	0.0	84.2	15.8
923.2(m)	sidecast extending greater than 20 feet treated to avoid erosion	31	0.0	22.6	77.4
923.4(j)	drainage ditches maintained to allow flow of water	28	10.7	85.7	3.6
914.6(f)	waterbreaks built to provide unrestricted discharge	26	0.0	80.8	19.2
923(d)	road located to avoid unstable areas	24	0.0	87.5	12.5
923.4(c)	erosion controls maintained during maintenance period	20	0.0	70.0	30.0
914.6(f)	waterbreaks built to spread water to minimize erosion	19	0.0	68.4	31.6
923.2(g)	excess material stabilized so as to avoid impact	19	0.0	36.8	63.2
923.2(k)	road constructed without overhanging banks	19	0.0	100.0	0.0

The results displayed in Table 9 may be biased by the design of the program. Lewis and Baldwin (1997) suggested in their statistical review of this project that implementation should be rated immediately following the completion of logging and prior to stressing storm events to provide an unbiased assessment of whether a practice was implemented correctly. That is, it is likely that some percentage of the problem points might not have been classed as Rule departures if they had been evaluated at the end of timber operations. CDF's Modified Completion Report monitoring will provide information on implementation following harvesting that may help us address this concern. The logistics and funding of the current version of the Hillslope Monitoring Program did not allow for two site visits by the contractor.

The data collected along road transects allows us to determine the proportion of problem features versus non-problem features, particularly for road drainage structures. The counts of existing road drainage structures with and without problem points is displayed in Table 10. For the total population of waterbreaks evaluated, approximately seven percent did not conform to Rule requirements or had an associated erosion feature. Rolling dips and culverted cross drains had deficiencies about five percent of the time. Note that multiple types of Rule requirement violations are possible at each drainage structure with a problem. Therefore the number of drainage structures with problems will be less than the counts for major and minor Rule departures. Additionally, the number of structures with problems is lower than the counts for Rule departures since Rule implementation was rated whenever there was an erosion feature present, regardless of whether or not it was associated with a specific drainage structure.

Table 10. Counts of drainage structures evaluated along road transects with and without problem points.

Drainage Structure Type	Total Number	Number with No Problems	Number with Problems	Percent with Problems
Waterbreaks	1,879	1,756	123	6.5
Rolling Dips	605	578	27	4.5
Leadoff Ditch	315	309	6	1.9
Culvert Cross Drain	306	291	15	4.9
Other Drainage Structure	39	38	1	2.6
Totals	3,144	2,972	172	5.5

The source, cause, and depositional area associated with the recorded erosion features were also documented during the evaluations of the road transects. The different erosion types and their dominant source areas are displayed in Table 11. Cutbank and sidecast sloughing features were primarily associated with road cut slopes, with a smaller component coming from fill slopes. Mass failures were mostly associated with fill slopes below roads. Gullying had many source areas, but was most commonly

Table 11. Number of source location codes and the number delivering sediment to the high or low flow channel for the recorded erosion features associated with the current THP or NTMP NTO on road transects.

Source Area	**Sloughing**		**Mass Failure**		**Gullying**		**Rilling**	
	#[1]	**# with delivery[2]**	**#[1]**	**# with delivery[2]**	**#[1]**	**# with delivery[2]**	**#[1]**	**# with delivery[2]**
Cut Slope	68	1	6	0	4	1	5	2
Fill Slope	17	5	15	9	54	18	30	5
Hillslope Above Road	4	0	6	2	7	3	10	1
Hillslope Below Road	1	0	0	0	0	0	0	0
Road Surface	1	0	2	1	45	18	542	66
Waterbar Ditch	0	0	0	0	7	1	5	3
Waterbar Outlet	1	0	0	0	96	12	61	6
Inside Ditch	0	0	0	0	20	4	15	3
Rolling Dip Ditch	0	0	0	0	3	3	5	1
Rolling Dip Outlet	0	0	0	0	26	4	7	0
Other Erosion Source	0	0	0	0	5	2	6	0
Totals	**92**	**6**	**29**	**12**	**267**	**66**	**686**	**87**

[1]Totals in Table 11 differ from Table 7 because of missing source code data.
[2]Corrected for missing data.

associated with waterbar outlets, fill slopes, and the road surface. Rilling, in contrast, was almost always associated with the road surface.

The causes of the recorded erosion features are shown in Table 12. Dominant causes for cutbank and sidecast sloughing included the cutslope being too tall, unstable terrain, the cutslope being too steep, steep side slopes, and unstable fill. The most commonly cited causes of mass failures along the road transects were unstable terrain, unstable fill, and steep side slopes. Approximately 85 percent of the gullies recorded were judged to be caused by drainage feature problems. Similarly, about 70 percent of the rills documented were coded as being associated with drainage feature problems. When rills occurred with road drainage structures (i.e., waterbreaks, rolling dips, lead off ditches) located somewhere along the length of the rill, the rill ended at the drainage structure 57 percent of the time. Highly erodible surface material and steep road gradient were also frequently cited causes of rilling.

Because drainage feature problems are the major cause associated with gullying and rilling on the road transects (Table 12), additional detail for this category is shown in Table 13. For gullying, cover (drainage structure did not discharge into vegetation, duff, slash, rocks, etc.) and spacing of drainage features (too far apart) were the most frequently cited problems. Inappropriate spacing of drainage structures was cited approximately 60 percent of the time for drainage feature problems associated with rilling. Also commonly recorded were inappropriate location to capture surface runoff and inadequate cover. Mass failures were usually not associated with drainage feature problems. When they were, inadequate cover and cross drain culvert shotgun outlets without adequate armoring at the point of discharge were the most frequent codes cited.

Similarly, cutbank or sidecast sloughing was usually not associated with a drainage feature problem. When it was, traffic impact on drainage structure function was the most frequently recorded problem.

Table 12. Number of recorded erosion cause codes related to development of identified erosion features associated with the current THP or NTMP NTO on road transects (note that multiple cause codes can be assigned to a single erosion feature).

Erosion Cause	**Sloughing**		**Mass Failure**		**Gullying**		**Rilling**	
	Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
Fill Slope too Long	1	1	0	0	0	0	1	0
Cut Slope too Steep	20	17	3	6	2	1	1	0
Cut Slope too Tall	35	29	5	9	0	0	2	0
Drainage Feature Problem	3	3	4	8	239	85	538	72
Highly Erosive Surface Material	8	7	3	6	16	6	99	13
Steep Side Slopes	13	11	9	17	1	0	15	2
Unstable Fill	13	11	12	23	5	2	1	0
Unstable Terrain	22	18	13	24	1	0	1	0
Rutting	0	0	0	0	3	1	27	4
Steep Road Gradient	0	0	0	0	5	2	52	7
Other Erosion Cause	4	3	4	7	8	3	13	2
Totals	119	100	53	100	280	100	750	100

Table 13. Number of drainage feature problems associated with erosion features on road transects (note that multiple drainage feature problem codes can be assigned to a single erosion feature).

Drainage Feature Problem	**Sloughing**		**Mass Failure**		**Gullying**		**Rilling**	
	Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
Blocked Ditch	2	9	0	0	4	1	6	1
Cover	4	17	2	29	142	34	86	10
Flow	3	13	0	0	9	2	7	1
Shotgun Outlet without Armoring	1	4	2	29	2	0.5	2	0
Location Inappropriate	2	9	0	0	81	20	110	13
Spacing	2	9	0	0	129	31	480	57
Divert	0	0	0	0	12	3	42	5
Runoff Escaped	0	0	0	0	5	1	7	1
Maintenance	0	0	1	14	11	3	47	6
Plugged Inlet	0	0	1	14	2	0.5	0	0
Rolling Dip Break	0	0	0	0	3	1	4	0.5
Height	0	0	0	0	0	0	3	0.5
Traffic	5	22	1	14	3	1	34	4
Other	4	17	0	0	10	2	7	1
Totals	23	100	7	100	413	100	835	100

Whether sediment actually reached a watercourse from the erosion features found along the road transects is of critical concern to the protection of beneficial uses of water. Figure 9 shows the percentage of identified erosion features that delivered sediment to channels. Since winter documentation of fine sediment delivery to streams was not possible with this program, the percentages of sediment delivery to the high or low flow channel displayed in Figure 9 are likely to underestimate total sediment delivery. The field team attempted to document the closest approach of sediment from a given erosion feature to the watercourse it was directed toward, using field evidence remaining in the dry spring, summer, and fall months. This evidence included: 1) fine and coarse sediment deposition on the forest floor, and 2) rill or gully discharge directly into the high or low flow channel.

The sediment delivery percentages to the high flow channel are similar to those reported in the interim Hillslope Monitoring Program report, after the evaluation of 150 THPs (CSBOF 1999). In that report, it was stated that the percentage of sloughing, mass failures, gullying, and rilling features delivering sediment to the channel was 6 percent, 47 percent, 18 percent, and 13 percent, respectively. Following the evaluation of 300 projects, the percentages of sediment delivery to the high or low flow channel for sloughing, mass failures, gullying, and rilling features are 6.2 percent, 39.3 percent, 24.5 percent, and 12.6 percent, respectively (Figure 9). No sediment was transported to the channel for 93.8 percent of the sloughing features, 60.7 percent of the mass wasting features, 75.5 percent of the gullies, and 87.4 percent of the rills. Of the rills that delivered sediment to watercourses, 70.2 percent delivered to Class III watercourses. For gullies that delivered sediment, 49.2 percent input sediment to Class III watercourses. Sediment delivery data was not reported for 4.8 percent of the rilling features, 1.1 percent of the gullies, 6.7 percent of the mass failures, and 23.4 percent of the sloughing events.

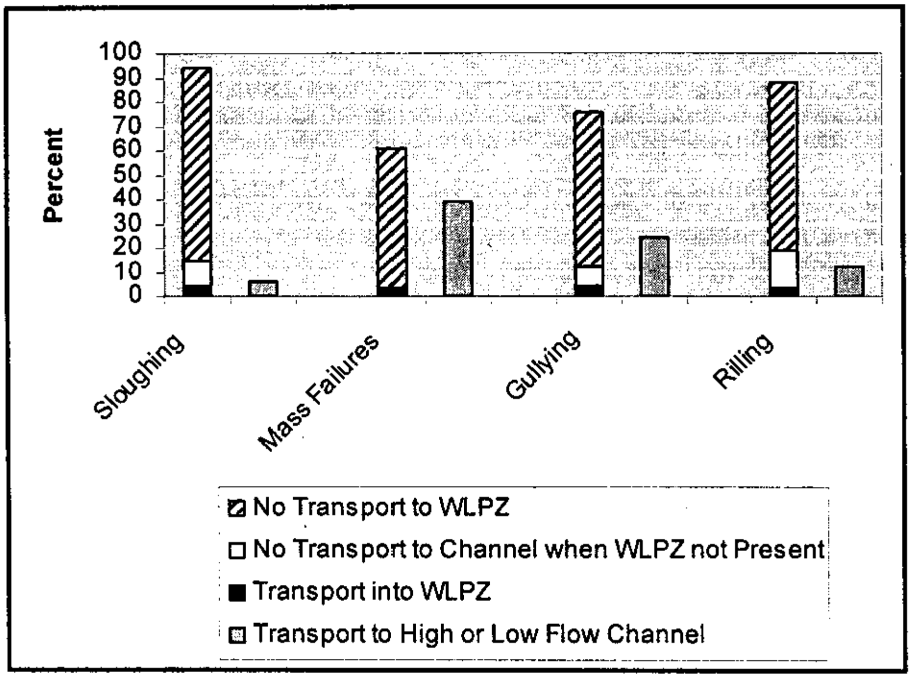

Figure 9. Percent of erosion features with dry season evidence of delivered sediment to the high or low flow channel of a watercourse from road transect erosion features related to the current THP or NTMP NTO.

Skid Trails

From 1996 through 2001, 480 randomly located skid trail transects were evaluated, covering a total of approximately 352,000 feet or 66.7 miles. The time of logging operations for approximately 90 percent of the skid trail transects was judged to be the dry season, with eight percent classified as winter operations, and two percent as either a combination of the wet and dry seasons or unknown. The silvicultural systems associated with the sampled skid trail transects were: 33% selection, 14% alternate prescription, 13% clearcut, 10% shelterwood, 9% commercial thinning, 5% transition, 4% seed tree, 2% sanitation salvage, and 2% rehabilitation, with 8% having combinations of silvicultural systems.[18] Data was not recorded on whether the skid trails were existing prior to the operation of the plan or created as part of the current project. The overall sample size (480 skid trails) is considerably lower than that for road transects because some of the THPs were entirely cable yarded. Field procedures and forms for skid trails are similar to those used for roads, so the results are presented in a similar manner.

As part of the skid trail transects, the field team rated the implementation and effectiveness of applicable Forest Practice Rules as they were encountered, and as part of an overall evaluation following completion of the 500 to 1,000 foot transects. A total of 26 questions were developed to answer in the field based on 22 Forest Practice Rule sections, since some Rules were broken down into separate components. In the overall evaluation of skid trail transects, the Rules were met or exceeded **95.1** percent of the time. For Forest Practice Rules where the sample size was adequate (i.e., 30 observations), seven Rule requirements were found to have combined minor and major departures greater than five percent (Table 14). The highest percentage of total departures from Forest Practice Rule requirements were for Rules requiring the installation of other erosion control structures where waterbreaks cannot disperse runoff, waterbreak spacing, and waterbreak maintenance. All the Forest Practice Rules evaluated had major departure percentages of less than five percent except for one: waterbreak spacing equals the standards specified in 14 CCR 914.6 (934.6, 954.6).

A total of 203 erosion features were found on the skid trail segments. The number of these features for each erosion type and observation period is shown in Table 15. Rilling accounted for more than 70 percent of the number of features. The total erosion volumes from cutbank/sidecast sloughing, mass failures, and gullying is estimated to be roughly 5, 1100, and 400 cubic yards, respectively. As was the case for the road transects, these volume estimates are based on the dimensions of voids remaining on the hillslopes, not the amount of sediment delivered to watercourse channels. Also similar to what was reported for the road transects, the number of erosion features for all types of erosion were lower in the period 1999 through 2001 than from 1996 to 1998. Possible reasons for this difference are given in the Discussion and Conclusions section of this report.

[18] Some skid trails were obliterated during site preparation activities.

The percentage of skid trail transects that had one or more erosion features of a given erosion type is shown in Table 16. Approximately 20 percent of the transects had at least one rill recorded, about seven percent had one or more gullies, and one percent had at least one mass failure.

Table 14. Skid trail related Forest Practice Rule requirements with more than 5 percent total departures based on at least 30 observations from the overall transect evaluation where implementation could be rated (note that some of the Rule sections are separated into components and the table is ordered by the percentage of total departures).

Forest Practice Rule	Description	Total Number	% Total Departure	% Minor Departure	% Major Departure
914.6(f)	where waterbreaks cannot disperse runoff, other erosion controls installed as needed	158	20.3	17.7	2.5
914.6(c)	waterbreak spacing equals standards	467	19.3	13.7	5.6
923.4(c)	waterbreaks maintained to divert runoff water	444	10.6	9.9	0.7
914.6(g)	waterbreaks have embankment of 6 inches	445	7.4	6.1	1.3
914.6(e)	waterbreaks installed for natural channels	219	6.4	3.7	2.7
914.6(g)	waterbreaks cut to minimum depth of 6 inches	445	5.8	4.7	1.1
914.6(c)	waterbreaks installed at 100 foot intervals on cable roads	213	5.6	4.2	1.4

Table 15. Skid trail transect erosion features related to the current THP or NTMP project.

Erosion Feature	Number of Features 1996-1998	Number of Features 1999-2001	Total Number of Features 1996-2001
Cutbank/sidecast Sloughing	3	1	4
Mass Failure	6	1	7
Gullying	35	12	47
Rilling	104	41	145
Totals	148	55	203

Table 16. Percent of skid trail transects with one or more erosion features associated with the current plan for selected types of erosion features.

Erosion Feature	Percent of Transects with One or More Features
Sloughing	0.8
Mass Failures	1.0
Gullying	6.7
Rilling	19.2

As with the road transects, when an erosion feature or other problem was found along the skid trail transects, implementation of the applicable Forest Practice Rule(s) was rated for that problem point. A total of 12 Rule requirements were rated for implementation at skid trail problem sites. Of these, nine Rules were associated with over 95 percent of the problem points (Table 17). All but one of these problem points were related to either minor or major departures from specific Forest Practice Rule requirements. Therefore, only about 0.2 percent of problem points were associated with situations where the Rule requirements were judged to have been met or exceeded, and 99.8 percent were associated with minor or major departures from Rule requirements.

Table 17. Problem point implementation ratings that account for over 95 percent of all the Forest Practice Rule requirements rated along skid trail transects.

Forest Practice Rule	Description of Rules Rated for Implementation at Problem Points	Number of Times FPR Cited	Meets/ Exceeds Rule (%)	Minor Departure (%)	Major Departure (%)
914.6(c)	waterbreak spacing equal standards	106	0.0	87.7	12.3
914.6(g)	waterbreaks have embankment of 6 inches	72	0.0	95.8	4.2
923.4(c)	waterbreaks maintained to divert water	62	0.0	100.0	0.0
914.6(f)	if waterbreaks do not work, other structures stall be installed	48	0.0	91.7	8.3
914.6(g)	waterbreaks cut to minimum depth of 6 inches	48	0.0	100.0	0.0
914.6(f)	waterbreaks allow discharge into cover	42	0.0	100.0	0.0
914.6(f)	waterbreaks--unrestricted discharge	42	0.0	100.0	0.0
914.6(f)	waterbreaks spread water to minimize erosion	25	0.0	92.0	8.0
914.6(g)	waterbars placed diagonally	24	4.2	95.8	0.0

The proportion of skid trail drainage features with and without problems is shown in Table 18. Nearly all these drainage structures were waterbreaks, and approximately four percent of them did not conform to Rule requirements or had an associated erosion feature. The number of waterbreaks with specific associated problems is much lower than the total counts of Rules rated for implementation at problem points (Table 17) because: 1) multiple Rule deficiencies are possible at each drainage structure with a problem, and 2) Rule implementation was rated at each erosion feature on a skid trail transect, whether or not it was associated with a specific drainage structure.

Table 18. Counts of drainage structures evaluated along skid trail transects with and without problem points.

Drainage Structure Type	Total Number	Number with No Problems	Number with Problems	Percent with Problems
Waterbreaks	2,940	2,830	110	3.7
Rolling Dips	51	50	1	2.0
Other Drainage Structure	1	1	0	0
Totals	2,992	2,881	111	3.7

As with the road transects, the source, cause, and depositional site associated with a recorded erosion feature was documented during the evaluation of skid trail transects. Cutbank and sidecast sloughing originated entirely from cut slopes, while mass failures were mostly associated with cut and fill slopes (Table 19). Over 90 percent of rilling features and two-thirds of gullying events were associated with the skid trail surface. About 24 percent of the skid trail gullies were related to waterbreak ditches or outlets.

Table 19. Number of source location codes and the number delivering sediment to the high or low flow channel for the recorded erosion features associated with the current THP or NTMP NTO on skid trail transects.

Source Area	Sloughing		Mass Failure		Gullying		Rilling	
	#	# with delivery	#	# with delivery	#	# with delivery	#	# with delivery
Cut Slope	4	0	2	0	0	0	0	0
Fill Slope	0	0	2	0	0	0	0	0
Hillslope Above Road	0	0	0	0	2	0	1	0
Skid Trail Surface	0	0	1	0	31	5	123	5
Waterbar Ditch	0	0	0	0	4	0	3	0
Waterbar Outlet	0	0	1	0	7	1	4	0
Inside Ditch	0	0	0	0	1	1	1	0
Rolling Dip Ditch	0	0	0	0	1	0	0	0
Rolling Dip Outlet	0	0	0	0	0	0	1	0
Totals	4	**0**	6	**0**	46	**7**	133	**5**

Erosion cause codes associated with the skid trail transects are displayed in Table 20. Mass failures on skid trails were mostly related to unstable terrain and unstable fill. Drainage feature problems contributed to gullying approximately 65 percent of the time, with highly erodible surface material and steep trail gradient each being cited about 10 percent of the time. Drainage feature problems were related to rilling features about 70 percent of the time, with highly erodible surface material and steep trail gradient contributing to the cause of about 15 percent and eight percent of the rills, respectively.

A summary of drainage feature problems found on skid trails is shown in Table 21. Cutbank/sidecast sloughing and mass failures were not found to be related to drainage feature problems. Approximately half of the drainage feature problems related to skid trail gullying were attributed to inadequate spacing of drainage structures, with another 20 percent related to inappropriate locations of the drainage structures to capture surface runoff. Similarly, almost 60 percent of the drainage feature problems related to rilling were attributed to inadequate spacing, with 17 percent related to inappropriate locations of the drainage structures and 12 percent associated with the inability of the drainage structure to divert runoff fully off the trail surface.

Table 20. Number of recorded erosion cause codes related to development of identified erosion features associated with the current THP or NTMP NTO on skid trail transects (note that multiple cause codes can be assigned to a single erosion feature).

Erosion Cause	**Sloughing**		**Mass Failure**		**Gullying**		**Rilling**	
	Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
Cut Slope too Steep	1	20	0	0	0	0	0	
Cut Slope too Tall	1	20	0	0	0	0	0	
Drainage Feature Problem	0	0	0	0	35	65	101	70
Highly Erosive Surface Material	2	40	1	8	5	9	22	15
Steep Side Slopes	1	20	2	15	2	4	2	1
Unstable Fill	0	0	3	23	3	5	1	1
Unstable Terrain	0	0	6	46	0	0	0	0
Rutting	0	0	0	0	0	0	1	1
Steep Skid Trail Gradient	0	0	0	0	5	9	12	8
Organic Matter in Fill	0	0	0	0	1	2	0	0
Other Erosion Cause	0	0	1	8	3	6	6	4
Totals	5	100	13	100	54	100	145	100

Table 21. Number of drainage feature problems associated with erosion features on skid trail transects (note that multiple drainage feature problem codes can be assigned to a single erosion feature).

Drainage Feature Problem	Sloughing		Mass Failure		Gullying		Rilling	
	Number	%	Number	%	Number	%	Number	%
Angle	0	0	0	0	0	0	2	1
Cover	0	0	0	0	7	12	5	3
Flow	0	0	0	0	2	4	0	0
Location Inappropriate	0	0	0	0	11	19	28	17
Spacing	0	0	0	0	26	46	92	56
Divert	0	0	0	0	5	9	19	12
Runoff Escaped	0	0	0	0	0	0	1	1
Maintenance	0	0	0	0	3	5	7	4
Height	0	0	0	0	0	0	1	1
Traffic	0	0	0	0	2	3	5	3
Other	0	0	0	0	1	2	4	2
Totals	0	0	0	0	57	100	164	100

The percentage of inventoried skid trail erosion features related to current operations that had dry season evidence of sediment reaching the high or low flow channel of a watercourse is shown in Figure 10. The percentages of sediment delivering features for sloughing, mass failures, gullying, and rilling features are 0, 0, 13.0, and 3.8 percent, respectively. Sediment delivery data was not reported for 8.3 percent of the rilling features, 2.1 percent of the gullies, 14.3 percent of the mass failures, and 0 percent of the sloughing events. No sediment was transported to the channel from any of the sloughing features or mass failures, 87 percent of the gullies, and 96.2 percent of the rills. For gullies that delivered sediment, 83.3 percent delivered sediment to Class III watercourses. All of the sediment delivered to channels from skid trail rills went to Class III watercourses. The proportions of erosion features delivering sediment from skid trails are considerably lower than that reported from similar types of erosion features found on the road transects (Figure 9).

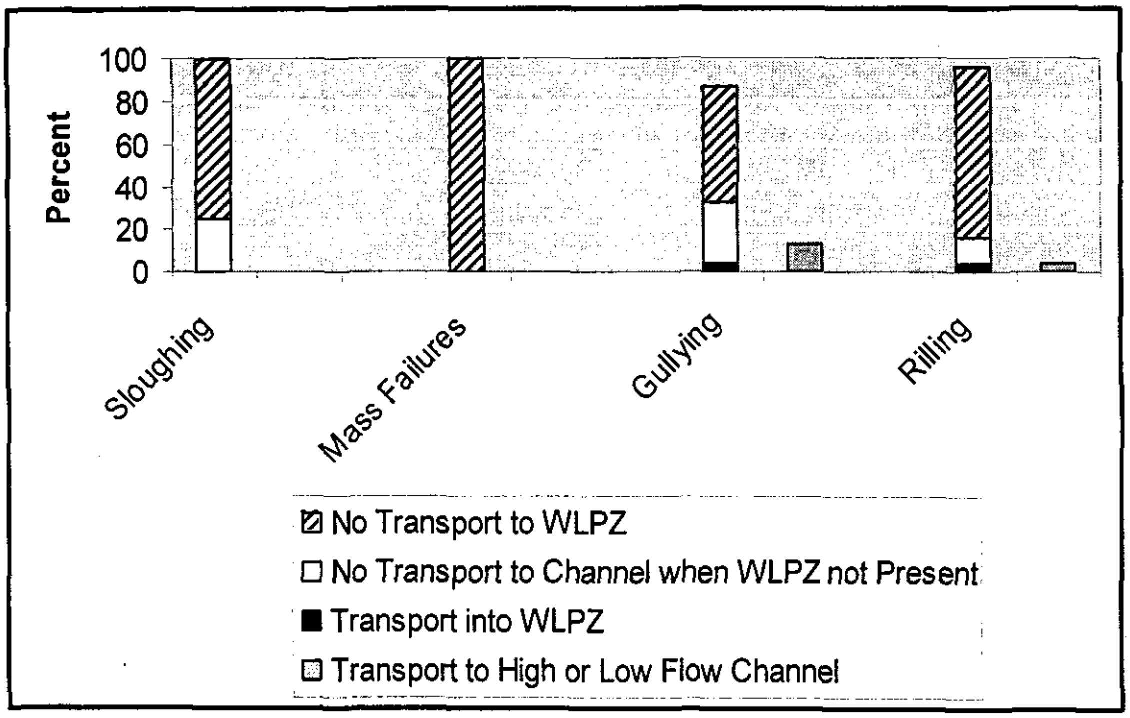

Figure 10. Percent of erosion features with dry season evidence of delivered sediment to the high or low flow channel of a watercourse from skid trail transect erosion features related to the current THP or NTMP NTO.

Landings

A total of 569 landings were evaluated from 1996 through 2001. Landing location and construction characteristics evaluated by the field team included: slope position, distance to the nearest watercourse, sideslope steepness, construction date, size, and fill dimensions. Landings were constructed on a ridge top, a "nose of a ridge", or above a break in slope about 85 percent of the time (Figure 11). Approximately 52 percent of the landings were more than 300 feet from the nearest watercourse receiving drainage off the landing, 31 percent were 100 to 300 feet away, 10 percent were from 50 to 100 feet, and seven percent were less than 50 feet from the nearest watercourse. Two percent of the landings were constructed on slopes greater than 65 percent, seven percent of the landings were on slopes from 46 to 65 percent, 35 percent of the landings were on slopes from 31 to 45 percent, and 56 percent of the landings were on slopes from 0 to 30 percent. Approximately 69 percent of the landings monitored were existing landings built prior to the current plan; 31 percent of the landings were classified as new features. About 88 percent of the landings were less than or equal to ¼ acre in size (Figure 12). Approximately 69 percent of the landings had a maximum fill thickness of 0 to five feet, 24 percent had a maximum thickness of six to 10 feet, and seven percent had a maximum thickness of greater than 10 feet.

Implementation and effectiveness of applicable Forest Practice Rules were rated both at problem points and for the whole landing for 23 separate requirements based on 20 FPR sections. Overall implementation related to landings was rated following complete inspection of the landing and its cut slope and fill slope areas. In the overall evaluation, the Rules were met or exceeded **93.5** percent of the time. For Rule requirements with at least 30 observations, four were found to have more than five percent major and minor departures (Table 22). The Rule with the highest percentage of major departures and total departures was 14 CCR 923.1(a) [943.1(a), 963.1(a)], which requires an RPF to map landings greater than ¼ acre in size or those requiring substantial excavation. A major departure from the Rule requiring treatment of fill material when it has access to a watercourse was assigned to four percent of the landings, and ten percent were judged to have either a minor or major departure from the Rule requiring adequate numbers of drainage features.

As with the road and skid trail transect evaluations, the field team rated the implementation and effectiveness of landing related Rules at specific problem points (Table 23). A total of 106 problem points were recorded under the general categories of landing surface, landing surface drainage, landing cut slopes, and landing fill slopes. About 89 percent of the landings had no problem points assigned. On the remaining 11 percent, approximately one-third of the problem points were related to rills or gullies that were formed from concentrated runoff below the outlet of a drainage structure on the surface of the landing. Problem points are fairly evenly distributed among the remaining 10 sources displayed in Table 23, but the sum of fill slope erosion problems is nearly as large the number of problems related to concentrated runoff from surface drainage structures.

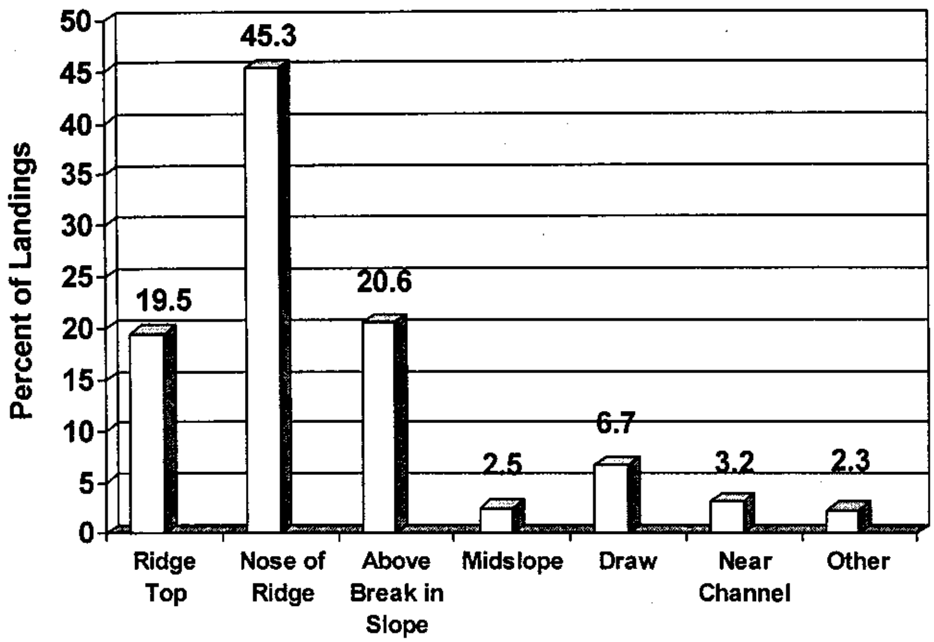

Figure 11. Distribution of landing geomorphic locations.

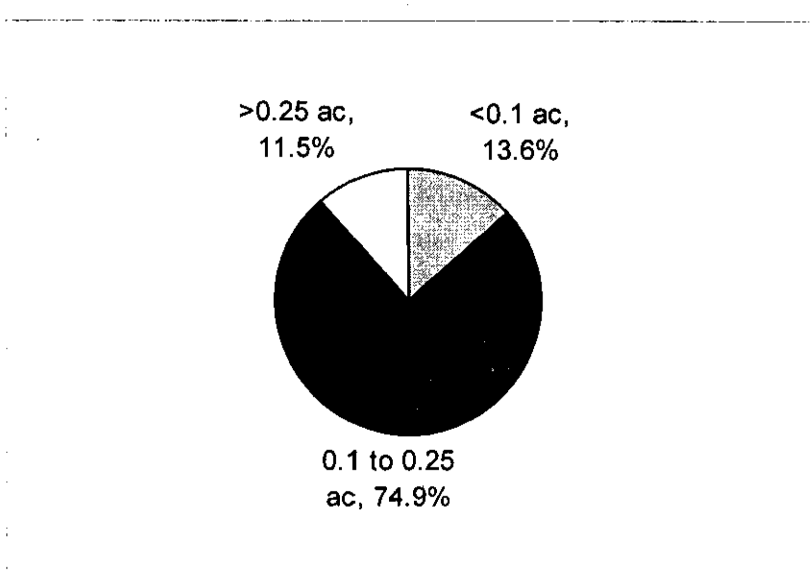

Figure 12. Landing size.

Table 22. Landing related Forest Practice Rule requirements with more than five percent total departures based on at least 30 observations from the overall evaluation where implementation could be rated (note that some of the Rule sections are separated into components and the table is ordered by the percentage of total departures).

Forest Practice Rule	Description	Total Number	% Total Departure	% Minor Departure	% Major Departure
923.1(a)	landings greater than 1/4 acre or requiring substantial excavation--shown on THP map	220	17.3	6.4	10.9
923.5(f)(4)	fill extending 20 feet with access to watercourse--treated	93	11.8	7.5	4.3
923.1(f)	adequate numbers of drainage structures	549	10.0	8.0	2.0
923.6	wet spots rocked or treated	154	5.8	5.8	0.0

At each problem point, the Forest Practice Rule(s) associated with that problem was rated for implementation (Table 24). Only 14 CCR 923.1(f) [943.1(f), 963.1(f)], which requires adequate numbers of drainage structures on landings to minimize erosion on landing surfaces, sidecast, and fills, was cited frequently. All of the problem points found on landings were judged to be caused by either minor or major departures from specific Forest Practice Rule requirements.

An overall effectiveness rating for each of the potential problem types listed in Table 23 was also completed for each landing. The complete summary of the landing effectiveness questions is displayed in Table A-1 in the Appendix. About 2.5 percent of the landings monitored had significant gullying on the landing surface. Of the landings with fill slopes (approximately two/thirds of the landings evaluated), about eight percent had gullies on the fill slopes and roughly three percent had slope failures that transported more than one cubic yard of material. For the landings with cut slopes (approximately 52 percent of the landings evaluated), roughly two percent had gullies on the cut slopes and about seven percent had slope failures with more than one cubic yard of material transported.

The landing evaluation also included a determination of the final location of sediment deposition originating from landing surfaces and fill slopes (Figure 13). Erosion features from two percent of the fill slopes produced sediment that entered channels, and another four percent of the time it reached the WLPZ. Similarly, erosion features from two percent of the drainage structures on the landing surfaces produced sediment that entered watercourses, and another six percent of the time it reached the WLPZ.[19]

Table 23. Distribution of problem points recorded at landings. Note that one landing can have multiple problem points.

Landing Area	Problem Type	Problem Count
Landing Surface	Rilling	8
	Gullying	9
Landing Surface Drainage	Erosion resulting from the drainage runoff structure or ditch	34
	Sediment movement from drainage structure	9
Landing Cut Slopes	Rilling	6
	Gullying	4
	Slope failures	5
Landing Fill Slopes	Rilling	8
	Gullying	8
	Slope failures	10
	Sediment movement to nearest channel	5
Total		106

Table 24. Problem point implementation ratings that account for 95 percent of all the Forest Practice Rule requirements rated at landings.

Forest Practice Rule	Description of Rules Rated for Implementation at Problem Points	Number of Times FPR Cited	Meets/ Exceeds Rule (%)	Minor Departure (%)	Major Departure (%)
923.1(f)	adequate numbers of drainage structures	63	0	76.2	23.8
923.5(f)(3)	landing sloped/ditched to prevent erosion	11	0	81.8	18.2
923.5(f)(2,4)	fill extending 20 feet with access to a watercourse--treated	9	0	33.3	66.7
923(g)	minimize cut/fill on unstable areas	6	0	0.0	100.0
923.1(d)	slopes greater than 65% or 50% within 100 feet-treated	6	0	50.0	50.0
923.5(f)(1)	slopes greater than 65% or 50% within 100 feet-treat edge	4	0	25.0	75.0
923.8	abandonment-minimize concentration of runoff	3	0	100.0	0.0

[19] Note that these ratings were only applied to landings where the appropriate features were present. For example, if no fill slopes were present, landing fill slope effectiveness questions were not answered. In total, 377 landings had fill slopes and 294 had cut slopes out of the 569 landings evaluated.

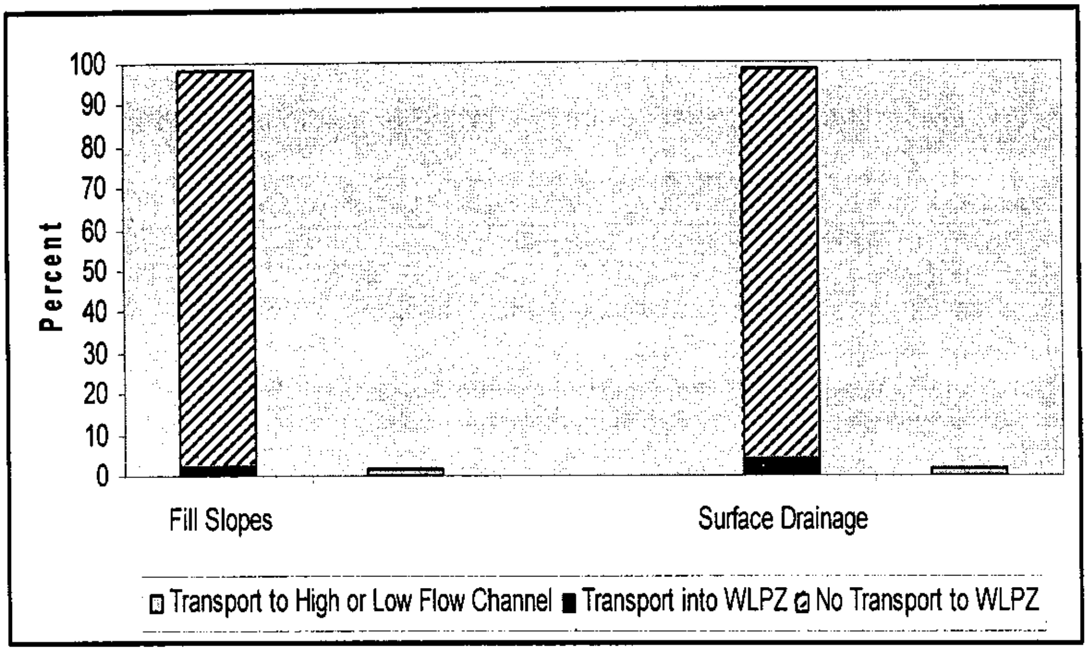

Figure 13. Percent of landing features related to the current THP or NTMP project that had dry season evidence of sediment delivered to either the WLPZ or the high/low flow channel of a watercourse.

Watercourse Crossings

A total of 491 watercourse crossings were evaluated from 1996 through 2001. Approximately 68 percent of these crossings had existing culverts (Figure 14), 12 percent were abandoned or removed road crossings, nine percent were fords, six percent were skid trail crossings, and two percent had bridges (Figure 15). The distribution of culvert sizes is displayed in Figure 16. The majority of pipe sizes are relatively small, reflecting the sampling criteria that favored choosing crossings located along road transects, which were often located above the break in slope near ridgelines. Approximately 64 percent of the crossings were existing road-related structures built prior to the beginning of the current plan; 18 percent were new road features; 12 percent were abandoned or removed crossings for roads; and six percent were removed, existing ford, or new skid trail crossings. Seventy-three percent of the crossings were associated with seasonal roads, 16 percent with permanent roads, four percent with temporary roads, six percent with skid trails, and less than one percent with abandoned roads. Forty-seven percent of the crossings were located in Class III watercourses, 46 percent in Class II drainages, six percent in Class I's, and less than one percent in Class IV watercourses.

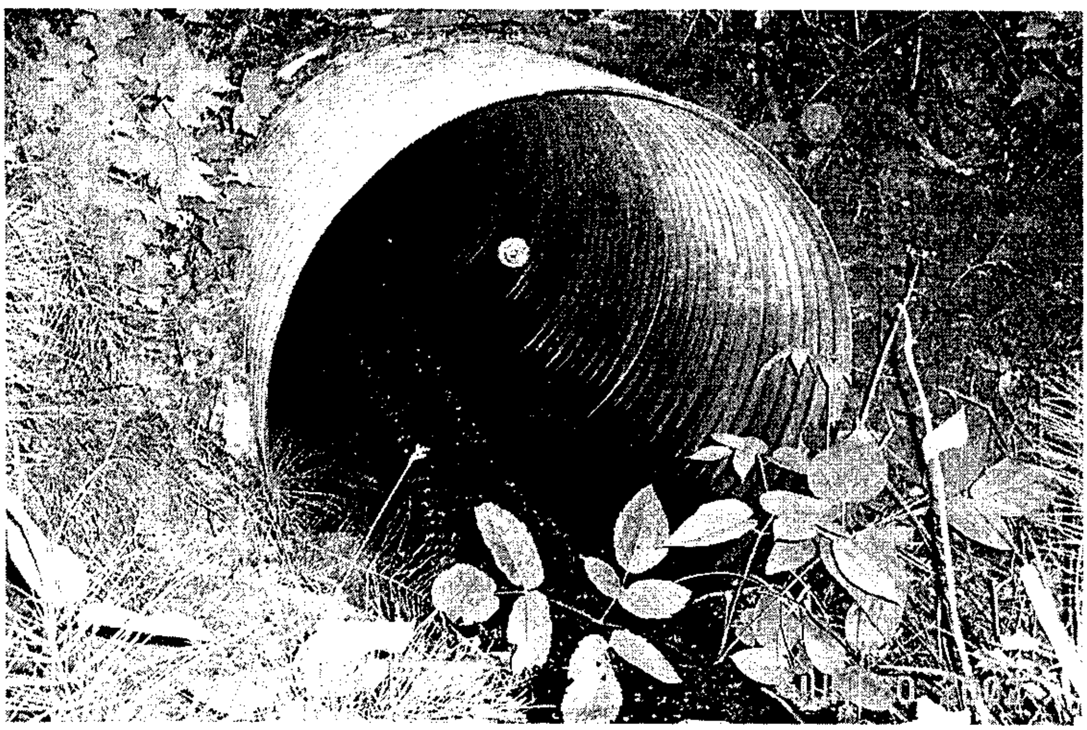

Figure 14. Typical watercourse crossing sampled in the Hillslope Monitoring Program. This culvert was a crossing included in the sample for the 2002 field season.

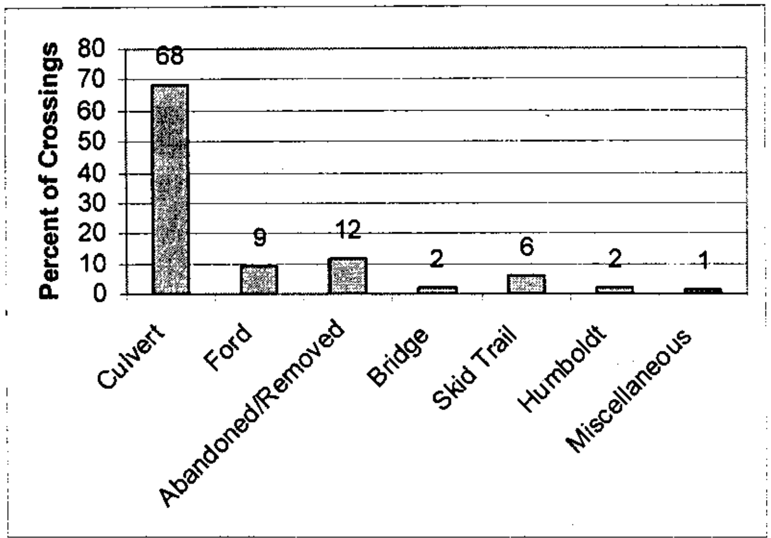

Figure 15. Distribution of watercourse crossing types evaluated from 1996 through 2001. The total number of crossings was 491.

Implementation and effectiveness of applicable Forest Practice Rules were rated both at problem points and for the whole crossing for 27 separate requirements from 24 Rule sections. Overall implementation of Rules related to watercourse crossings was rated following the complete inspection of the crossing, including the fill slope areas and the road segments draining to the crossing. In the overall evaluation, the Rules were met or exceeded **86.3** percent of the time. For Rule requirements with at least 30 observations, 21 were found to have more than five percent major and minor departures (Table 25). The Rules with the highest percentages of total departures were 14 CCR **923(o)** [943(o), 963(o)], **923.2(h)** [943.2(h), 963.2(h)], and **923.2(d)** [943.2(d), 963.2(d)], which prohibit discharge onto fill without appropriate energy dissipators; require appropriate size, numbers, and locations of structures to minimize erosion; and require fills across channels to be built to minimize erosion, respectively. Nine Rules had major departure percentages of more than five percent, which is substantially more than were found for the other hillslope areas (roads, skid trails, landings, and watercourse protection zones). Additional requirements with high levels of departures included Rules dealing with crossing diversion potential and proper crossing abandonment.

The field team rated the implementation and effectiveness of FPRs at problem points for specific components of watercourse crossings when they were encountered during the field inspection (Table 26). A total of 482 problem points were recorded under the general categories of crossing fill slopes, road surface drainage to the crossing, culverts, non-culverted crossings, removed or abandoned crossings, and road approaches at abandoned crossings. Problem points were identified on 45 percent of the crossings, indicating that deficient crossings often had more than one problem point. The most frequent problems were: culvert plugging, diversion potential, fill slope gullies, scour at the outlet of the culvert, ineffective road surface cutoff waterbreaks, and fill slope mass failures.

To determine if the high overall rate of crossing problems is coming from older crossings or continuing under current Rules, the database was queried to separate results from existing crossings, newly installed crossings, abandoned/removed road crossings, and skid trail crossings (Table 26). This revealed that the 88 new crossings had 68 total problem points, the 313 existing crossings (including culverts, fords, Humboldt crossings, and bridges) had 366 problem points, the 61 abandoned/removed road crossings had 43 problem points, and the 29 skid trail crossings had five problem points, which gives average values of 0.77, 1.17, 0.70, and 0.17 problem points per crossing for new, existing, abandoned/removed, and skid trail crossings, respectively.

A two-sample T test was used to test the difference between the means of the number of problem points for existing and new **culverted** crossings (the results are displayed in Table 27). This analysis revealed that the average of 0.77 problem points for new culvert crossings is significantly different (<0.01) than the average of 1.22 problem points at existing culverted crossings. However, problem points related to diversion potential, fill slope gullies, culvert plugging, and cut-off waterbreaks on roads draining to the crossing were still relatively common at new culvert crossings.

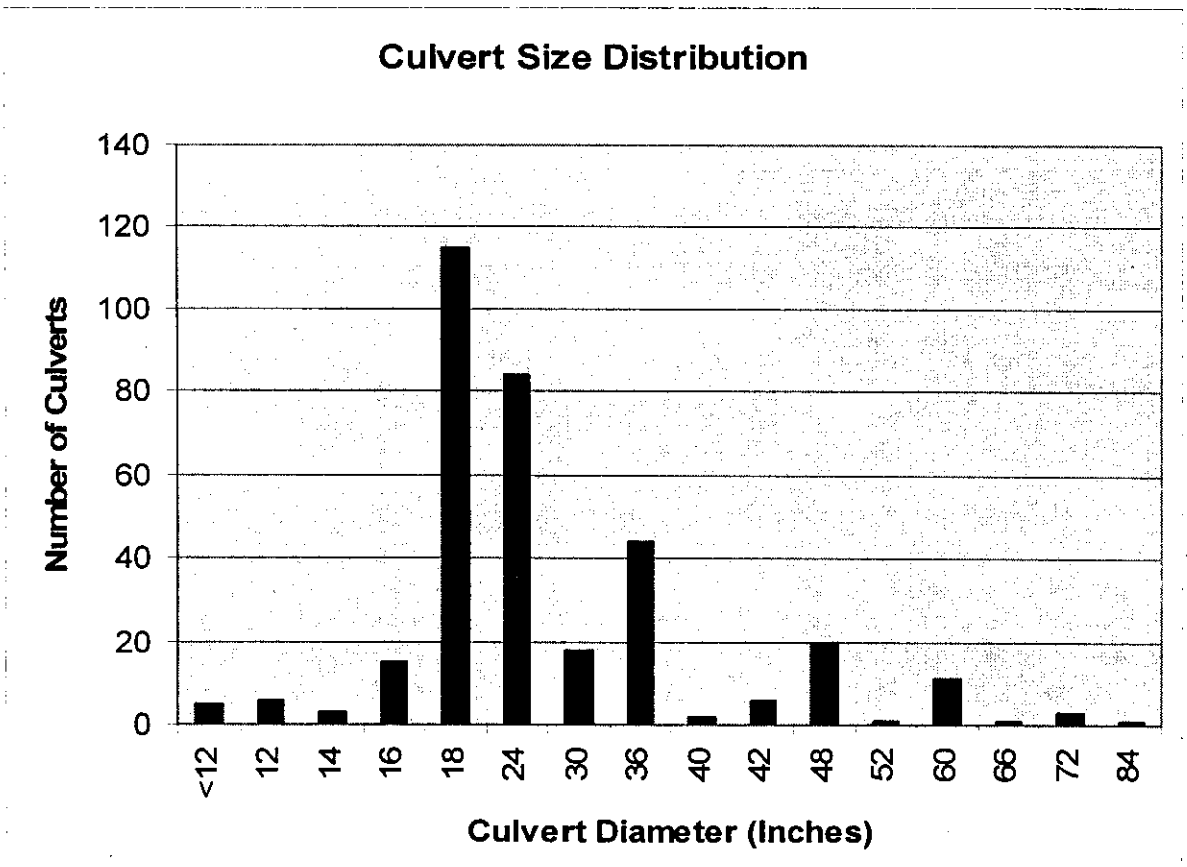

Figure 16. Culvert size distribution for watercourse crossings with pipes.

Table 25. Watercourse crossing related Forest Practice Rule requirements with more than five percent total departures based on at least 30 observations from the overall evaluation where implementation could be rated (note that some of the Rule sections are separated into components and the table is ordered by the percentage of total departures).

Forest Practice Rule	Description	Total Number	% Total Departure	% Minor Departure	% Major Departure
923.2(o)	no discharge on fill unless energy dissipators present	388	23.7	11.1	12.6
923.2(h)	size, number, and location of structures minimizes erosion	394	20.6	9.4	11.2
923.2(d) Coast	fills across channels built to minimize erosion	295	19.0	9.2	9.8
923.4(n)	crossing/approaches maintained to avoid diversion	403	16.6	12.7	4.0
923.4(1)	trash racks installed where there is abundant LWD	89	15.7	13.5	2.2
923.8	abandonment—minimize concentration of runoff	65	15.4	10.8	4.6
923.(c)	waterbreaks maintained to divert into cover	339	15.3	12.1	3.2
923.3(e)	crossing/fills built to prevent diversion	398	14.6	9.0	5.5
923.4(d)	crossing open to unrestricted passage of water	480	14.2	10.2	4.0
923.4(d)	trash racks installed where needed at inlets	78	14.1	10.3	3.8
923.8(d)	abandonment--pulling/shaping of fills	61	13.1	3.3	9.8
923.8(c)	abandonment--grading of road for dispersal	63	11.1	6.3	4.8
923.3(d)(2)	removed--cut bank sloped back to stop slumping	63	11.1	4.8	6.3
923.8(b)	abandonment--stabilization of exposed cuts/fills	63	11.1	6.3	4.8
923.3(d)(1)	removed--fills excavated to reform channel	64	10.9	7.8	3.1
923.2(h)	size, number, location of structures sufficient to carry runoff	394	10.7	3.6	7.1
923.8(e)	abandonment--fills excavated to reform channel	59	10.2	5.1	5.1
923.4	trash racks in place as specified in the THP	80	10.0	10.0	0.0
923.8(e)	abandonment--cutbanks sloped back	59	6.8	0.0	6.8
923.4(f)	50-year flood flow requirement	372	5.4	3.8	1.6
923.2(e)	throughfills built in one-foot lifts	39	5.1	2.6	2.6

Table 26. Distribution of problem points recorded for existing, new, abandoned, and skid trail watercourse crossings. Note that one crossing can have multiple problem points.

Crossing Feature	Problem Type	Existing Crossings (n = 313)	New Crossings (n = 88)	Road Abandoned/ Removed (n = 61)	Skid Trail Removed/ Ford (n = 29)	Totals
Fill Slopes	Vegetative cover	11	4	1	0	16
	Rilling	24	4	0	0	28
	Gullies	35	10	1	1	47
	Cracks	5	2	0	0	7
	Slope failure	28	4	2	0	34
Road Surface Draining to Crossing	Rutting	10	1	2	0	13
	Rilling	6	2	2	1	11
	Gullies	5	1	3	0	9
	Surfacing of approaches	5	2	2	1	10
	Cut-off waterbar	29	6	2	1	38
	Inside ditch condition	11	0	0	0	11
	Ponding	7	4	0	0	11
Culverts	Scour at inlet	5	0	NA	NA	5
	Scour at outlet	35	3	NA	NA	38
	Diversion potential	38	10	NA	NA	48
	Plugging	45	9	NA	NA	54
	Alignment	2	1	NA	NA	3
	Degree of corrosion	3	0	NA	NA	3
	Crushed inlet/outlet	8	0	NA	NA	8
	Pipe length	1	0	NA	NA	1
	Gradient	26	2	NA	NA	28
	Piping	10	1	NA	NA	11

Crossing Feature	Problem Type	Existing Crossings (n = 313)	New Crossings (n = 88)	Road Abandoned/ Removed (n = 61)	Skid Trail Removed/ Ford (n = 29)	Totals
Non-Culvert Crossings	Armoring	9	1	1	0	11
	Scour at outlet	5	1	1	0	7
	Diversion	3	0	0	1	4
Removed or Abandoned	Bank stabilization	NA	NA	5	0	5
	Rilling of banks	NA	NA	1	0	1
	Gullies	NA	NA	5	0	5
	Slope failure	NA	NA	2	0	2
	Channel configuration	NA	NA	5	0	5
	Excavated material and cutbank	NA	NA	3	0	3
	Grading and shaping	NA	NA	3	0	3
Road Approaches at Abandoned Crossings	Grading and shaping of road surface	NA	NA	2	0	2
Totals		**366**	**68**	**43**	**5**	**482**

936

Table 27. Distribution of watercourse crossing types and average numbers of problem points assigned for each crossing type.

Crossing Type	Number of Crossings	Number of Problem Points	Average Number of Problem Points/ Crossing
Existing Culvert	251	306	1.22*
New Culvert	83	64	0.77*
Existing Ford	40	39	0.98
New Ford	4	4	1.00
Abandoned/Removed (road)	61	43	0.70
Abandoned/Removed (skid trail)	19	1	0.05
Existing Skid Trail (ford)	8	4	0.50
New Skid Trail (ford)	2	0	0
Existing Humboldt	7	17	2.43
New Humboldt	1	0	0
Existing Bridge	11	0	0
Existing Rolling Dip	2	1	0.5
Other	2	3	1.50
Totals	**491**	**482**	**0.98**

* A two-sample T test comparing the number of problem points at existing versus new culverted crossings revealed that the means of these groups are significantly different at alpha < 0.01.

As with the other hillslope monitoring area categories, when a problem point was discovered, the field team rated the implementation and effectiveness of applicable Forest Practice Rule(s) associated with that problem (Table 28). Problems at crossings were associated with poor implementation of 24 Rule requirements, with 15 being cited as responsible for 95 percent of the problem points. All of the problem points were caused by either minor or major departures from specific Rule requirements. Overall, approximately 51 percent of the implementation ratings at the crossing problem points were recorded as minor Rule departures, while 49 percent were rated as major departures.

An overall effectiveness rating for each of the potential problem types listed in Table 26 was also completed for each crossing. A complete summary of watercourse crossing effectiveness questions is displayed in Table A-2 in the Appendix. Significant scour at the outlet of culvert crossings was found 33 percent of the time, with some degree of plugging occurring 24 percent of the time. Some level of diversion potential was noted for about 27 percent of the culverted crossings. Approximately 11 percent of the fill slopes at crossings had some amount of slope failure present. The road surface drainage cutoff structure above the crossing allowed all or some of the water running down the road to reach the crossing at about 23 percent of the sample sites. For abandoned or removed crossings, approximately 82 percent had channels established close to natural grade and orientation, with about 18 percent having minor or major differences.

Sediment delivery to watercourses is assumed to be 100 percent at crossings since these structures are built directly in and adjacent to the channels. Therefore, the evaluation of sediment delivery from the various types of problems associated with crossings was not conducted.

Table 28. Problem point implementation ratings that account for 95 percent of all the Forest Practice Rule requirements rated at watercourse crossings.

Forest Practice Rule	Description of Rules Rated for Implementation at Problem Points	Number of Times FPR Cited	Meets/ Exceeds Rule (%)	Minor Departure (%)	Major Departure (%)
923.2(h)	size, number, and location of structures minimizes erosion	126	0	43.7	56.3
923.2(o)	no discharge on fill unless energy dissipators installed	118	0	39.8	60.2
923.4(n)	crossing/approaches maintained to avoid diversion	71	0	77.5	22.5
923.2(h)	size, number, and location of structures sufficient to carry runoff	68	0	44.1	55.9
923.2(d) Coast	fills across channels built to minimize erosion	67	0	29.9	70.1
923.3(e)	crossing/fills built to prevent diversion	58	0	51.7	48.3
923.4(d)	crossing open to unrestricted passage of water	55	0	69.1	30.9
923.4(c)	waterbreaks maintained to divert into cover	43	0	74.4	25.6
923.8	abandonment—minimizes concentration of runoff	16	0	56.3	43.8
923.2(h)	size, number, and location of structures-maintains natural drainage pattern	15	0	73.3	26.7
923.8(d)	abandonment--pulling/shaping of fills appropriate	11	0	27.3	72.7
923.3(d)(2)	removed crossings--cut bank sloped back to prevent slumping and to minimize erosion	10	0	40.0	60.0
923.8(c)	abandonment--grading of road for dispersal	9	0	55.6	44.4
923.8(b)	abandonment--stabilization of exposed cuts/fills	9	0	55.6	44.4
923.3(d)(1)	removed crossings--fills excavated to reform channel	7	0	71.4	28.6

Watercourse Protection Zones (WLPZs, ELZs, EEZs)

From 1996 through 2001, 683 randomly located watercourse and lake protection zone (WLPZ) transects, equipment limitation zone (ELZ) transects, and equipment exclusion zone (EEZ) transects were evaluated, covering a total of approximately 510,800 feet or 96.8 miles for all three categories. The distribution of transects for each watercourse class is displayed in Figure 17. Approximately 17 percent of the WLPZs were associated with Class I watercourses (21.5 miles), 56 percent with Class IIs (64.4 miles), 27 percent with Class IIIs (10.4 miles), and less than one percent with Class IV waters (0.5 miles). Class III watercourses were not sampled as part of the Hillslope Monitoring Program from 1996 through 1999, but were included in 2000 and 2001.[20] For about 36 percent of the watercourse protection zone transects, the slope distance from the channel bank to the nearest road was greater than 150 feet; 18 percent had a distance of 100 to 150 feet; 25 percent had a distance of 50 to 100 feet, and 21 percent had a distance of less than 50 feet. The type of yarding upslope from the transect was classified as tractor 69 percent of the time, cable 22 percent, cable/tractor 6 percent, helicopter 2 percent, and tractor/helicopter less than 1 percent. Roads were located in 75 WLPZs, one equipment limitation zone (ELZ), and one equipment exclusion zone (EEZ).[21]

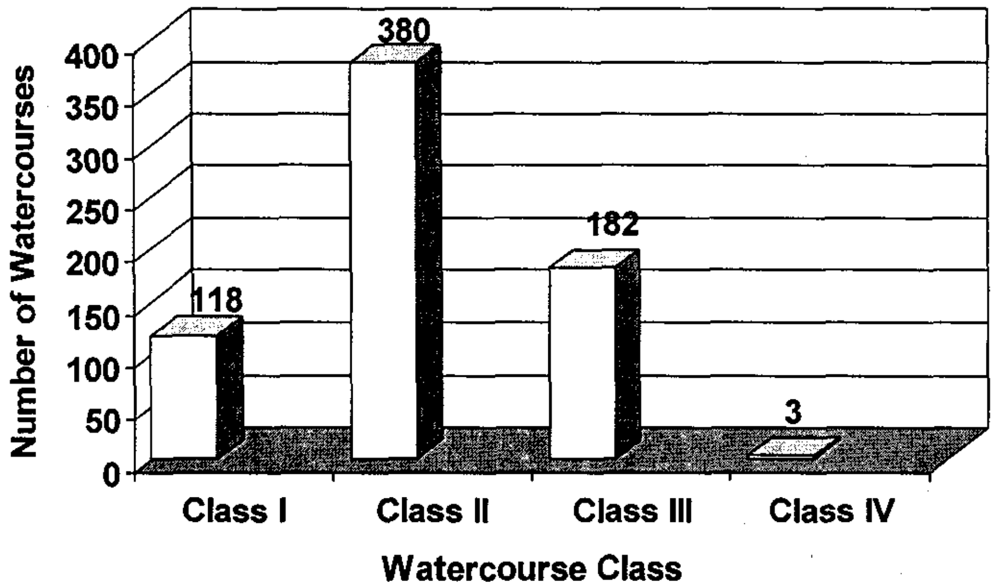

Figure 17. Distribution of watercourse classes evaluated from 1996 to 2001.

[20] Twelve Class III watercourses with WLPZs were evaluated in 1999 and 2 Class III watercourses with WLPZs were evaluated in 1997.

[21] WLPZs are not required for Class III watercourses. ELZs have been required for Class IIIs since January 1, 1998 (see 14 CCR 916.4(c)(1)). EEZs are often specified for these types of watercourses as well. ELZs allow heavy equipment in the zone only where explained in the THP and approved by the Director; EEZs are zones where heavy equipment is totally excluded.

As part of the WLPZ , ELZ, and EEZ transects, the field team rated the implementation and effectiveness of applicable Forest Practice Rules as they were encountered and as part of a subsequent overall evaluation following completion of the transect. A total of 56 questions were developed from 34 Rule sections and answered in the overall evaluation. When considering all the Forest Practice Rules related to watercourse protection zones, the implementation rate where the Rules were met or exceeded was **98.4** percent. The five Rule requirements with at least 30 observations and five percent or more major and minor departures are shown in Table 29. Three of these Rules relate to the requirement for the RPF to evaluate riparian areas for sensitive conditions, including the use of existing roads within the standard WLPZ and unstable and erodible watercourse banks. These factors are to be identified in the THP and considered when proposing WLPZ widths and protection measures. The other two Rules in Table 29 require that WLPZ widths must be at least equal to that specified in Table 1 (14 CCR 916.5 [936.5, 956.5]) in the Forest Practice Rules.

Very few erosion features associated with the current plan were found on the watercourse protection zone transects (Table 30). A total of 37 erosion features were recorded, with mass failures accounting for almost 50 percent. Most of the mass failures documented in the watercourse protection zones, however, were judged to either predate the current THP (127 features), were created after the THP but were not affected by the THP (17 features), or it was impossible to determine the feature date (17 features). The frequency of the erosion features associated with the current plan per mile of watercourse protection zone transect monitored is displayed in Table 31. Total erosion volumes for mass failures, sloughing, and gullying were approximately 2,900, 50, and 100 cubic yards, respectively. As was the case for the road and skid trail transects, these volume estimates are based on the dimensions of the voids remaining

Table 29. Watercourse protection zone (WLPZ, ELZ, and EEZ) related Forest Practice Rule requirements with more than five percent total departures based on at least 30 observations for the overall transect evaluation where implementation could be rated (note that some of the Rule sections are separated into components and the table is ordered by the percentage of total departures).

Forest Practice Rule	Description	Total Number	% Total Departure	% Minor Departure	% Major Departure
916.2(a)(4)	sensitive conditions--existing roads in WLPZ—appropriate mitigation measure(s) applied	133	9.0	4.5	4.5
916.4(a)	sensitive conditions--existing roads in WLPZ—identified in the THP	132	7.6	3.8	3.8
916.4(a)	sensitive conditions--erodible banks—identified in the THP	316	6.0	5.4	0.6
916.4(b)(3)	width of WLPZ conforms to Table 1 in the FPRs	593	5.6	4.7	0.8
916.4(b)	WLPZ widths as wide as specified in Table 1 in the FPRs	597	5.5	4.5	1.0

Table 30. Watercourse protection zone (WLPZ, ELZ, EEZ) transect erosion features associated with the current THP or NTMP NTO.

Erosion Feature	Number of Features 1996-1998	Number of Features 1999-2001	Total Number of Features 1996-2001
Cutbank/sidecast Sloughing	1	3	4
Mass Failure	13	5	18
Gullying	4	2	6
Rilling	5	4	9
Totals	23	14	37

on the hillslopes, not the amount of sediment delivered to watercourse channels. Also, similarly to what was reported for the road and skid transects, the number of erosion features for the various types of erosion were generally lower in the period 1999 through 2001 than from 1996 to 1998 (Table 30). Possible reasons for this difference are provided in the Discussion and Conclusions section of this report.

The percentage of watercourse protection zone transects that had one or more erosion features associated with the current plan of a given erosion type is shown in Table 32. Approximately 1.3 percent of the transects had at least one rill recorded, about 0.7 percent had one or more gullies, 2.0 percent had at least one mass failure, and 0.6 percent had sloughing present. These percentages are much lower than were found on roads and skid trails (see Tables 8 and 16).

When an erosion feature or other problem was found along the watercourse protection zone transects, implementation of the applicable Forest Practice Rule(s) was also rated for that problem point. A total of 27 Rule requirements were rated for implementation at watercourse protection zone problem sites. Of these, 20 Rules were associated with over 95 percent of the problem points (Table 33). When considering all the ratings

Table 31. Frequency of various types of erosion features associated with the current plan for the watercourse protection zone transects monitored.

Erosion Type	Class I (# features/mile)	Class II (# features/mile)	Class III (# features/mile)
Cutbank/Sidecast Sloughing	0	0.05	0.1
Mass Failure	0.4	0.2	0.2
Gullying	0.1	0.05	0.1
Rilling	0.1	0.1	0.1
Totals	0.6	0.4	0.5

Table 32. Percent of watercourse protection zone transects (all watercourse classes combined) with one or more erosion features associated with the current plan for selected types of erosion features.

Erosion Feature	Percent of Transects with One or More Features
Sloughing	0.6
Mass Failures	2.0
Gullying	0.7
Rilling	1.3

assigned at problem points encountered, about seven percent were associated with situations where the Rule requirements were found to have been met or exceeded and roughly 93 percent of the problem points were associated with minor or major departures from Rule requirements. The most commonly cited Rules rated for implementation at problem points were: 1) an inappropriate WLPZ width, 2) trees were not felled away from the watercourse channel, and 3) heavy equipment was not excluded from the watercourse protection zone and the approved THP did not permit this activity.

Canopy cover was measured with the spherical densiometer from 1996 through 1998 (Figure 18) and the sighting tube from 1999 through 2001. Mean total canopy cover measurements are displayed in Table 34. In all cases, average post-harvest values were above 70 percent. Average canopy values were also determined for each of the three CDF Forest Practice Districts for the sighting tube data (Figure 19). Mean values were highest in the Coast Forest Practice District (approximately 80 percent for both Class I and IIs) and lower in the interior districts. Lower values inland are probably related to warmer, drier conditions and the presence of slower growing tree species. In all cases, mean total canopy levels exceeded the Forest Practice Rule requirements in place for Class II watercourses. This is likely true for Class I watercourses as well, but overstory and understory canopy were not differentiated in this project as described by the Rules.[22]

Surface (or ground) cover was evaluated at 100 foot intervals along the watercourse protection zone transects for Class I, II, and III watercourses (Table 35). In all cases, surface cover exceeded the post-harvest Rule standard of 75 percent. Surface cover was generally similar for the three different Forest Practice Districts. Southern District Class I surface cover was slightly lower than that found in the other two districts. In the Coast Forest Practice District, high precipitation and summer fog near the ocean promote an environment that is quickly covered with surface vegetation. In the drier

[22] Since pre-harvest canopy measurements were not made at the THP and NTMP project sites, it is not possible to state what the change in canopy was due to timber harvesting activities associated with the current plan.

inland districts, bare soil is common in some locations even prior to logging. For all three districts, Class II and III surface cover means were higher than that for Class I watercourses.

Table 33. Problem point implementation ratings that account for over 95 percent of all the Forest Practice Rule requirements rated along watercourse protection zone segments.

Forest Practice Rule	Description of Rules Rated for Implementation at Problem Points	Number of Times FPR Cited	Meets/ Exceeds Rule (%)	Minor Departure (%)	Major Departure (%)
916.4(b)(3)	width of WLPZ conforms to Table 1	43	0	62.8	37.2
916.4(b)	WLPZ widths as wide as specified in Table 1	42	0	59.5	40.5
916.3(e)	trees in WLPZ felled away from channel	25	4	60.0	36.0
916.4(d)	heavy equipment excluded from the zone unless explained and approved	13	0	46.2	53.8
916.5(e)"I"	Class II--50% of total canopy left in WLPZ	11	0	45.5	54.5
916.3(c)	roads, landings outside of WLPZs	10	0	30.0	70.0
916.5(b)	beneficial uses consistent with WLPZ classes	9	0	33.3	66.7
916.2(a)(4)	sensitive conditions--unstable banks--mitigation measure(s) applied	8	0	100.0	0.0
916.4(b)	THP provides for upslope stability	8	25	62.5	12.5
916.5(a)(3)	side slope classes used to determine WLPZ width and protective measures	7	0	71.4	28.6
916.4(b)	THP provides for protection of water temperature	7	28.6	42.9	28.6
916.2(a)(4)	sensitive conditions--existing roads in WLPZ-- mitigation measure(s) applied	6	0	16.7	83.3
916.3(g)	Class I/II--2 living conifers per acre 16 in. or greater DBH, 50 ft tall retained within 50 feet of the watercourse	6	16.7	66.7	16.7
916.4(a)	sensitive conditions--existing roads in WLPZ identified in the THP	6	0	33.3	66.7
916.4(b)	THP provides for channel stabilization	6	33.3	33.3	33.3
916.4(b)	THP provides for filtration of organic material	4	50	50.0	0.0
916.5(e)"G"	Class I--50% overstory and 50% understory retained	3	0	100.0	0.0
916.4(a)	sensitive conditions--erodible banks identified in the THP	3	0	100.0	0.0
916.4(b)(4)	WLPZ width segregated by slope class	3	0	100.0	0.0
916.4(c)(3)	Class III--soil removed or stabilized	3	0	66.7	33.3

Table 34. Mean WLPZ total canopy cover measurements.

Year/Location	Class I Canopy Cover (%)	Class II Canopy Cover (%)
1996—North Coast Spherical Densiometer	79	77
1997 to 1998—Statewide Spherical Densiometer	74	75
1999 to 2001—Statewide Sighting Tube	73	75

Figure 18. Measuring canopy cover with the spherical densiometer in western Mendocino County in 1996.

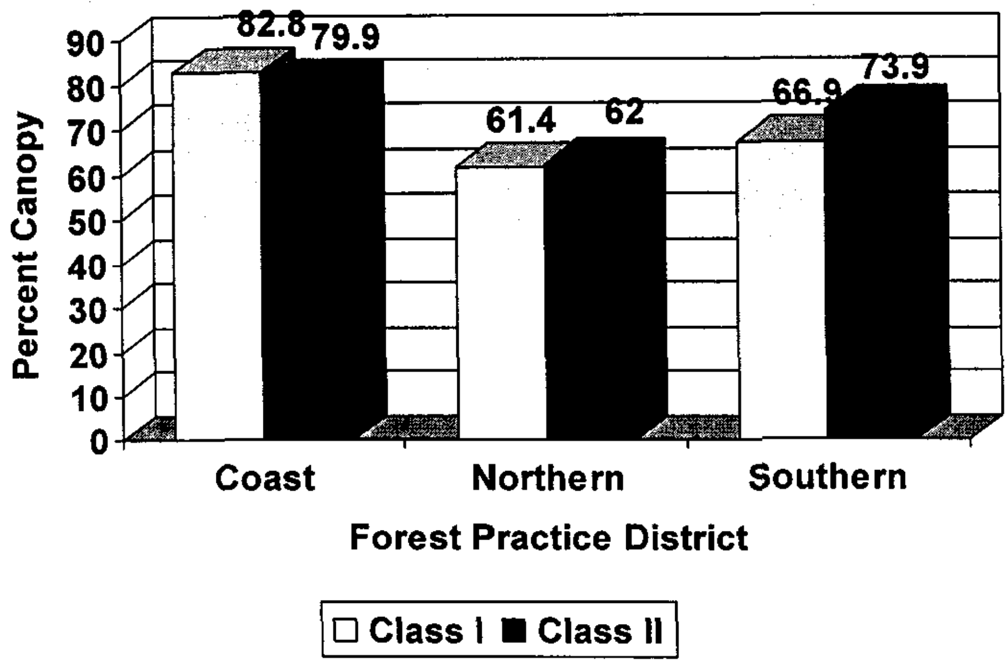

Figure 19. Total canopy cover percentages for Class I and II watercourses from 1999 through 2001 by Forest Practice District (data measured with a sighting tube).

Table 35. Mean surface cover values for the three CDF Forest Practice Districts.

CDF Forest Practice District	Class I Surface Cover (%)	Class II Surface Cover (%)	Class III Surface Cover (%)
Coast	82.5	97.1	98.3
Northern	81.9	95.3	93.0
Southern	76.2	95.4	97.6

Mean watercourse protection zone widths were estimated or measured as part of the transect effectiveness evaluation process. Mean widths for Forest Practice Rule side slope categories are shown in Table 36. It was often difficult for the field team to determine the upper extent of the WLPZ—particularly where selective silvicultural systems were used above the WLPZ. Flagging used to denote the WLPZ was often gone or difficult to locate following several overwintering periods, resulting in the estimation of WLPZ widths in some cases. It is also unknown exactly how many of the WLPZs sampled utilized the allowable reduction granted for cable yarding systems (50 foot reduction for Class I and 25 foot reduction for Class II watercoures). Thirty percent of the WLPZ transects had cable or helicopter yarding upslope of the transect (this includes areas that were listed as both cable and tractor). As reported above (Table 29), WLPZ width problems were only cited on about six percent of the transects, and major departures for the overall evaluation were only recorded for one percent of the transects.

The percentage of inventoried watercourse protection zone erosion features related to current operations that had dry season evidence of sediment reaching the high or low flow channel of a watercourse is shown in Figure 20. The percentages of sediment delivering features for sloughing, mass failures, gullying, and rilling features are 66.7, 64.3, 83.3, and 88.9 percent, respectively. No sediment was transported to the channel for 33.3 percent of the sloughing features, 35.7 percent of the mass failures, 16.7 percent of the gullies, and 11.1 percent of the rills. Of the rills that delivered sediment to watercourses, 12.5 percent delivered to Class III watercourses. For gullies that delivered sediment, 20 percent input sediment to Class III watercourses. Sediment delivery data was not reported for 0 percent of the rilling features, 0 percent of the gullies, 22.2 percent of the mass failures, and 25 percent of the sloughing events. The proportions of erosion features delivering sediment in watercourse protection zones are considerably higher than that reported from similar types of erosion features found on the road and skid trail transects (Figures 9 and 10), due to the close proximity of these features to the channel.

Table 36. Mean WLPZ width estimates.

Watercourse Class	Side Slope Gradient Category (%)	Mean WLPZ Width (feet)	Standard Forest Practice Rule Width (feet)
I	<30	79	75
	30 to 50	96	100
	≥50	119	150[23]
II	<30	53	50
	30 to 50	72	75
	≥50	90	100[12]

[23] 50 foot and 25 foot reductions in WLPZ width are allowed with cable yarding for Class I and II watercourses, respectively (see Table 1, 14 CCR 916.5 [936.5, 956.5]).

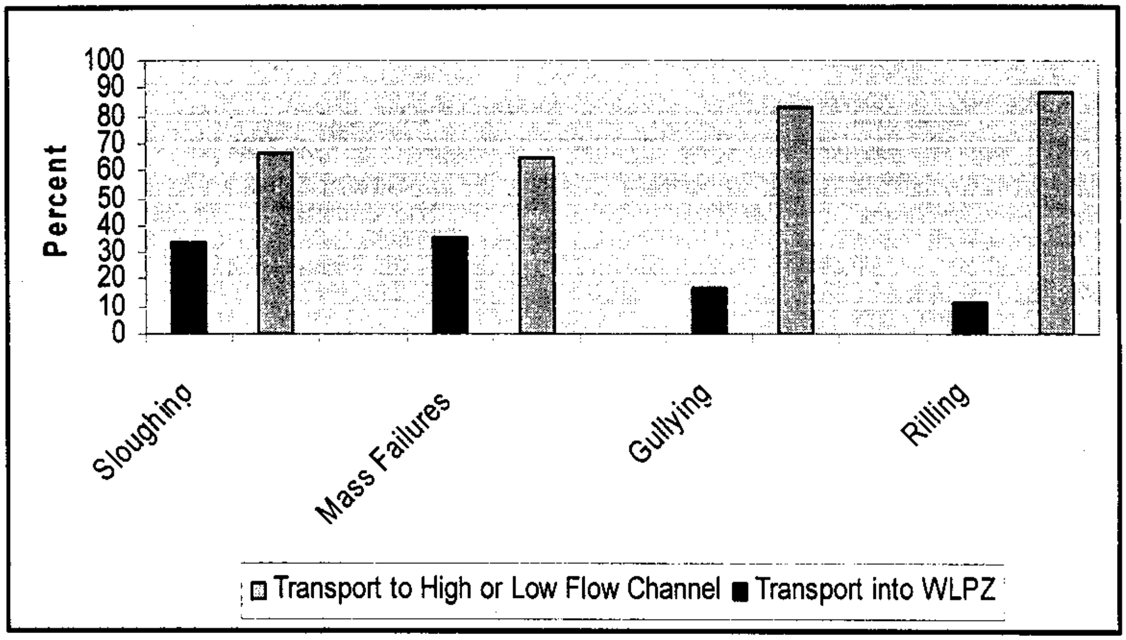

Figure 20. Percent of erosion features with dry season evidence of delivered sediment to the high or low flow channel of a watercourse from watercourse protection zone transect features associated with the current THP or NTMP project.

Large Erosion Events

While the sampling approach for roads, skid trails, landings, watercourse crossings, and watercourse protection zones utilized a very detailed evaluation for a small portion of a THP or NTMP Project, the inventory of large erosion events and associated site and management factors covered a significant portion of the THP or NTMP Project area as a whole. This more extensive approach was used in an attempt to determine the impacts of large erosion events, which may be responsible for a majority of hillslope erosion while occurring on a very limited portion of the landscape that a randomized sample approach is likely to miss. This is particularly important where mass wasting is the dominant erosional process (Rice and Lewis 1991, Lewis and Rice 1989, Lee 1997).

Erosion sites with: 1) 100 cubic yards or more on hillslopes, and 2) 10 cubic yards or more at failed watercourse crossings, were documented wherever they were found. Large erosion events were identified primarily when traveling within the THP, either by foot or in a vehicle, as part of the evaluations for randomly located road segments, skid trail segments, landings, crossings, and watercourse protection zones. Additional large erosion events were identified from THP maps. Recorded information included the size and type of erosional feature, site conditions, and specific timber operations. Where specific Forest Practice Rules could be connected to a feature, they were recorded as well. These types of evaluations were completed only for the statewide hillslope monitoring work (1997 through 2001).[24]

In-unit mass wasting was not included in this inventory because surveys of logging unit(s) were not required in the other components of the Hillslope Monitoring Program. Therefore, the impacts of the Forest Practice Rules on in-unit mass wasting, other than those large erosion events primarily triggered by the roads, skid trails, watercourse crossings, and landings evaluated within the plan, were largely undetermined (Stillwater Sciences 2002).[25]

A total of 50 large erosion events were located on the 250 THPs and NTMP projects included in this portion of the Hillslope Monitoring Program. These events were found on 37 THPs, or 15 percent, with nine plans having multiple features. Of the 50 total

---

[24] The 1996 large erosion event monitoring in Humboldt and Mendocino Counties was considered a pilot project to further refine how the data would be collected. The initial procedure used in 1996 is described in Tuttle (1995). The process was modified significantly based on information provided by the Hillslope Monitoring Program contractors who completed the field work in Mendocino and Humboldt Counties during 1996.

[25] Additional information on this subject can be found for Humboldt County watersheds in PWA (1998a, 1998b) and Marshall (2002), Mendocino County in Cafferata and Spittler (1998), and Northern California in general as part of the Critical Sites Erosion Study (Durgin et al. 1989, Lewis and Rice 1989, Rice and Lewis 1991). Also, the California Geological Survey has preliminary data on frequency of mass wasting events in clearcut units and adjacent uncut units in Jackson Demonstration State Forest, located near Fort Bragg, California (contact Mr. Thomas Spittler, CGS, Santa Rosa, CA). Information on mass wasting related to forestry operations in Oregon is available in Robison et al. (1999).

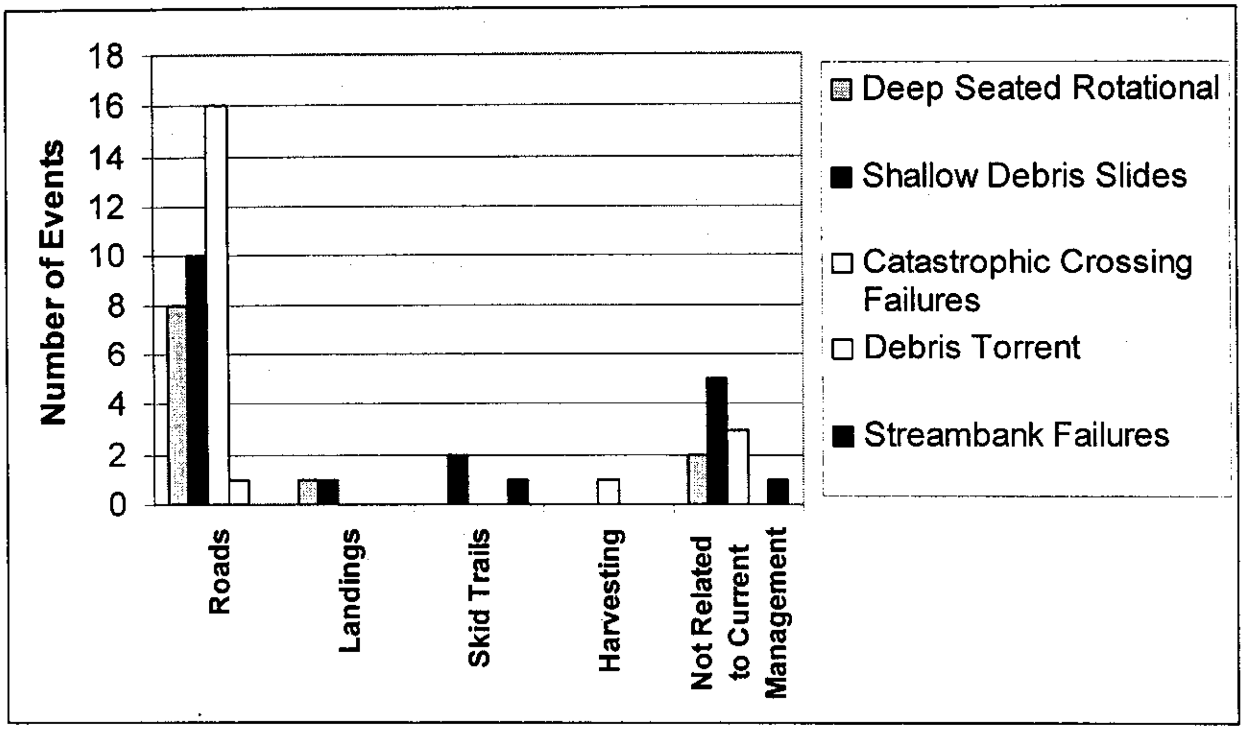

Figure 21. Primary causes of large erosion events and type of feature (note that multiple causes were assigned in some instances).

features, 39 were classified as being related to current timber management activities (Figure 21).

As shown in Table 37, nearly all of the shallow debris slide features were found in the Coast Forest Practice District, as were the majority of the deep seated rotational features. Since there were 4.7 and 2.3 times more THPs and NTMP projects in the Coast Forest Practice District when compared to the Southern and Northern Districts (Table 1), respectively, the actual frequency of catastrophic crossing failures is much higher in the inland districts. This can be partly explained by the very large rain-on-snow event which occurred in January 1997, which was at least a 100-year recurrence interval runoff event in many parts of the Sierra Nevada Mountains. Streambank failures related to the current plan and debris torrents were recorded infrequently. As with the numbers of erosion features recorded on road, skid trail, and watercourse protection zone transects, the numbers of large erosion events were considerably lower in period from 1999 through 2001 (15 features) than during the 1997-1998 period (35 features) (Figure 22).

Average volumes for the various types of erosion features related to current management activities in all three Forest Practice Districts were as follows: deep seated rotational failures—19,800 cubic yards, shallow debris slide features—3,500 cubic yards, catastrophic crossing failure features—65 cubic yards, streambank failures—600 cubic yards, and debris torrent features—550 cubic yards.

Table 37. Frequency distribution of large erosion events that were encountered on THPs and NTMP projects evaluated from 1997 through 2001.

Type of Feature	Coast	Northern	Southern	Total
Deep seated rotational	7	3	1	11
Shallow debris slide	14	3	0	17
Debris torrent	1	0	0	1
Streambank Failure	1	0	1	2
Catastrophic crossing failure	6	6	7	19
Totals	29	12	9	50

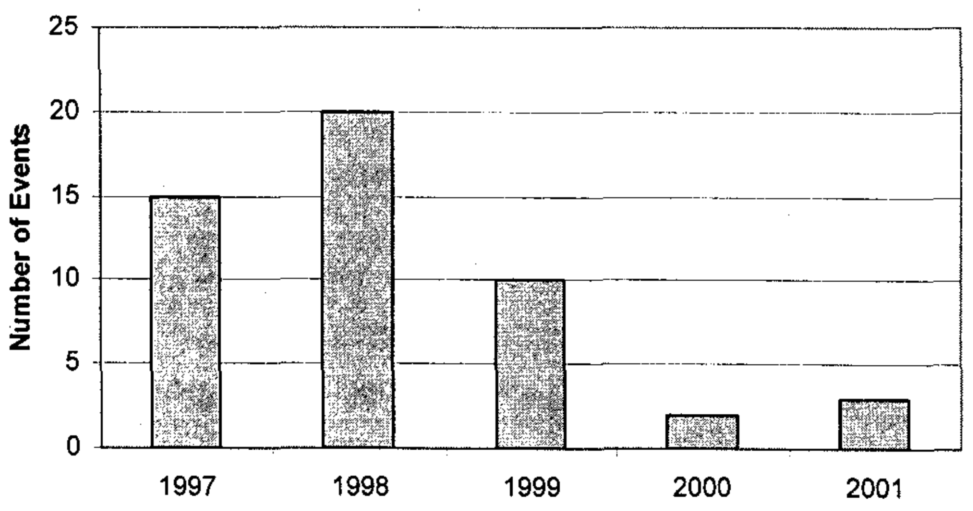

Figure 22. Year data was recorded on the large erosion events inventoried.

Most of the inventoried large erosion events related to management activities in the current plan were associated with roads (35), with smaller numbers of events associated with skid trails (3), landings (2), and harvesting (1). Cause codes and associated features are displayed in Figure 21, while specific cause codes are shown in Table 38 (multiple cause codes were assigned in some instances, so the total is greater than the 39 events). The most frequent causes of management related large erosion events were: cutbanks with slope support removed; subsurface water concentration;

culverts with plugged inlets; fill slopes with overloaded, deep sidecast; and culverts which were judged to be too small.

Table 38. Management related causes of inventoried large erosion events (note that multiple causes were often assigned to a single event).

Type of Feature	Cause of Feature	Count
Roads	Waterbars-discharge onto erodible material	3
	Waterbars-improperly constructed or located	3
	Fill slopes-too steep	3
	Fill slopes-overloaded, deep sidecast	6
	Fill slopes-poorly compacted	4
	Fill slopes-excessive organic material	1
	Culverts too small	5
	Culverts-discharge onto erodible material	2
	Culverts-inlet plugged	8
	Culverts-broken and leaking into the roadbed	1
	Inside ditch-ditch blocked and/or diverted	1
	Inside ditch-other drainage onto road not handled	4
	Cutbanks- too steep	3
	Cutbanks-slope support removed	11
	Subsurface flow alteration	1
	Cross drains-too small	1
	Cross drains-discharge onto erodible material	1
	Cross drains-improperly constructed or located	3
	Subsurface water concentrations-discharge onto erodible material	9
Skid Trails	Waterbars-not properly draining area	2
	Cutbanks-too steep	1
	Cutbanks-slope support removed	2
	Surface water concentration-rilling and gullying	1
	Surface water concentration-discharge on erodible material	2
Landings	Cutbanks-too steep	1
	Cutbanks-slope support removed	1
	Fill slopes-excessive organic material	1
	Waterbars-discharge onto erodible material	1
	Subsurface flow alteration	1
Harvesting	Alteration of natural drainage during yarding	1

Non-Standard Practices and Additional Mitigation Measures

Additional mitigation measures beyond the standard Rule requirements are often added to THPs. These mitigations may be the basis for acceptance and approval of proposed in-lieu or alternative practices and, ultimately, the THP. This summary should be considered an initial, first-phase review of non-standard practices (including in-lieu and alternative practices) and additional mitigation measures, from which future work can be built upon. Further evaluation of the implementation and effectiveness of these types of practices is needed.

A more complete evaluation approach was not developed during the Pilot Monitoring Program (1993-1995) due to the difficulty in addressing the variability of prescriptions developed for site specific problems (Lee 1997), but is needed for future monitoring work. The Hillslope Monitoring Program Interim Report (CSBOF 1999) did not address this topic, so this is the first time that these data have been summarized. It is important to note that site-specific practices and/or additional mitigation measures often did not apply at the randomly selected transects and features, so the totals reported below are a small sample that does not include all of the types of practices that were included in the THPs and NTMP projects. Additionally, the features were not examined to the same degree of rigor as on the randomly located transects evaluated for standard Rule compliance and at large erosion sites, and the narrative evaluations were based on requirements specified in the THP provided to the contractors, some of which may have been modified through amendments that were not reviewed.[26]

A brief summary of the qualitative responses provided for non-standard practice and additional mitigation measure implementation and effectiveness follows for each feature type.

<u>Roads</u>

Of the 568 road transects evaluated in the field, a total of 45 transects had entries in the Hillslope Monitoring Program database for the implementation and effectiveness of non-standard practices or additional mitigation measures. The most commonly approved non-standard practice was the use of roads in WLPZs,[27] followed by roads on steep slopes (greater than 65 percent). Frequently prescribed additional mitigation measures were: 1) seeding and mulching or rocking road surfaces and 2) decreasing the distance between waterbreaks (to high or extreme erosion hazard rating standards). As shown in Table 39, about 15 percent of these sites had existing or potential problems, of which four percent was associated with lack of implementation and nine percent with

[26] The field team was not always supplied with a complete set of the reviewing agencies' Pre-Harvest Inspection reports and Amendments to the THP.

[27] Currently, construction or reconstruction of a road within a WLPZ is an in-lieu practice (14 CCR 916.3(c) [936.3(c), 956.3(c)], except at new crossings approved as part of the Fish and Game Code process. Use of existing roads in WLPZs is addressed in 14 CCR 916.4(a) [936.4(a), 956.4(a)], but is not considered an in-lieu practice.

acceptable implementation. Overall, the specified practices were not fully implemented at about 13 percent of the applicable sites, and approximately 70 percent were judged to be properly implemented and effective. For approximately three percent of the applicable sites, full implementation of the specified measures was lacking but effectiveness was judged to be acceptable.

Skid Trails

Non-standard practices or additional mitigation measures were evaluated at thirty-seven of the 480 skid trail transects completed for this project. The most common practices included: 1) more frequent waterbreak spacing than required by the standard Rules, 2) tractor operations on slopes steeper than permitted by the standard FPRs, and 3) use of existing skid trails in watercourse protection zones. As shown in Table 40, only four of these practices (9 percent) were described as having existing or potential problems, of which three were associated with poor implementation and one with acceptable implementation. The specified practices were not fully implemented on approximately 25 percent of the applicable sites and were judged to be properly implemented and effective about 60 percent of the time.

Landings

A total of 28 landings had entries for non-standard practices or additional mitigation measures, out of a possible 569 features. Nearly all of these were alternatives with approval for use of WLPZ landings, usually in conjunction with additional mitigation measures that generally specified the use of seeding and mulching or rocking. As shown in Table 41, about seven percent of the sites where these practices and measures were applied had existing or potential problems, all of which were associated with acceptable implementation. About four percent of the practices were not fully implemented and almost 90 percent were properly implemented and effective.

Watercourse Crossings

Of the 491 watercourse crossings evaluated, non-standard practices or additional mitigation measures were evaluated at 18 sites as part of the hillslope monitoring process. Common mitigation measures applied at these sites included: mulching and seeding fill slopes or abandoned crossings, and use of rock for inlet or road approaches. As shown in Table 42, three of the practices at these 18 crossings (about 11 percent) had existing or potential problems, of which all were associated with acceptable implementation. Approximately 15 percent of the practices were not fully implemented. Fifty-six percent of the practices evaluated were judged to be properly implemented and effective.

Watercourse Protection Zones (WLPZs, ELZs, and EEZs)

Of the 683 watercourse protection zones transects evaluated in the field, 56 transects had entries in the Hillslope Monitoring Program database for the implementation and effectiveness of non-standard practices or additional mitigation measures. Commonly specified practices and mitigation measures were: 1) use of existing roads within WLPZs, 2) use of existing skid trails in the WLPZ , 3) no-cut WLPZs, 4) additional canopy retention requirements in the WLPZ over the standard Rule, and 5) wider WLPZs than required by the standard Rule. When evaluating the frequent practice of using existing WLPZ roads, the field team often stated that there was no *apparent* sediment delivery to the watercourse channel. It is important to recognize that these inspections were completed in the dry summer and fall months, when observation of possible fine sediment transport during winter storm events was not possible.

Table 43 displays the implementation and effectiveness ratings for the non-standard practices and additional mitigation measures for watercourse protection zones. About eight percent of these practices and measures were applied had existing or potential problems, of which one percent was associated with poor implementation and seven percent with acceptable implementation. Approximately five percent of the practices were not fully implemented. Seventy-four percent of the practices were properly implemented and effective (see the comments about fine sediment transport above).

Table 39. Summary of recorded non-standard practices and additional mitigation measures for roads.

Non-Standard Practice	Count	I/E	I/P	I/UE	UI/E	UI/P	NI/E	NI/P	NI/U
Use of WLPZ road	20	17	2		1				
No harvesting between road and stream	1	1							
Extreme EHR waterbar spacing	2	1					1		
High EHR waterbar spacing with 12 inch waterbars	1	1							
High erosion hazard rating for waterbar spacing	4			1				1	2
Use of reduced waterbar spacing	2	1	1						
Place hay bale at WLPZ waterbar outlets	1	1							
Seed and mulch road surface	4	4							
Straw mulch on road	3	3							
Road rocking	6	6							
Rock crossing approaches	1		1						
Rock Class III crossings	1	1							
Road on >65% slopes	3	3							
Roads on >65% slope and road segment >15% grade	1	1							
Full bench road construction	2	2							
Full bench road construction on unstable slopes<65%	1							1	
Outslope roads	2			1			1		
Endhauling	1	1							
Place fill in safe location	2			1					1
Push excess material to slopes <40%	1	1							
No sidecast	2	2							
No deposition from clearing cutbanks and/or brow log	1								1
Remove overhanging banks	1			1					
Reconstruct roads in wet areas	1	1							
Road moved and new crossing installed	1	1							
Class III off of road/improve drainage through landing	1	1							
Road abandonment	1								1
Remove culvert	1					1			
Winter hauling limited to firm road surface	1		1						
No winter hauling when sediment can reach stream	2		2						
Dip out crossing and mulch	1	1							
Use of excavator	1	1							
Whole tree yarding from road	1			1					
Block road	2	1						1	
Totals	76	52	7	5	1	1	2	3	5
Percent	100	68.4	9.2	6.6	1.3	1.3	2.6	4	6.6

"I/E" = Implemented and Effective/No Problem Observed
"I/P" = Implemented and Problem or Potential Problem Exists
"I/UE" = Implemented and Unknown Effectiveness
"UI/E" = Unknown Implementation and Effective/No Problem Observed
"UI/P" = Unknown Implementation and Problem or Potential Problem Exists
"NI/E" = Not Implemented and Effective/No Problem Observed
"NI/P" = Not Implemented and Problem or Potential Problem Exists
"NI/U" = Not Implemented and Unknown Effectiveness

Table 40. Summary of recorded non-standard practices and additional mitigation measures for skid trails.

Non-Standard Practice	Count	I/E	I/P	I/UE	UI/E	UI/P	NI/E	NI/P	NI/U
Use of WLPZ skid trail	4	2	1	1					
Use of WLPZ road for heavy equipment	1	1							
More frequent waterbar spacing than standard rule	2	1						1	
Waterbreak spacing at extreme EHR	7	4					1		2
Waterbreak spacing at high EHR	9	4					2	2	1
High EHR waterbar spacing with 12 inch waterbars	2			2					
Seed and mulch removed skid trail crossing	2	1		1					
Mulch approaches ot removed skid trail crossing	1	1							
Seed and mulch skid trails in WLPZ	2	1					1		
Seed and mulch skid trails on slopes >40%	1						1		
Seed and slash skid trails	1	1							
Slash and mulch skid trails	1	1							
Chip and slash skid trails	1	1							
Use of existing skid trails on slopes >65%	4	4							
Use of tractors in cable area	1	1							
Use of existing skid trails without watercourse crossings	2	2							
Skid trail crossing of Class II watercourse	1			1					
Tractor yarding during dry conditiong in winter period	1	1							
Tractor crossing of Class IV watercourse	1			1					
Totals	44	26	1	6	0	0	5	3	3
Percent	100	59.1	2.3	13.6	0	0	11.4	6.8	6.8

"I/E" = Implemented and Effective/No Problem Observed
"I/P" = Implemented and Problem or Potential Problem Exists
"I/UE" = Implemented and Unknown Effectiveness
"UI/E" = Unknown Implementation and Effective/No Problem Observed
"UI/P" = Unknown Implementation and Problem or Potential Problem Exists
"NI/E" = Not Implemented and Effective/No Problem Observed
"NI/P" = Not Implemented and Problem or Potential Problem Exists
"NI/U" = Not Implemented and Unknown Effectiveness

Table 41. Summary of recorded non-standard practices and additional mitigation measures for landings.

Non-Standard Practice	Count	I/E	I/P	I/UE	UI/E	UI/P	NI/E	NI/P	NI/U
Use of WLPZ landing	17	15	2						
Use of ELZ landing	1	1							
Rock landing surface	4	4							
Seed and mulch landing surface	4	4							
Slash and mulch landing surface	2	2							
Inslope landing, mulch, install brow log	1	1							
Drain to avoid discharge on fillslope	1								1
Install ditch for drainage	1						1		
Outslope landing	2	2							
Seed and mulch, install brow log, hay bale	1	1							
Seed landing	2	2							
Mulch landing	3	3							
Install brow log on landing surface	2	1	1						
Landing >1/4 ac for helicopter yarding	1	1							
Helicopter landing in WLPZ	1	1							
Relocate landing away from Class III watercourse 50 feet	1	1							
Rechannel watercourse	1	1							
Totals	45	40	3	0	0	0	1	0	1
Percent	100	88.9	6.7	0	0	0	2.2	0	2.2

"I/E" = Implemented and Effective/No Problem Observed
"I/P" = Implemented and Problem or Potential Problem Exists
"I/UE" = Implemented and Unknown Effectiveness
"UI/E" = Unknown Implementation and Effective/No Problem Observed
"UI/P" = Unknown Implementation and Problem or Potential Problem Exists
"NI/E" = Not Implemented and Effective/No Problem Observed
"NI/P" = Not Implemented and Problem or Potential Problem Exists
"NI/U" = Not Implemented and Unknown Effectiveness

Table 42. Summary of recorded non-standard practices and additional mitigation measures for watercourse crossings.

Non-Standard Practice	Count	I/E	I/P	I/UE	UI/E	UI/P	NI/E	NI/P	NI/U
Rock road at crossing	4	2		1					1
Install 3/4 inch rock	1		1						
Rock Class III watercourse crossing	1	1							
Rock armor inlet of crossing	2	2							
Seed and mulch fill slopes at watercourse crossing	1		1						
Seed and mulch banks of removed crossing	1						1		
Straw mulch removed watercourse crossing	1	1							
Mulch 20 feet on either side of the crossing	1	1							
Seed and mulch road surface approaches to crossing	1	1							
Straw mulch new or reconstructed crossing	1			1					
Hydromulch fill slopes	2			2					
Use of existing watercourse crossing	2	2							
Install trash rack	1						1		
Install standpipe	2	2							
Remove 36 inch pipe, rock armor for slope stabilization	1	1							
Use of gravel ford crossing	1			1					
Install concrete sacks to stabilize downstream fill slope	1	1							
Install brow logs, berm logs	1						1		
Rechannel Class III watercourse along road	1	1							
Block road	1		1						
Totals	27	15	3	5	0	0	3	0	1
Percent	100	55.6	11.1	18.5	0	0	11.1	0	3.7

"I/E" = Implemented and Effective/No Problem Observed
"I/P" = Implemented and Problem or Potential Problem Exists
"I/UE" = Implemented and Unknown Effectiveness
"UI/E" = Unknown Implementation and Effective/No Problem Observed
"UI/P" = Unknown Implementation and Problem or Potential Problem Exists
"NI/E" = Not Implemented and Effective/No Problem Observed
"NI/P" = Not Implemented and Problem or Potential Problem Exists
"NI/U" = Not Implemented and Unknown Effectiveness

Table 43. Summary of recorded non-standard practices and additional mitigation measures for watercourse protection zones (WLPZs, ELZs, and EEZs). [see the previous tables for the definitions of the abbreviations used below]

Non-Standard Practice	Count	I/E	I/P	I/UE	UI/E	UI/P	NI/E	NI/P	NI/U
Use of existing WLPZ road for hauling	19	18		1					
Use of existing road and landing in WLPZ	1			1					
Reconstruction of road in WLPZ	1	1							
Use of existing WLPZ road for skidding logs	1	1							
Use of existing WLPZ skid trail	2	2							
Extreme EHR waterbreak spacing	1	1							
Seed and mulch existing WLPZ road	2	1							1
Slash pack skid trails	1	1							
Seed and mulch removed skid trail crossing	1	1							
Rocked road in WLPZ	3	3							
Rocked cross drains on WLPZ road	1	1							
No sidecast in WLPZ from existing road	1	1							
No harvesting in WLPZ	5	3		1					1
No harvesting in WLPZ except at cable corridors	1			1					
Equipment exclusion zone (EEZ) established	1	1							
EEZ 10 feet for Class III watercourse	1	1							
No equipment in WLPZ between road and stream	1	1							
No harvesting in WLPZ between road and stream	1	1							
Reduction in WLPZ width from 150 ft to 115 ft	1	1							
WLPZ width increased to 200 ft	2	2							
WLPZ width increased to 150 ft	1			1					
WLPZ width increased to 100 ft	1	1							
WLPZ width 150 ft; no variable zone based on slope	1							1	
Class II WLPZ 75 ft regardless of slope	1	1							
WLPZ width wider than standard Rule requirement	3	2		1					
WLPZ width--maximum distance possible in Rules	1	1							
75% retention of overstory vegetation	1	1							
70% overstory and 50% understory retention	1			1					
70% overstory retention	4		3	1					
70% total canopy retention	3	1	2						
50% canopy retention in ELZ for Class III watercourse	2			2					
Retain 5 largest trees in WLPZ	1	1							
Retain 5 trees/acre >32 inches DBH	1	1							
Very limited harvesting in WLPZ	2	2							
Removal of debris jams in channel	2	2							
Remove slash from WLPZ	1								1
Allow tree falling to occur across watercourse	2	1		1					
Exception to Rule requiring 2 conifers >16 in w/in 50 ft	1	1							
Totals	76	56	5	11	0	0	0	1	3
Percent	100	73.7	6.6	14.5	0	0	0	1.3	3.9

Discussion and Conclusions

Project Limitations

The Hillslope Monitoring Program has primarily reviewed Timber Harvesting Plans, with a very limited evaluation of Nonindustrial Timber Management Plans. Exemptions, Emergency Notices, and Conversions have not been monitored. The THP "Review Process" and the degree to which this process contributes to water quality problems has not been considered (Lee 1997). Also, since winter documentation of fine sediment delivery to streams was not possible with this program, the percentages of sediment delivery to watercourse channels from erosion features found on roads, landings, and skid trails are likely to underestimate total sediment delivery. Analysis completed on the data set to date has primarily been composed of frequency counts and has been limited by time and access to database analysts. Additional data analysis will be conducted in the future.

Key points regarding what has been learned are summarized and discussed below.

Implementation rates of the Forest Practice Rules related to water quality are high, and individual practices required by the Forest Practice Rules are effective in preventing hillslope erosion features when properly implemented.

Table 44 shows that overall ratings of the FPRs for each monitoring subject area are high—over 90% for all but watercourse crossings. This result is similar to what has been reported for other western states. For example average implementation rates for BMPs have been reported as 96 percent, 94 percent, and 92 percent in Oregon, Montana, and Idaho, respectively (Ice et al. 2002). In California, implementation of applicable Rules at problem points was nearly always (98% overall) found to be less than that required by the FPRs (Table 45). Therefore, problem points were almost always caused by non-compliance with the FPRs. These results are consistent with findings reported in earlier studies conducted in California (Dodge et al. 1976, CSWRCB 1987). The above conclusion refers to "individual practices," since the THP Review and inspection process was not evaluated as part of the Hillslope Monitoring Program.

Table 44. Summary of acceptable (i.e., meets or exceeds requirements) Forest Practice Rule implementation ratings for transects (roads, skid trails, watercourse protection zones) and features (landings and watercourse crossings) as a whole.

Hillslope Monitoring Program Sample Area	% Acceptable Implementation
Road Transects	93.2
Skid Trail Transects	95.1
Landings	93.5
Watercourse Crossings	86.3
Watercourse Protection Zones (WLPZ, ELZ, EEZ)	98.4
Total	94.5

Table 45. Summary of Forest Practice Rule implementation ratings at problem points for individual Hillslope Monitoring Program evaluation areas.

Hillslope Monitoring Program Sample Area	Percent Acceptable Implementation	Percent Major or Minor Departure from Requirements
Road Transects	2	98
Skid Trail Transects	0	100
Landings	0	100
Watercourse Crossings	0	100
Watercourse Protection Zones	7	93
Total	2	98

Watercourse crossing problems remain frequent, with nearly half the crossings evaluated having at least one problem point.

Large numbers of problem points were found at crossings. Reasons for this include:

- crossings are sometimes built incorrectly,
- many types of crossings have a relatively short expected life,
- culverts are sized with planned failure if a discharge event exceeds a selected recurrence interval (often 50 or 100 years),
- culverted crossings are often not built to properly accommodate large wood and sediment,
- maintenance of crossings—particularly culverts—is often difficult due to remote locations, lack of staff, and road passage problems in winter months,
- abandonment principles are subjective, difficult to apply in the field, and require considerable experience for proper implementation,
- upgrading old crossings can be very expensive, and
- shared use agreements on roads with crossings can complicate the responsibility and timing of improvement work.

The most frequent types of crossing problems encountered during the hillslope monitoring work were culvert plugging, diversion potential, fill slope gullies, scour at the outlet of the culvert, ineffective road surface cutoff waterbreaks, and fill slope mass failures. These problems are primarily related to the design, construction, and maintenance of crossings. Replacing and upgrading numerous crossings along a road segment can be a large, difficult, and expensive task for a landowner. Inventorying for the worst crossings with the most potential for adverse impacts to water quality and developing a plan to complete the work may be a realistic solution (see Flanagan et al. 1998). Gucinski et al. (2001) list several techniques for decreasing the negative hydrologic effects of roads, several of which relate to crossings.

Proper crossing abandonment requires considerable expertise and experience. Guidelines for accomplishing this work are provided in Weaver and Hagans (1994). Long-term sediment savings can be provided by removing crossings that will eventually fail (Madej 2001), but a small short-term flush of sediment is likely to occur during the first winter following heavy equipment work. Weaver (2001) estimated that this will often be on the order of 5 to 10 cubic yards per crossing.[28] Monitoring of crossing removal work in the Caspar Creek watershed found that an average of approximately 10 cubic yards was eroded from abandoned crossings during the first winter (excluding the one crossing in the South Fork that was retaining old splash dam deposits—see the Summary of Related Studies section earlier in this report for additional details).

Roads with drainage structure problems are the main cause of sediment delivery to stream channels.

About half the road transects evaluated by the Hillslope Monitoring Program field crews had one or more rills, approximately 25 percent had at least one gully, and four percent had a mass failure associated with the current plan. Forest Practice Rules related to these features were nearly always found to be out of compliance, usually due to drainage feature problems. Specifically, these problems were most often related to having: 1) inadequate size, number, and location of drainage structures to carry runoff water and minimize erosion, and 2) inadequate waterbreak spacing and waterbreak discharge into cover. About six percent of all evaluated drainage structures had problem points assigned to them. Gullies delivered sediment to channels about 24.5 percent of the time and rills about 12.6 percent of the time.

The monitoring results reported here are consistent with those described by MacDonald and Coe (2001—see the Related Studies section of this report). For their sites in the Central Sierra Nevada Mountains, they found that 16 percent of the segments and 20 percent of the road length had gullies or sediment plumes that were within 10 meters (32.8 feet) of a stream channel. In this study, contributing surface area multiplied by slope (A*S) was the best predictor of road surface erosion, and decreasing A*S by improving and maintaining road drainage was recommended to reduce erosion on native surfaced roads. In other words, proper spacing of rolling dips, waterbreaks, and where necessary, culvert cross drains, is a key component to reducing road surface erosion. Numerous publications have described techniques to reduce road surface erosion (see for example Burroughs and King 1989).

Hillslope monitoring results in Oregon are also consistent with data collected in California. Robben and Dent (2002) report that non-compliance with road related BMPs, especially drainage and maintenance requirements, was the largest source of sediment delivery to stream channels in their BMP compliance monitoring project. They also state that because the surveys were performed in the dry season, they likely underestimated the number of sediment delivery sources and total eroded volume. Skaugset and Allen (1998) stated that relief of road drainage at stream crossings was the most common source of sediment delivery in western Oregon. This study found that 25 percent of the surveyed road length delivered sediment directly to a stream channel. Additionally, Luce and Black (1999) found that sediment production was related to road surfaces, unvegetated ditches, and cutslope lengths draining to stream channels.

[28] This estimate was made based on field work conducted in Humboldt County.

Watercourse protection zones provide for adequate retention of post-harvest canopy and surface cover, and for prevention of harvesting related erosion.

Class I watercourses made up approximately 17 percent of the evaluated watercourses, 56 percent were Class IIs, and 27 percent were Class IIIs. Statewide, mean post-harvest total canopy cover exceeded 70 percent, regardless of instrument used for measurement. Mean total canopy exceeded Forest Practice Rule requirements in all three Forest Practice Districts, and was approximately 80 percent in the Coast Forest Practice District for both Class I and II watercourses. Surface cover exceeded 75 percent for all watercourse types in all three Forest Practice Districts. Required WLPZ widths generally met Rule requirements, with major departures from Rule requirements recorded only about one percent of the time. Additionally, the frequency of erosion events related to current timber operations in watercourse protection zones was very low for Class I, II, and III watercourses.

These results are consistent with the Modified Completion Report Monitoring program data collected by CDF Forest Practice Inspectors discussed earlier in the Related Studies section (Brandow 2002). Canopy measurements were remarkably similar for Class I and II watercourses in all three Forest Practice Districts. Similarly, erosion features related to the current operations in Class I and II WLPZs have been very rare.

With the federal listing of coho salmon as a threatened species in 1997 for the Southern Oregon/Northern California Coasts Coho ESU, it has been a common practice in the Coast Forest Practice District to either have 70 percent post-harvest canopy in Class I watercourses (CDF 1997) or prescribe no-harvest zones.[29] Greatly reduced harvesting within WLPZs has also been a common practice for interior area THPs in recent years. However, total canopy cover in the interior area is lower than on the Coast, which is probably due to past harvesting, slower conifer growth rates, and drier growing conditions for understory vegetation.

The monitoring work described in this report does not allow conclusions to be made regarding instream channel conditions for fish habitat (CSBOF 1999), and evaluating the biological significance of the Rules was not part of this program. For example, no relationship between post-harvest canopy levels and acceptable water temperatures for coldwater fish species can be determined from the data collected in this study. This type of monitoring has been and is currently being conducted in numerous locations throughout the state (see for example Lewis et al. 2000 and James 2001). Instream sediment production from timber operations conducted under the modern Forest Practice Rules, and impacts to macroinvertebrate communities and anadromous fish are available from the Caspar Creek watershed study (see Lewis et al. 2001, Rice et al. 2002, Bottorff and Knight 1996, Nakamoto 1998, and the summary provided in the

---

[29] The July 2000 Threatened and Impaired Watersheds Rule Package approved by the BOF requires at least 85 percent overstory canopy post-harvest for the first 75 feet for planning watersheds with listed or candidate anadromous salmonid species, but THPs accepted by CDF after July 1, 2000 (when the Rule package went into effect) have not been included in the plans evaluated by the Hillslope Monitoring Program to date.

Related Studies section of this report). Additionally, research is underway by Drs. Mary Ann Madej (USGS) and Peggy Wilzbach (HSU) on the relative importance of size-specific, inorganic vs. organic components of the suspended load of streams and the influence of these components on stream health, as reflected in the efficiency of growth of juvenile salmonids and their invertebrate food base. This work is being conducted in the Caspar Creek and Redwood Creek watersheds of California. Data on large wood loading and recruitment in second-growth redwood/Douglas-fir watersheds found in the Coast Forest Practice District is available in Benda et al. (2002).

Landings and skid trails are not producing substantial impacts to water quality.

Erosion problems on landing surfaces, cut slopes, and fill slopes were relatively rare. Only about 11 percent of the landings evaluated were assigned problem points and the largest category of these occurrences was related to rills or gullies that formed from concentrated runoff below the outlet of a landing surface drainage structure. Dry season evidence of sediment delivery from landing surface drainage and fill slope erosion features to watercourse channels was recorded only seven and six times, respectively, from 569 landings.

Rill and gully erosion features on skid trails were found to deliver sediment to watercourse channels 3.8 percent and 13 percent of the time, respectively. Nearly all of these erosion problems were related to improper implementation of FPRs specifying installation of drainage structures. Low rates of sediment delivery from skid trails with properly installed and functioning drainage structures are not surprising, since earlier work in California has shown that skid trails used under the current Forest Practice Rules have not had a large impact on water quality. For example, Euphrat (1992) studied sediment transport related to timber harvesting in the Mokelumne River watershed in the central Sierra Nevada Mountains. The data he collected on numerous skid trails revealed that sediment was not transported to watercourses, and the data implied that relatively little material flowed off other well drained skid trail segments. Additionally, data collected by MacDonald and Coe (2001) in the central Sierra Nevada Mountains has shown that most harvest units (primarily tractor logged with skid trails) and landings produced relatively little sediment. Recently, Benda (2002) reported no erosion off well drained skid trails at the Southern Exposure research site in the Antelope Creek watershed in Tehama County.

The frequency of erosion events has decreased substantially in the last three years of the program.

The numbers of rills, gullies, mass failures and cutbank/sidecast sloughing features found on road, skid trail, and watercourse protection zone transects and the number of large erosion events decreased for the period from 1999 through 2001 when compared to 1996 through 1998. The primary reason for this decrease is probably reduced storm size, intensity, and frequency after the winter of 1997/1998. The January 1997 storm produced a 100-year discharge event in many Sierra Nevada Mountain watersheds, and was also a very significant event in the Coast Forest Practice District. For example, in southern Humboldt County in the Bull Creek basin, the January 1997 event is the flood of record, surpassing even the legendary December 1964 flood. The following winter of 1997/1998 (water year 1998) was a strong El Niño winter, with large, nearly continuous storm events. This hydrologic year produced the winter of record for total precipitation in the Caspar Creek watershed and produced numerous legacy road related landslide features in the South Fork basin (Cafferata and Spittler 1998). Maximum annual instantaneous peak discharge values for three free flowing stream systems located throughout Northern and Central California are displayed in Figure 23 and show much higher values in water years 1995, 1996, and 1997, when compared to those that occurred in 1998 through 2001. Therefore, it is possible to conclude that the Hillslope Monitoring Program study period has included large stressing storm events that have tested the Forest Practice Rules related to water quality—particularly in the first three years of the project.

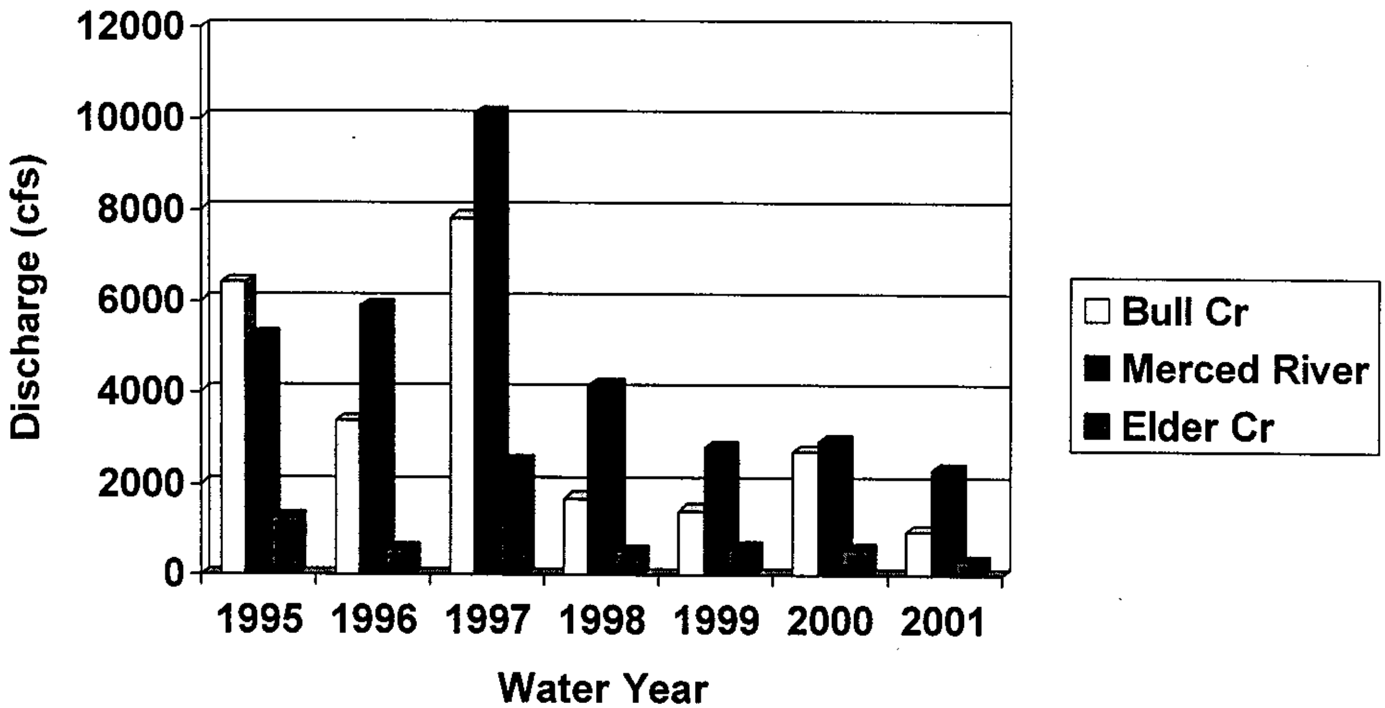

Figure 23. Stream gauging station maximum annual instantaneous peak discharge data for three free flowing river systems. The Merced River at Happy Isles is located in Yosemite National Park in the central Sierra Nevada Mountains, Bull Creek is located in southern Humboldt County, and Elder Creek is located in western Mendocino County.

The connection between storm size and intensity and the frequency of erosion features is supported by the results that Coe and MacDonald (2002), who noted large interannual variability in sediment production rates over three years of monitoring at their central Sierra Nevada sites, and attributed these differences to the magnitude and type of the precipitation. For example, sediment production for the 1999-2000 winter was 3 to 11 times higher than the sediment production rates for the 2000-2001 winter.

Additional reasons for reduced erosion feature frequency for the second three year period include increased familiarity with field methods and a change in the THP selection process. The lead contractor for the project, Mr. Roger Poff, has stated that rilling on road and skid trail transects may have been overestimated during the first two years (1996 and 1997) of the project, primarily because of the complexity of the data recording process and the learning curve required to successfully complete adequate data collection. Rills were not usually measured to determine if they met the stated criteria for this type of feature and were probably tallied too frequently (R.J. Poff, personal communication). Also, there were more small non-industrial landowner THPs and NTMP projects, with generally smaller plan size for the period from 2000 to 2001, which probably reduced the opportunity for finding the various types of erosion features.

The Hillslope Monitoring Program results to date are similar to data collected on CDF violations for THPs related to water quality.

Water quality violations of the Rules are identified and corrected, where possible, as part of the normal CDF Forest Practice Inspection process. Information from CDF's Forest Practice Program Database shows that 975 violations were issued on the 4,749 THPs open from 1998 through 2000.[30] These violations can be separated into three basic groups: harvesting practices and erosion control (347), watercourse and lake protection (308), and logging roads and landings (320). The FPRs with the highest number of violations generally involved waterbreak requirements, timber operations in the winter period, proper removal of temporary crossings, roads and landings located outside of WLPZs, removal of debris from very small watercourses, WLPZ trees felled away from the watercourse, removal of accidental depositions in watercourses, crossings open to unrestricted passage of water, size/number/location of drainage structures adequate to minimize erosion, and crossing removal adequate to prevent erosion. This type of information complements the data from the Hillslope Monitoring Program and CDF's Modified Completion Report monitoring work. Together, these three independent data sources allow cross-checking and corroboration of the results of each type of monitoring (Ice et al. 2002).

[30] This data analysis was completed by Mr. Clay Brandow, CDF, Sacramento.

Several reasons exist for why THPs with approved Work Completion Reports can have relatively high percentages of total departures from Forest Practice Rule requirements.

The deviations from the FPRs reported in the 1999 Interim Report (CSBOF 1999) for THPs with approved Work Completion Reports has prompted criticism of the adequacy of the CDF's inspection and enforcement program (see for example, Stillwater Sciences 2002). Reasons for these post-inspection Rule problems include:

- CDF Forest Practice Inspectors focus on the whole THP to identify threats to water quality and often will not find minor departures. Most of the Rule departures associated with problem points in the six years of hillslope monitoring have been minor departures with little or no direct impact to water quality. Of all the total number of departures for the problem point sites, 76.5 percent have been minor and 23.5 percent major departures. The category with the highest percentage of major departures is watercourse crossings, with approximately 49 percent major departures at identified problem points.

- CDF inspectors must balance the time necessary to enforce the repairing of a single or small problem against forgone inspections on other plans where there may be significant numbers of problems or a significant consequence from a problem.

- Some FPRs are qualitative in nature, and a minor deviation identified in the Hillslope Monitoring Program when an erosion feature is found would not necessarily trigger a rule violation by CDF during an inspection before the erosion occurred. A common example of this type of Rule is 14 CCR 923.2(h) [943.2(h), 963.2(h)], which requires drainage structures of sufficient size, number and location to minimize erosion.

- In the Hillslope Monitoring Program, major departures are assigned for sediment delivery with or without a significant departure from Rule requirements.

Several steps have been taken to improve implementation of the FPRs related to water quality since 1999. These include implementation of the Modified Completion Report monitoring process by CDF Forest Practice Inspectors in 2000 (see discussion on this program in the Related Studies section of this report), BOF passage of a rule requiring RPF supervision of active logging operations in 2000,[31] and information dissemination/ training related to monitoring results provided to CDF Foresters and RPFs in California.

[31] This Rule was passed by the BOF in 2000 and went into effect on January 1, 2001. See 14 CCR 1035.1, Registered Professional Forester Responsibility.

Preliminary results on the use of non-standard practices and additional mitigation measures indicate the need for more thorough inspection and a more focused study design to adequately examine the implementation and effectiveness of these practices.

The determination of whether proposed non-standard practices (i.e., alternatives, in-lieus, exceptions, etc., collectively referred to as non-standard practices) and additional mitigation measures are appropriate for a given site is a major component of the Timber Harvesting Plan Review Process, so there is clearly a need for monitoring the adequacy of these practices. However, the focus of the Hillslope Monitoring Program has been on evaluating the adequacy of standard Forest Practice Rules, so results from the limited data collected on non-standard practices should be considered as preliminary.

The data collected to date show that existing or potential problems were found on approximately 15 percent of road transects, 7 percent of landings, 11 percent of crossings, 9 percent of skid trail transects, and 8 percent of watercourse protection zone transects where non-standard practices and additional mitigation measures were prescribed. Improper implementation of these practices was 13 percent on roads, 25 percent on skid trails, 4 percent on landings, 15 percent at crossings, and 5 percent for watercourse protection zones. These results are consistent with the findings for the standard Forest Practice Rules for watercourse protection zone transects, with both standard and non-standard Rules having high overall implementation ratings and few problems. Additionally, these preliminary results suggest that better implementation of non-standard practices could be achieved with more thorough inspection by RPFs and CDF Forest Practice Inspectors.

The California Forest Practice Rule requirements with the lowest overall implementation related to water quality have been identified and education efforts related to these Rules are required.

To focus on areas where improvement in Rule design or implementation would provide the greatest benefits to water quality, Table 46 summarizes the 20 Forest Practice Rule requirements with four percent or more major departures (the table shows 24 Rule requirements, but one Rule was cited for both roads and landings[32], and three Rules were cited for both roads and crossings). The need for improved implementation of these Rule requirements, in particular, should be made known to RPFs, LTOs, and CDF Forest Practice Inspectors. Seven rule requirements relate to roads, one to skid trails, two to landings, 13 to watercourse crossings, and one to watercourse protection zones.

[32] Note that 14 CCR 923.1(a) is a THP mapping requirement and does not directly cause an adverse impact water quality.

Table 46. Forest Practice Rule requirements with at least four percent major departures based on at least 30 observations where implementation could be rated (note this table was developed from Tables 6, 14, 22, 25, and 29).

Location	Rule No.	Description of Rule	Major Departure %
Roads	914.6(f)	where waterbreaks do not work--other erosion controls installed	4.2
Roads	923.1(f)	adequate numbers of drainage structures to minimize erosion	4.8
Roads	923.2(h)	size, number, and location of structures sufficient to carry runoff water	5.3
Roads	923.1(a)	landing on road greater than ¼ acre or requiring substantial excavation--shown on THP map	11.5
Roads	923.2(h)	size, number, and location of structures sufficient to minimize erosion	4.1
Roads	923.2(d) Coast	fills constructed with insloping approaches, berms, rock armoring, etc., to minimize erosion	4.7
Roads	923.2(m)	sidecast extending greater than 20 feet with access to a watercourse protected by a WLPZ treated to reduce erosion	7.4
Skid Trails	914.6(c)	waterbreak spacing equals standards	5.6
Landings	923.1(a)	landings greater than ¼ acre or requiring substantial excavation--shown on THP map	10.9
Landings	923.5(f)(4)	sidecast or fill extending greater than 20 feet with access to watercourse—treated to reduce erosion	4.3
Crossings	923.2(o)	no discharge on fill unless suitable energy dissipators are used	12.6
Crossings	923.2(h)	size, number, and location of structures minimizes erosion	11.2
Crossings	923.2(d) Coast	fills across channels built with insloping approaches, berms, rock armoring, etc., to minimize erosion	9.8
Crossings	923.4(n)	crossing/approaches maintained to avoid diversion	4.0
Crossings	923.8	abandonment—minimize concentration of runoff	4.6
Crossings	923.3(e)	crossing/fills built to prevent diversion	5.5
Crossings	923.4(d)	crossing open to unrestricted passage of water	4.0
Crossings	923.8(d)	abandonment--pulling/shaping of fills	9.8
Crossings	923.8(c)	abandonment--grading of road for dispersal of water flow	4.8
Crossings	923.3(d)(2)	removed--cut bank sloped back to prevent slumping and to minimize soil erosion	6.3
Crossings	923.8(b)	abandonment--stabilization of exposed cuts/fills	4.8
Crossings	923.2(h)	size, number, location of structures sufficient to carry runoff	7.1
Crossings	923.8(e)	abandonment--fills excavated to reform channel	5.1
WLPZs	916.2(a)(4)	sensitive conditions--existing roads in WLPZ—appropriate mitigation measure(s) applied	4.5

Recommendations

Based on the results compiled from six years of Hillslope Monitoring Program data, we recommend the following items:

TRAINING

1. Develop robust training programs based on monitoring results for LTOs, RPFs, CDF Forest Practice Inspectors, and members of other reviewing agencies. Training program agendas will be tailored to the needs of the various targeted audiences.

2. Require more thorough and consistent inspection of watercourse crossings by CDF Forest Practice Inspectors and other reviewing agencies based on the above training programs.

3. Inform CDF Forest Practice Inspectors on monitoring results at the annual CDF Forest Practice enforcement training course in Fort Bragg. Note that while the course is offered annually, each Inspector attends the class every four years. Additionally, inform CDF Forest Practice Inspectors of monitoring results and needed improvements at annual forester meetings.

4. Develop a Licensed Timber Operator (LTO) implementation guidance document for installation of watercourse crossings and road drainage structures. This effort should be coordinated with the other reviewing agencies, particularly the California Department of Fish and Game. The goal is to produce a relatively simple document that quickly and simply illustrates the most important principles for successful crossing and drainage structure design and installation. For example, some of the concepts to include for crossings would be proper: gradient, alignment, diversion potential, pipe length, armoring, etc.

5. Raise awareness of key hillslope monitoring findings to forest landowners, the public, Licensed Timber Operators, RPFs, and other interested parties. This is to be accomplished through updates provided to the BOF's Licensing News, the CLFA Update, CDF Mass Mailings to RPFs, and other regularly produced newsletters.

6. Work with the California Licensed Foresters Association (CLFA), Associated California Loggers (ACL), Forest Landowners of California (FLOC), the California Forestry Association (CFA), and other forestry related trade associations to develop workshops that address key issues identified through hillslope monitoring. For example, a CLFA workshop on watercourse crossings is scheduled for March, 2003.

ROAD MANAGEMENT PLAN

7. Upgrade those watercourse crossings with problems, including old, existing structures, with a voluntary, cooperative Road Management Plan, including an agreed to schedule to complete upgrading work.

MODIFICATIONS FOR THE HILLSLOPE MONITORING PROGRAM

8. Revise the Hillslope Monitoring Program to adequately examine: 1) additional mitigation measures applied to THPs, and 2) non-standard practices applied to THPs (including in-lieu and alternative practices).

9. Revise the Hillslope Monitoring Program to: 1) address the changes in the Forest Practice Rules since the BOF passed the Threatened and Impaired Watersheds Rule Package in July 2000, and 2) reduce emphasis on semi-qualitative assessments by conducting more rigorous and scientifically defensible tests of individual practice effectiveness (e.g., pre and post-harvest, overstory/understory, conifer/hardwood canopy data; detailed information on watercourse crossings built as part of the current plan under the Threatened and Impaired Watersheds Rule Package, allowing for passage of wood and sediment as well as 100-year flood flows; and detailed information on newly constructed road drainage structures, including contributing surface area, slope, surfacing, grading, erosion problems, sediment delivery, etc.).

WORK NEEDED TO COMPLEMENT THE HILLSLOPE MONITORING PROGRAM

10. Continue to support the implementation and funding of instream monitoring projects that have a peer-reviewed study design, including pre-project data collection, to answer questions about Forest Practice Rule effectiveness and compliance with Regional Water Quality Control Board Basin Plan standards.

Literature Cited

Benda, L.E. 2002. Southern Exposure Study: wood recruitment and erosion studies. Power Point presentation to the California State Board of Forestry and Fire Protection, November 2002 Meeting, Sacramento, CA.

Benda, L.E., P. Bigelow, T.M. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, Northern California, U.S.A. Can. J. For. Res. 32: 1460-1477. In press.

Bottorff, R.L. and A.W. Knight. 1996. The effects of clearcut logging on stream biology of the North Fork of Caspar Creek, Jackson Demonstration State Forest, Fort Bragg, CA -- 1986 to 1994. Unpubl. Final Rept. prepared for the California Department of Forestry and Fire Protection, Contract No. 8CA63802. May 1996. Sacramento, CA. 177 p. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Brandow, C. 2002. Modified Completion Report Monitoring Update—Power Point Presentation prepared for the California State Board of Forestry and Fire Protection's Monitoring Study Group meeting held at the CDF Mendocino Unit Headquarters—Howard Forest, located near Willits, CA, September 17, 2002.

Burroughs, E.R. and J.G. King. 1989. Reduction of soil erosion on forest roads. Gen. Tech. Rep. INT-264. Ogden, UT. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 21 p.

Cafferata, P.H. and T.E. Spittler. 1998. Logging impacts of the 1970's vs. the 1990's in the Caspar Creek watershed. In: Ziemer, R.R., technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story, 1998 May 6; Ukiah, CA. General Tech. Rep. PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. P. 103-115. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

California Department of Forestry and Fire Protection (CDF). 1997. Coho salmon (*Oncorhynchus kisutch*) considerations for timber harvests under the California Forest Practice Rules. CDF Mass Mailing to all RPFs dated April 29, 1997. Sacramento, CA. 49 p.

California State Board of Forestry (CSBOF). 1993. Assessing the effectiveness of California's Forest Practice Rules in protecting water quality: recommendations for a pilot monitoring project and longer term assessment program. Prepared by the Monitoring Study Group (MSG) with assistance from William M. Kier Associates. Sacramento, CA. 55 p.

California State Board of Forestry and Fire Protection (CSBOF). 1999. Hillslope monitoring program: monitoring results from 1996 through 1998. Interim Monitoring Study Group Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, CA. 70 p. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

California State Board of Forestry and Fire Protection (CSBOF). 2000. Monitoring Study Group Strategic Plan. Sacramento, CA. 24 p. http://www.fire.ca.gov/bof/board/msg_strplan.html

California State Water Resources Control Board (CSWRCB). 1987. Final report of the Forest Practice Rules assessment team to the State Water Resources Control Board (the "208 Report"). Sacramento, CA. 200 p.

Coe, D. and L.H. MacDonald. 2001. Sediment production and delivery from forest roads in the Central Sierra Nevada, California. Eos Trans. American Geophysical Union, 82(47), Fall Meeting Suppl., Abstract H51F-03. http://www.agu.org/meetings/waisfm01.html

Coe, D. and L.H. MacDonald. 2002. Magnitude and interannual variability of sediment production from forest roads in the Sierra Nevada, California. Poster Session Abstract, Sierra Nevada Science Symposium 2002, October 7-10, 2002, Lake Tahoe, CA. http://danr.ucop.edu/wrc/snssweb/post_aquatic.html

Dodge, M., L.T. Burcham, S. Goldhaber, B. McCulley, and C. Springer. 1976. An investigation of soil characteristics and erosion rates on California forest lands. Final Report, Department of Conservation, Division of Forestry. Sacramento, CA. 105 p.

Durgin, P.B., R.R. Johnston, and A.M. Parsons. 1989. Critical sites erosion study. Tech. Rep. Vol. I: Causes of erosion on private timberlands in Northern California: Observations of the Interdisciplinary Team. Cooperative Investigation by CDF and USDA Forest Service Pacific Southwest Forest and Range Experiment Station. Arcata, CA. 50 p.

Euphrat, F.D. 1992. Cumulative impact assessment and mitigation for the Middle Fork of the Mokelumne River, Calaveras County, California. Unpublished Ph.D. dissertation, University of California, Berkeley. 107 p.

Euphrat, F., K.M. Kull, M. O'Connor, and T. Gaman. 1998. Watershed assessment and cooperative instream monitoring plan for the Garcia River, Mendocino County, California. Final Report submitted to the Mendocino Co. Resource Conservation District and the California Department of Forestry and Fire Protection. Sacramento, CA. 112 p.

Flanagan, S.A., M.J. Furniss, T.S. Ledwith, S.Thiesen, M. Love, K.Moore, and J. Ory. 1998. Methods for inventory and environmental risk assessment of road drainage crossings. USDA Forest Service. Technology and Development Program. 9877--1809—SDTDC. 45 p. http://www.stream.fs.fed.us/water-road/w-r-pdf/handbook.pdf

Gucinski, H., M.J. Furniss, R.R. Ziemer, and M.H. Brookes, editors. 2001. Forest roads: a synthesis of scientific information. USDA Forest Service General Technical Report PNW-509. Portland, Oregon: Pacific Northwest Research Station, Forest Service, U.S. Department of Agriculture. 103 p. http://www.fs.fed.us/pnw/pubs/gtr509.pdf

Ice, G., L. Dent, J. Robben, P. Cafferata, J. Light, B. Sugden, and T. Cundy. 2002. Programs assessing implementation and effectiveness of state forest practice rules and BMPs in the west. Paper prepared for the Forestry Best Management Practice Research Symposium, April 15-17, 2002, Atlanta, GA. Journal of Water, Air and Soil Pollution Focus. In press. 24 p.

James, C. 2001. Background information on research conducted at Southern Exposure research site. Document produced for the State Board of Forestry and Fire Protection for the October 2001 meeting. Sierra Pacific Industries, Redding, CA. 15 p.

Johnson, R. D. 1993. What does it all mean? Environmental Monitoring and Assessment 26: 307-312.

Knopp, C. 1993. Testing indices of cold water fish habitat. Unpublished Final Report submitted to the North Coast Regional Water Quality Control Board and the California Department of Forestry under Interagency Agreement No. 8CA16983. Sacramento, CA. 56 p. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

Koehler, R.D., K.I. Kelson, and G. Mathews. 2001. Sediment storage and transport in the South Fork Noyo River watershed, Jackson Demonstration State Forest. Final Report submitted to the California Department of Forestry and Fire Protection, Sacramento, CA. Report Prepared by William Lettis and Associates, Walnut Creek, CA. 29 p. plus figures and tables.

Lee, G. 1997. Pilot monitoring program summary and recommendations for the long-term monitoring program. Final Report submitted to the California Department of Forestry. CDF Interagency Agreement No. 8CA27982. Sacramento, CA. 69 p. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

Lemmon, P.E. 1956. A spherical densiometer for estimating forest overstory density. Forest Science 2(1): 314-320.

Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and sediment transport in the Caspar Creek watersheds. In: Ziemer, R.R., technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story, 1998 May 6; Ukiah, CA. General Tech. Rep. PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. P. 55-69. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Lewis, J. 2002. Hydrologic data for the Caspar Creek watershed study—Power Point Presentation prepared for the Annual Caspar Creek Watershed Study Meeting, Fort Bragg, CA, May 9, 2002. USDA Forest Service, Pacific Southwest Research Station, Arcata, CA.

Lewis, T.E., D.W. Lamphear, D.R. McCanne, A.S. Webb, J.P. Krieter, and W.D. Conroy. 2000. Regional assessment of stream temperatures across northern California and their relationship to various landscape-level and site-specific attributes. Forest Science Project, Humboldt State University Foundation, Arcata, CA. 400 p.

Lewis, J. and J. Baldwin. 1997. Statistical package for improved analysis of hillslope monitoring data collected as part of the Board of Forestry's long-term monitoring program. Unpublished Final Report submitted to the California Department of Forestry and Fire Protection under Agreement No. 8CA95056. Sacramento, CA. 50 p. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

Lewis, J., S.R. Mori, E.T. Keppeler, and R.R. Ziemer. 2001. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. In: M.S. Wigmosta and S.J. Burges (eds.) Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. Water Science and Application Volume 2, American Geophysical Union, Washington, D.C. P. 85-125. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Lewis, J. and R. Rice. 1989. Critical sites erosion study. Tech. Rep. Vol. II: Site conditions related to erosion on private timberlands in Northern California: Final Report. Cooperative Investigation by the California Department of Forestry and the USDA Forest Service Pacific Southwest Forest and Range Experiment Station, Arcata, CA. 95 p.

Lisle, T.E. 1993. The fraction of pool volume filled with fine sediment in northern California: relation to basin geology and sediment yield. Final Report submitted to the California Department of Forestry. Sacramento, CA. 9 p.

Lisle, T. E., and S. Hilton. 1999. Fine bed material in pools of natural gravel bed channels. Water Resources Research 35(4):1291-1304. http://www.fire.ca.gov/bof/pdfs/Lisle99WR35_4.pdf

Luce, C.H. and T.A. Black. 1999. Sediment production from forest roads in western Oregon. Water Resources Research 35(8): 2561-2570.

Maahs, M. and T.J. Barber. 2001. The Garcia River instream monitoring project. Final Report submitted to the California Department of Forestry and Fire Protection. Mendocino Resource Conservation District, Ukiah, CA. 96 p. http://www.fire.ca.gov/bof/pdfs/Garcia_River_Instream.pdf

MacDonald, L.H. and D. Coe. 2001. Sediment Production and Delivery from Forest Roads in the Central Sierra Nevada, California. Progress Report dated January 2001 submitted to the USDA Forest Service, Pacific Southwest Region, Vallejo, CA. 17 p.

Madej, M.A. 2001. Erosion and sediment delivery following removal of forest roads. Earth Surface Processes and Landforms 26: 175-190.

Marshall, G. 2002. Rapid review of engineering geologic conditions for specific Timber Harvesting Plans in the Elk River watershed. California Division of Mines and Geology Memorandum submitted to Mr. Ross Johnson, Deputy Director for Resource Management, California Department of Forestry and Fire Protection. Memorandum dated January 11, 2002. 32 p.

McKittrick, M.A.. 1994. Erosion potential in private forested watersheds of northern California: a GIS model. Unpublished final report prepared for the California Department of Forestry and Fire Protection under interagency agreement 8CA17097. Sacramento, CA. 70 p. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

Nakamoto, R. 1998. Effects of timber harvest on aquatic vertebrates and habitat in the North Fork Caspar Creek. In: Ziemer, Robert R., technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story, 1998 May 6; Ukiah, CA. General Tech. Rep. PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. P. 87-95. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Pacific Watershed Associates (PWA). 1998a. Sediment source investigation and sediment reduction plan for the Bear Creek watershed, Humboldt County, California. Unpublished Report prepared for the Pacific Lumber Company. Arcata, CA. 42 p. plus appendices and maps.

Pacific Watershed Associates (PWA). 1998b. Sediment source investigation and sediment reduction plan for the North Fork Elk River watershed, Humboldt County, California. Unpublished Report prepared for the Pacific Lumber Company. Arcata, CA. 50 p. plus appendices and maps.

Poff, R.J. and C. Kennedy. 1999. Pilot study of Class III watercourses for the hillslope monitoring Program. Final report submitted to the California Department of Forestry and Fire Protection. Sacramento, CA. 6 p.

Rae, S.P. 1995. Board of Forestry pilot monitoring program: instream component. Unpubl. Rept. submitted to the California Department of Forestry under Interagency Agreement No. 8CA28103. Sacramento, CA. Volume One. 49. p. Volume Two - data tables and training materials.

Reid, L.M. and M.J. Furniss. 1999. On the use of regional channel-based indicators for monitoring. Unpublished draft paper. USDA Forest Service Pacific Northwest Research Station, Corvallis, OR.

Rice, R.M. and P.A. Datzman. 1981. Erosion associated with cable and tractor logging in northwestern California. In: Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS Publ. 132. Christchurch, New Zealand. P. 362-374. http://www.rsl.psw.fs.fed.us/projects/water/IAHS132rice.pdf

Rice, R.M. and J. Lewis. 1991. Estimating erosion risks associated with logging and forest roads in northwestern California . Water Resources Bulletin 27(5): 809-818. http://www.rsl.psw.fs.fed.us/projects/water/RiceLewis91.pdf

Rice, R.M., F.B. Tilley, and P.A. Datzman. 1979. A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. USDA Forest Service Research Paper PSW-146. Berkeley, California: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 12 p. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Rice, R.M., R.R. Ziemer, and J. Lewis. In press. Evaluating forest management effects on erosion, sediment, and runoff: Caspar Creek and northwestern California. Chapter in: Lessons from the Grandmasters of Watershed Management. Society of American Foresters monograph. Bethesda, Maryland: Society of American Foresters. 18 p. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Robards, T.A, M.W. Berbach, P.H. Cafferata, and B.E. Valentine. 2000. A comparison of techniques for measuring canopy in watercourse and lake protection zones. Calif. Forestry Note No. 115. California Department of Forestry and Fire Protection, Sacramento, CA. 15 p.

Robben, J. and L. Dent. 2002. Oregon Department of Forestry Best Management Practices Compliance Monitoring Project: Final Report. Oregon Department of Forestry Forest Practices Monitoring Program, Technical Report 15. Salem, OR. 68 p.

Robison, E.G., K.A. Mills, J. Paul, L. Dent, and A. Skaugset. 1999. Storm impacts and landslides of 1996: Final Report. Oregon Department of Forestry. Forest Practices Technical Report No. 4. Salem, OR. 145 p.

Skaugset, A. and M.M. Allen. 1998. Forest road sediment and drainage monitoring project. Report for private and state lands in western Oregon. Oregon Department of Forestry, Salem, OR. 20 p.

Spittler, T.E. 1995. Geologic input for the hillslope component for the pilot monitoring program. Unpublished Final Report submitted to the California Department of Forestry under Interagency Agreement No. 8CA38400. Sacramento, CA. 18 p. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

Staab, B. 2002. USDA Forest Service water quality management program. Power Point Presentation prepared for the Central Valley Regional Water Quality Control Board Silvicultural Waivers Workshop, September 5, 2002, Redding, CA. USDA Forest Service, Pacific Southwest Region, Vallejo, CA.

Stillwater Sciences. 2002. Review of the Hillslope Monitoring Program report addressing the effectiveness of Forest Practice Rules in preventing sediment input to streams. Unpublished report presented to the State Water Resources Control Board hearing on SB 390, waivers for waste discharge requirements, July 17, 2002, Sacramento, CA. 5 p.

Strickler, G.S. 1959. Use of the densiometer to estimate density of forest canopy on permanent sample plots. USDA Forest Service Research Note PNW 180. Portland, Oregon: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture. 5 p.

Tuttle, A.E. 1995. Board of Forestry pilot monitoring program: hillslope component. Unpubl. Rept. submitted to the California Department of Forestry and the State Board of Forestry under Contract No. 9CA38120. Sacramento, CA. 29 p. Appendix A and B - Hillslope Monitoring Instructions and Forms. http://www.fire.ca.gov/bof/board/msg_supportedreports.html

U.S. Forest Service (USFS). 1992. Investigating water quality in the Pacific Southwest Region: best management practices evaluation program - user's guide. Region 5. San Francisco, CA 158 p.

Weaver, W.E. 2001. Testimony to the State Water Resources Control Board regarding monitoring requirements for Timber Harvesting Plan 1-97-520 HUM, Pacific Lumber Company, June 25-26, 2001. Sacramento, CA.

Weaver, W.E. and D.K. Hagans. 1994. Handbook for forest and ranch roads. Final Report prepared for the Mendocino Resource Conservation District, Ukiah, CA. 161 p.

Ziemer, R.R., technical coordinator. 1998. Proceedings of the conference on coastal watersheds: the Caspar Creek story. 1998 May 6; Ukiah, CA. General Tech. Rep. PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. 149 p. http://www.rsl.psw.fs.fed.us/projects/water/caspubs.html

Glossary

Abandonment – Leaving a logging road reasonably impassable to standard production four wheel-drive highway vehicles, and leaving a logging road and landings, in a condition which provides for long-term functioning of erosion controls with little or no continuing maintenance (14 CCR 895.1).

Alternative practice – Prescriptions for the protection of watercourses and lakes that may be developed by the RPF or proposed by the Director of CDF on a site-specific basis provided that several conditions are complied with and the alternative prescriptions will achieve compliance with the standards set forth in 14 CCR 916.3 (936.3, 956.3) and 916.4(b) [(936.4(b), 956.4(b)]. 14 CCR 916.6 (936.6, 956.6). More general alternative practices are permitted under 14 CCR 897(e).

Beneficial uses of water – As described in the Porter-Cologne Water Quality Control Act, beneficial uses of water include, but are not limited to: domestic, municipal, agricultural, and industrial supply; power generation; recreation; aesthetic enjoyment; navigation; and preservation and enhancement of fish and wildlife, and other aquatic resources or preserves. In Water Quality Control Plans, the beneficial uses designated for a given body of water typically include: domestic, municipal, agricultural, and industrial supply; industrial process; water contact recreation and non-water contact recreation; hydropower generation; navigation; groundwater recharge; fish spawning, rearing, and migration; aquatic habitat for warm-water species; aquatic habitat for coldwater species; and aquatic habitat for rare, threatened, and/or endangered species (Lee 1997).

Best management practice (BMP) - A practice or set of practices that is the most effective means of preventing or reducing the generation of nonpoint source pollution from a particular type of land use (e.g., silviculture) that is feasible, given environmental, economic, institutional, and technical constraints. Application of BMPs is intended to achieve compliance with applicable water quality requirements (Lee 1997).

Canopy - the foliage, branches, and trunks of vegetation that blocks a view of the sky along a vertical projection. In the Hillslope Monitoring Program, this was estimated from 1996 through1998 with a spherical densiometer and from 1999 through 2001 with a sighting tube. The Forest Practice Rules define canopy as "the more or less continuous cover of branches and foliage formed collectively by the crowns of adjacent trees and other woody species" (14 CCR 895.1).

Cutbank/sidecast sloughing – Shallow, surficial sliding associated with either the cutbank or fill material along a forest road or skid trail, with smaller dimensions than would be associated with mass failures.

Feature - Any constructed component of a landing, road, skid trail, or watercourse crossing (e.g., cut bank, fill slope, inside ditch, cross drain, water break).

Exception – A non-standard practice for limitations on tractor operations (14 CCR 914.2(f)(3), 934.2(f)(3), 954.2(f)(3)).

Gully - Erosion channels deeper than 6 inches (no limitation on length or width). Gully dimensions were estimated.

In-lieu practice – These practices apply to Rule sections for watercourse protection where provision is made for site specific practices to be proposed by the RPF, approved by the Director and included in the THP in lieu of a stated Rule. The RPF must reference the standard Rule, explain and describe each proposed practice, how it differs from the standard practice, indicate the specific locations where it will be applied, and explain and justify how the protection provided by the proposed practice is at least equal to the protection provided by the standard Rule (14 CCR 916.1, 936.1, 956.1).

Large erosion event - These events were defined for the Hillslope Monitoring Program as 100 cubic yards for a mass failure void left on a hillslope, or at least 10 cubic yards for catastrophic crossing failures.

Mass failure – Downslope movement of soil and subsurface material that occurs when its internal strength is exceeded by the combination of gravitational and other forces. Mass erosion processes include slow moving, deep-seated earthflows and rotational failures, as well as rapid, shallow movements on hillslopes (debris slides) and in downstream channels (debris torrents).

Minor/major departure – Major departures were assigned to problem points when sediment was delivered to watercourses, or when there was a substantial departure from Rule requirements (e.g., no or few waterbreaks installed for an entire transect). Minor departures were assigned for slight Rule departures where there was no evidence that sediment was delivered to watercourses (e.g., WLPZ width slightly less than that specified by the Rule).

Non-standard practice - A practice other than a standard practice, but allowable by the Rules as an alternative practice, in-lieu practice, waiver, exclusion, or exemption (Lee 1997).

Parameter - The variable being studied by sampling, observation, or measurement (Lee 1997).

Permanent road – A road which is planed and constructed to be part of a permanent all-season transportation facility. These roads have a surface which is suitable for the hauling of forest products throughout the entire winter period and have drainage structures, if any, at watercourse crossings which will accommodate the fifty-year flow. Normally they are maintained during the winter period (14 CCR 895.1). After July 1, 2000, watercourse crossings associated with permanent roads have been required to accommodate the estimated 100-year flood flow, including debris and sediment loads.

Problem point - In the Hillslope Monitoring Program the occurrence of: 1) erosion features (rills, gullies, mass failures, or cutbank/sidecast sloughing) found at sample sites or along transects, 2) canopy reduction, streambank erosion, or ground cover reduction in a watercourse protection zone, or 3) Forest Practice Rule violations (e.g., waterbreak improperly constructed) (Lee 1997).

Process - The procedures through which the Rules/BMPs are administered and implemented, including: (a) THP preparation, information content, review and approval by RPFs, Review Team agencies, and CDF decision-makers, and (b) the timber operations completion, oversight, and inspection by LTOs, RPFs, and CDF inspectors (Lee 1997).

Quality assurance - The steps taken to ensure that a product (i.e., monitoring data) meets specified objectives or standards. This can include: specification of the objectives for the program and for data (i.e., precision, accuracy, completeness, representativeness, comparability, and repeatability), minimum personnel qualifications (i.e., education, training, experience), training programs, reference materials (i.e., protocols, instructions, guidelines, forms) for use in the field, laboratory, office, and data management system (Lee 1997).

Quality control - The steps taken to ensure that products which do not meet specified objectives or standards (i.e., data errors and omissions, analytical errors) are detected and either eliminated or corrected (Lee 1997).

Repeatability - The degree of agreement between measurements or values of a monitoring parameter made under the same conditions by different observers (Lee 1997).

Rill - Small surface erosion channels that (1) are greater than 2 inches deep at the upslope end when found singly or greater than 1 inch deep where there are two or more, and (2) are longer than 20 feet if on a road surface or of any length when located on a cut bank, fill slope, cross drain ditch, or cross drain outlet. Dimensions were not recorded.

Rules - Those Rules that are related to protection of the quality and beneficial uses of water and have been certified by the SWRCB as BMPs for protecting the quality and beneficial uses of water to a degree that achieves compliance with applicable water quality requirements (Lee 1997). Forest Practice Rules are included in Title 14 of the California Code of Regulations (14 CCR).

Seasonal road – A road which is planned and constructed as part of a permanent transportation facility where: 1) commercial hauling may be discontinued during the winter period, or 2) the landowner desires continuation of access for fire control, forest management activities, Christmas tree growing, or for occasional or incidental use for harvesting of minor forest products, or similar activities. These roads have a surface adequate for hauling of forest products in the non-winter period; and have drainage structures, if any, at watercourse crossings which will accommodate the fifty-year flood flow. Some maintenance usually is required (14 CCR 895.1). After July 1, 2000, all permanent watercourse crossings have been required to accommodate the estimated 100-year flood flow, including debris and sediment loads.

Standard practice - A practice prescribed or proscribed by the Rules (Lee 1997).

Surface cover – The cover of litter, downed woody material (including slash, living vegetation in contact with the ground, and loose rocks (excluding rock outcrops) that resist erosion by raindrop impact and surface flow (14 CCR 895.1).

Temporary road – A road that is to be used only during the timber operation. These roads have a surface adequate for seasonal logging use and have drainage structures, if any, adequate to carry the anticipated flow of water during the period of use (14 CCR 895.1).

Waterbreak – A ditch, dike, or dip, or a combination thereof, constructed diagonally across logging roads, tractor roads and firebreaks so that water flow is effectively diverted. Waterbreaks are synonymous with waterbars (14 CCR 895.1).

Appendix

Table A-1. Landings--effectiveness ratings.

Evaluation Category	Number of Observations	Description
Surface Rilling and Gullying		
a. Rilling on Landing Surface	430	None
	79	Less than 1 rill/100 ft (0-20%)
	16	Some rilling (less than 1 rill/20 ft of transect)
	0	Greater than 1 rill/20 ft (greater than 20%)
	2	Greater than 20% of landing drained by rills
	41	0-20% of landing drained by rills
b. Gullies on Landing Surface	461	None
	90	Less than 1 gully per 100 ft transect
	3	Some gullying (less than 1 gully per 20 ft of transect)
	0	Gullying that exceeds 1 gully per 20 ft of transect
	11	Gullying present with recorded dimensions
Surface Drainage		
a. Drainage Runoff Structure	270	No evidence of erosion from concentrated flow where drainage leaves landing surface or drainage outlet
	54	Rills or gullies present but do not extend greater than 20 ft below edge of landing or drainage outlet
	24	Presence of rills or gullies which extend greater than 20 ft below edge of landing or drainage outlet
b. Sediment Movement	325	No evidence of transport to WLPZ
	14	Sediment deposition in WLPZ but not to channel
	7	Evidence of sediment transport to, or deposition in channel
Landing Cut Slopes		
a. Rilling	274	No evidence of rills
	15	Rills present but do not extend to drainage structure or ditch
	5	Rills present and extend to drainage structure or ditch
b. Gullies	289	No evidence of gullies
	1	Gullies present but do not extend to drainage structure or ditch
	4	Gullies present and extend to drainage structure or ditch

Evaluation Category	Number of Observations	Description
Landing Cut Slopes		
c. Slope Failures	272	Less than 1 cubic yard of material moved
	18	More than 1 cubic yard moved but it is not transported to drainage structure or ditch
	3	More than 1 cubic yard moved, some material transported to drainage structure or ditch
Landing Fill Slopes		
a. Rilling	332	No evidence of rills
	42	Rills present but do not extend to drainage channels below toe of fill
	2	Rills present and extend to drainage channels below toe of fill
b. Gullies	345	No evidence of gullies
	26	Gullies present, but do not extend to drainage channels below toe of fill
	5	Gullies present and extend greater than a slope length below toe of fill
c. Slope Failures	355	No material moved
	12	Less than 1 cubic yard moved
	8	More than 1 cubic yard moved but does not enter channel
	2	More than 1 cubic yard moved, some material enters channel
d. Sediment Movement	363	No evidence of transport to WLPZ
	8	Sediment deposition in WLPZ but not carried to channel
	6	Evidence of sediment transport to, or deposition in channel

986

Table A-2. Crossings--effectiveness ratings.

Evaluation Category	Number of Observations	Description
Fill Slopes at Crossings		
a. Vegetative Cover	285	Vigorous dense cover or fillslope of stable material
	101	Less than full cover, but greater than 50% if fillslope has effective cover or is of stable material
	24	Less than 50% of fillslope has effective cover or is of stable material
b. Rilling	332	Rills may be evident, but are infrequent, stable and no evidence of sediment delivery to channel
	46	Few rills present (less than 1 rill per lineal 5 ft) and not enlarging, with little apparent deposition in channel
	32	Numerous rills present (greater than 1 rill per lineal 5 ft), apparently enlarging or with substantial evidence of delivery to channel
c. Gullies	344	None
	14	Gullies present, not enlarging, little apparent deposition in channel
	12	Gullies present and enlarging or threatening integrity of fill
	40	Gully with dimensions provided
d. Cracks	378	None evident
	22	Cracks present, but appear to be stabilized
	7	Cracks present and widening, threatening integrity of fill
e. Slope Failure	302	None
	64	Less than 1 cubic yard (lowest category available in 1996, "none" was not available)
	18	0 to 1 cubic yard of material
	27	Greater than 1 cubic yard of material
Road Surface Draining to Crossings		
a. Rutting	403	No ruts present
	61	Some ruts present, but design drainage not impaired
	13	Rutting impairs road drainage
b. Rilling	433	Little or no evidence of rills
	32	Rills occupy less than 10% of road surface area, or do not leave road surface
	11	Rills occupy greater than 10% of surface and continue off road surface onto crossing or fill
c. Gullies (>6 in deep)	383	None
	8	Gully with dimensions provided

987

Evaluation Category	Number of Observations	Description
d. Surfacing of Crossing Approach	359	No loss of road surface
	31	Less than 30% of road surface area degraded by surface erosion
	5	Greater than 30% of road surface area degraded by surface erosion
e) Cut-off Waterbar Condition	248	Functional
	49	Allows some water to reach crossing location
	25	Allows all water running down the road to reach crossing location
f) Inside Ditch Condition	107	Open
	19	Some sediment/debris accumulation
	6	Blocked with sediment/debris
g. Ponding	400	No evidence of ponded water
	61	Ponding present, but does not appear to threaten integrity of fill
	12	Ponding present and is causing fill subsidence or otherwise threatening integrity of fill
h. Road Surface Drainage	53	Stable drainage with little or no sediment delivery to stream
(only used in 1996)	22	Slight sediment delivery but configuration is stable or stabilizing
	8	Continuing sediment delivery to stream and configuration is unstable/degrading
Culverts		
a. Scour at Inlet	316	No evidence of scour
	15	Scour evident but extends less than 2 channel widths above inlet and no undercutting of crossing fill
	5	Scour evident that extends more than 2 channel widths above inlet or scour is undercutting crossing fill
b. Scour at Outlet	226	No evidence of scour
	74	Scour evident, but extends less than 2 channel widths below outlet, and no undercutting of crossing fill
	36	Scour evident that extends more than 2 channel widths below outlet, or scour undercuts crossing fill
c. Diversion Potential	243	Crossing configured to minimize fill loss (road doesn't slope downward from crossing in at least one direction)
	62	Crossing has road that slopes downward in at least one direction with drainage structure
	30	If culvert fails, flow will be diverted out of channel and down roadway
d. Plugging	257	No evidence of sediment or debris
	50	Sediment and/or debris is accumulating, less than 30% of inlet or outlet is blocked
	29	Sediment and/or debris is blocking greater than 30% of inlet or outlet

Evaluation Category	Number of Observations	Description
e. Alignment	270	Appropriate
	2	Low angle channel approach
	3	High angle channel approach or discharge is not in channel
f. Degree of Corrosion	222	None to slight (metal discolored but not missing)
	18	Moderate--some corroded metal missing but pipe still competent
	2	Severe--pipe can be punctured with screwdriver or similar tool
g. Crushed Inlet/Outlet	251	None
	23	Pipe deformed but less than 30% of inlet/outlet blocked
	1	Pipe deformed and greater than 30% of inlet/outlet blocked
h. Pipe Length	323	Appropriate
	10	Length causing only minor amount of gullying or fill slope erosion
	2	Length directly related to large gullies or fillslope erosion around pipe
i. Gradient	230	Appropriate--at base of fill and at grade of original streambed
	26	Pipe inlet set slightly too low or slightly too high in fill
	21	Pipe inlet set too high or too low, causing debris accumulation, or water to under cut the culvert
j. Piping	263	No evidence of flow beneath or around culvert
	14	Flow passes beneath or around culvert, or piping erosion evident
Non-Culvert Crossing		
a. Armoring	60	Appropriate
	12	Minor downcutting evident at crossing due to inadequate armoring
	8	Major downcutting evident at crossing due to inadequate armoring
b. Scour at Outlet	59	No evidence of scour
	19	Scour evident, but extends less than 2 channel widths below outlet, and no undercutting of crossing fill
	6	Scour evident that extends more than 2 channel widths below outlet, or scours undercuts crossing fill
c. Diversion	77	Crossing configured to minimize fill loss (road does not slope downward from crossing in at least one direction)
	3	Crossing has road that slopes downward in at least one direction but is unlikely to divert flow down road
	3	Overflow will be diverted down road

989

Evaluation Category	Number of Observations	Description
Removed or Abandoned		
a. Bank Stabilization	60	Vigorous dense vegetation cover or other stabilization material
	21	Less than full cover, but greater than 50% of channel bank has effective cover or has stable material
	4	Less than 50% of channel bank has effective cover or is composed of stable material
b. Rilling of Banks	79	Rills may be evident but infrequent, stable, with no sediment delivery to channel
	5	Few rills present (less than 1 per lineal 5 ft) and rills not enlarging
	1	Numerous rills present (greater than 1 rill per lineal 5 ft) or apparently enlarging
c. Gullies	80	None evident
	5	Gully with dimensions provided
d. Slope Failures	82	Less than 1 cubic yard of material
	2	Greater than 1 cubic yard of material moved but does not enter stream
	1	Greater than 1 cubic yard of material moved, material enters stream
e. Channel Configuration	69	Wider than natural channel and close to natural watercourse grade and orientation
	12	Minor differences from natural channel in width, grade, or orientation
	3	Narrower than natural channel width, or significant differences from natural channel grade or orientation
f. Excavated Material	77	Sloped to prevent slumping and minimize erosion
	4	Slumps or surface erosion present, but less than 1 cubic yard of material enters channel
	1	Slumps or surface erosion present, greater than 1 cubic yard of material enters channel
g. Grading and Shaping	72	No evidence of erosion or sediment discharge to channel due to failures of cuts, fills or sidecast
	10	Less than 1 cubic yard of material transported to channel due to failures of fills or sidecast
	2	Greater than 1 cubic yard material transported to channel due to failures of fills or sidecast
Road Approaches at Abandoned Crossings		
a. Grading and Shaping	60	No evidence of concentrated water flow to channel from road surface (in excess of designed drainage or erosion of drainage facility)
	9	Less than 1 cubic yard of material transported to channel from eroded surface soil on road approaches
	2	Greater than 1 cubic yard of material transported to channel from eroded surface soil on road approaches

CD-ROM
USDA Forest Service (USFS) 2002 Landscape dynamics and forest management. Gen Tech Rep. RMRS-GTR-101-CD. Fort Collins.
US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

see attached file.