Trends in Streamflow and Suspended Sediment After Logging, North Fork Caspar Creek[1]

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Abstract

Streamflow and suspended sediment were intensively monitored at fourteen gaging stations before and after logging a second-growth redwood (*Sequoia sempervirens*) forest. About 50 percent of the watershed was harvested, primarily by clear-cutting with skyline-cable systems. New road construction and tractor skidding were restricted to gently-sloping ridge top locations, and watercourse protections were enforced.

Storm peak flows increased as much as 300 percent in clear-cut watersheds, but as antecedent wetness increased, percentage increases declined. In the first five to seven years after logging, the average two-year peak flow increased 27 percent in clear-cut watersheds and 15 percent in partially clear-cut watersheds. Changes in flows are attributable to reduced canopy interception and transpiration. Peak flows and flow volumes had recovered to near-pretreatment levels by about 10 years after logging, when renewed increases occurred from precommercial thinning.

Annual suspended sediment loads in the years following logging increased 123 to 238 percent in four of the five clear-cut watersheds. Loads did not change significantly at most downstream sites as sediment was deposited in the main stem. Channel erosion and changes in storage appear to be important mechanisms for explaining suspended sediment trends at Caspar Creek. Ten years after logging, storm-event sediment yields at one clear-cut tributary were near pretreatment levels, but were elevated again in year 12. At another, yields have remained well above pretreatment levels in the 12 years since harvest.

Key words: clear-cutting, logging effects, peak flow, streamflow, suspended sediment,

Introduction

In 1985, a multiple-basin watershed study was initiated in the North Fork of the Caspar Creek Experimental Watershed, in north coastal California. The study is a cooperative effort by the USDA Forest Service, Pacific Southwest Research Station and the California Department of Forestry and Fire Protection to investigate the impacts of harvesting second-growth redwoods under the Z'Berg-Nejedly Forest Practices Act of 1973. Although the logging included large clear cuts (maximum clear-cut size has since been reduced under California rules from 32 to 12 ha), erosional impacts were limited by careful road design and greatly restricted use of

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tractors. The Proceedings of the Conference on Coastal Watersheds: The Caspar Creek Story (Ziemer, 1998) and Lewis and others (2001) reported results of the North Fork study through HY1996 (hydrologic year from August 1, 1995 to July 31, 1996). This paper extends the results through HY2003.

Methods

Study location

The Caspar Creek Experimental Watersheds are located about seven km from the Pacific Ocean and about 10 km south of the town of Fort Bragg in northwestern California. Elevation ranges from 37 to 320 m. Soils in the basin are well-drained clay loams derived from Franciscan sandstone and weathered coarse-grained shale of Cretaceous age.

The climate is typical of low-elevation coastal watersheds of the Pacific Northwest. Winters are mild and wet, characterized by periods of low-intensity (maximum 2.6 cm/hr) rainfall. Snow is rare. Average annual precipitation is 1170 mm. Typically, 95 percent falls during the months of October through April. Summers are moderately warm and dry with maximum temperatures moderated by frequent coastal fog. Mean annual runoff is 650 mm.

Like most of California's north coast, the watersheds were clear-cut and broadcast burned largely prior to 1900. By 1985, the North Fork watershed supported a 100-year-old second-growth forest composed of coast redwood (*Sequoia sempervirens* (D.Don) Endl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.).Sarg.), and grand fir (*Abies grandis* (Dougl. ex D.Don) Lindl.).

Measurements

The North and South Forks of Caspar Creek (draining 473 ha and 424-ha, respectively) have been gaged continuously since 1962 using 120° V-notch weirs widening to concrete rectangular sections for high discharges. In 1985, three rated sections were constructed on the main stem upstream of the North Fork weir, and 10 Parshall flumes were installed on North Fork subwatersheds with drainage areas of 10 to 77 ha. Two of the original redwood Parshall flumes were replaced with fiberglass Montana flumes in HY1999 and 2001.

Since HY1986, stream discharge has been recorded at all gaging stations using electronic data loggers equipped with pressure transducers. From HY1986 to HY1995, suspended sediment was automatically sampled using real-time stage measurements to control a pumping sampler (Thomas 1989). Since HY1996, turbidity is recorded along with stage, and the sampling logic has been altered to use real-time turbidity (Lewis and Eads 2001).

Treatments

Ten areas were designated for harvest in compliance with the California Forest Practice Rules in effect in the late 1980s *(fig. 1)*. Two of these areas (13 percent of the North Fork watershed) were harvested in 1985 and 1986 with the intent of excluding them from the study. However, this harvest affects all subsequent analyses of North Fork weir data. After a calibration period between 1985 and 1989, clear-cut logging began elsewhere in the North Fork in May 1989 and was completed in January 1992. These clear-cuts occupied 30 to 99 percent of treated watersheds and totaled 162 ha. Between 1985 and 1992, 46 percent of the North Fork watershed was clear-cut, 1.5 percent was thinned, and two percent was cleared for road right-of-way. Of the fourteen gaged watersheds in the North Fork, five were clear-cut, three were left as unlogged controls, and six included mixtures of clear-cut and unlogged areas. In HY1996, stream gaging was discontinued at all but two of the clear-cut watersheds, two of the controls, and three of the partially clear-cut watersheds.

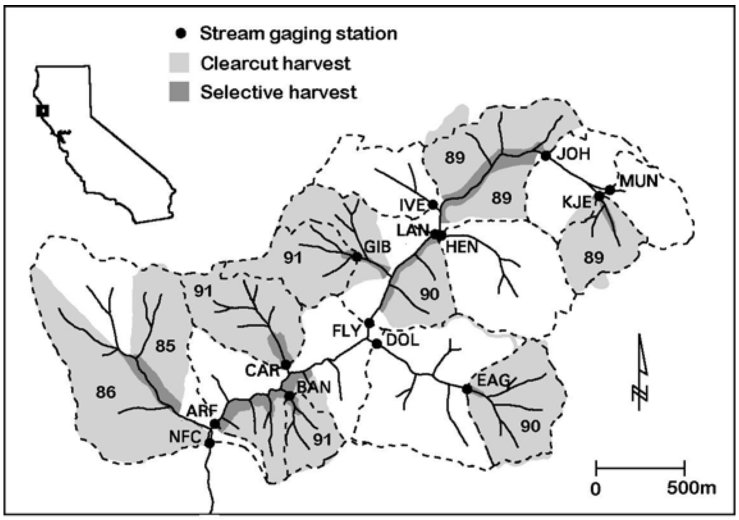

Figure 1—North Fork Caspar Creek gaging stations and harvest units.

Harvest was conducted under stream-buffer rules that mandated equipment exclusion and 50 percent canopy retention within 15 to 46 m of watercourses providing aquatic habitat or having fish present. Most of the yarding (81 percent of the clear-cut area) was accomplished using skyline-cable systems. Yarders were situated on upslope landings constructed well away from the stream network. New road construction and tractor skidding was restricted to ridgetop locations with slopes generally less than 20 percent. Four harvest blocks, 92 ha total, were broadcast burned and later treated with herbicide. Pre-commercial thinning in 1995, 1998, and 2001 eliminated much of the dense revegetation and reduced basal area in treated units by about 75 percent.

Results

Storm peaks

Lewis and others (2001) analyzed peak flow response to clear-cutting in the North Fork using 526 observations from HY1986 to HY1996, representing 59 storms on 10 treated watersheds. After logging, eight of the 10 tributary watersheds experienced increased storm peaks ($p < .005$) relative to those predicted on the basis of the controls for an uncut condition. In clear-cut units, individual storm peaks increased as much as 300 percent, but most increases were less than 100 percent. The largest increases occurred during early season storms. As basin wetness increased, percentage peak flow increases declined *(fig. 4)*. In the larger, partially clear-cut

North Fork watersheds, smaller peak flow increases were observed. Under the wettest antecedent moisture conditions of the study, increases over the first five to seven years after logging averaged 23 percent in clear-cut watersheds and 3 percent in partially clear-cut watersheds. The average increase in storm peak with a two-year return period was 27 percent in the clear-cut watersheds and 15 percent in the partially clear-cut watersheds (Ziemer 1998) for this five to seven year period. While variability is great, ongoing measurements clearly show a recovery to near pre-treatment flow conditions 10 years post-harvest and the suggestion of a renewed response to the pre-commercial thinning *(fig. 2)*.

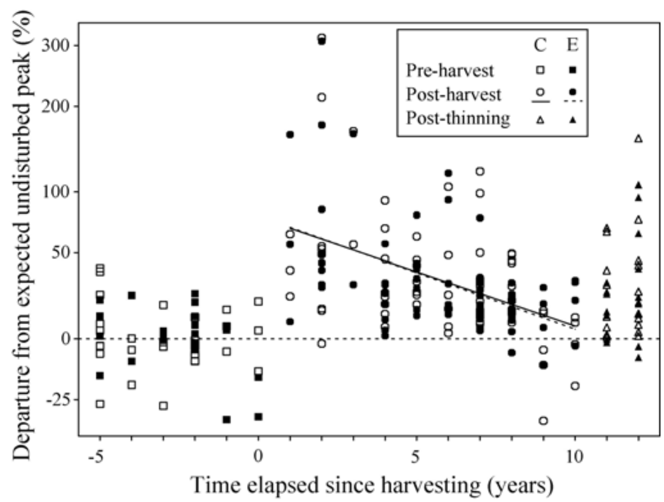

Figure 2—Peak flows observed in North Fork clear-cut units C and E from HY1986 through HY2003. Expected undisturbed peak is based on log-log regressions of pre-harvest peak flows at CAR and EAG on the mean of the corresponding peak flows at control watersheds HEN and IVE.

Wetter soils resulting from reduced transpiration in logged units explain some of the observed increases in streamflow. In addition, because of reduced canopy interception, 28 percent more precipitation is delivered to the forest floor after clear-cut logging in these second-growth redwood stands (Reid and Lewis 2006). Under forested conditions, canopy interception is significant even during the wettest mid-season storms. Loss of interception is therefore expected to maintain wetter soil conditions in logged terrain throughout the rainy season.

Lewis and others (2001) fit an empirical model expressing the HY1986-1996 North Fork peak flows as a function of peaks in the control watersheds, antecedent wetness, proportion of area logged, and time since logging. In this follow-up, a slightly simplified version of that model was refit, using generalized non-linear least squares, to all peak flows before pre-commercial thinning (HY1986-2001).

$$\ln(y_{ij}) = \beta_{0i} + \beta_{1i}\ln(y_{Cj}) + \left[\left(1-\beta_2(t_{ij}-1)\right)c_{ij} + \beta_3 c'_{ij}\right]\left[\beta_4 + \beta_5\ln(y_{Cj}) + \beta_6\ln(w_j)\right] + \varepsilon_{ij} \quad (1)$$

where

y_{ij} = unit area peak flow at treated watershed *i*, storm *j*,

y_{Cj} = mean of unit area peak flows at control watersheds HEN and IVE in storm *j*,

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*,

c_{ij} = proportion of watershed *i* logged in water years prior to that of storm *j*,

c'_{ij} = proportion of watershed *i* logged in the fall prior to storm *j* (in the same water year)

w_j = wetness index at start of storm *j*, computed from daily streamflow (30-day half-life) at South Fork weir

ε_{ij} = independent normally distributed errors with variance inversely proportional to a power function of watershed area

β_{0i} and β_{1i} are "location" parameters to be estimated for each watershed *i*, and

β_2, β_3, β_4, β_5, and β_6 are parameters describing the effects of the explanatory variables

The first two terms in the model predict the peak flow in the absence of disturbance. The first bracketed term represents vegetation removal and regrowth, and the terms in the second set of brackets are the main effect of vegetation change (β_4) and interactions of vegetation change with storm size and antecedent wetness. The coefficient estimates and their standard errors are given in *table 1*. This model fits the data well (r^2 = 0.95) and residuals are normally distributed with standard error equivalent to 25 percent of the predicted peak.

Table 1—*Parameter estimates for storm peaks and flow volume models.*

		----------Storm peak----------			-------Storm flow volume-------		
Parameter	**Effect**	**Estimate**	**Std error**	**p**	**Estimate**	**Std error**	**p**
β_2	Recovery	0.101	0.0063	<0.0001	0.110	0.0059	<0.0001
β_3	Fall logging	0.447	0.0965	<0.0001	0.876	0.0926	<0.0001
β_4	Vegetation reduction	1.290	0.2596	<0.0001	2.824	0.2287	<0.0001
β_5	Storm size interaction	-0.110	0.0363	0.0025	-0.140	0.0392	0.0004
β_6	Wetness interaction	-0.278	0.0177	<0.0001	-0.298	0.0178	<0.0001

The fitted value of 0.101 for the coefficient β_2 implies recovery of peak flows to pretreatment conditions after 11 growing seasons, in concordance with *figure 2*. A 95 percent confidence interval for β_2 implies recovery in 10 to 12 years. The fitted value of 0.447 for β_3 suggests that the effect on peak flows during the first winter was reduced by about 55 percent because much of the harvest occurred late in the growing season, after substantial transpiration had occurred. The storm size interaction indicates that the proportional increase in peak flows was smaller for larger events, and the wetness interaction indicates that increases in peak flows are greatest during low antecedent wetness conditions.

Model (1) was used to predict peak flows without accounting for the change in cover following thinning. *Figure 3* shows the departures from peak flows predicted by this model for the two clear-cut watersheds, CAR and EAG, that are still being monitored. Departures, e_{ij}, are converted to percentage of predicted peak through the transformation 100exp(e_{ij}). The recovery trend depicted in *figure 2* is not visible in *figure 3* because the model accounts for the recovery. However, the mean post-thinning departure from the predicted peak is 26 percent (the 95 percent confidence interval is 16 to 37 percent). These departures are greatest when antecedent wetness is greatest *(fig. 4)*, suggesting that mechanisms similar to those responsible for increasing peaks after clear-cutting are involved in changing peaks after thinning.

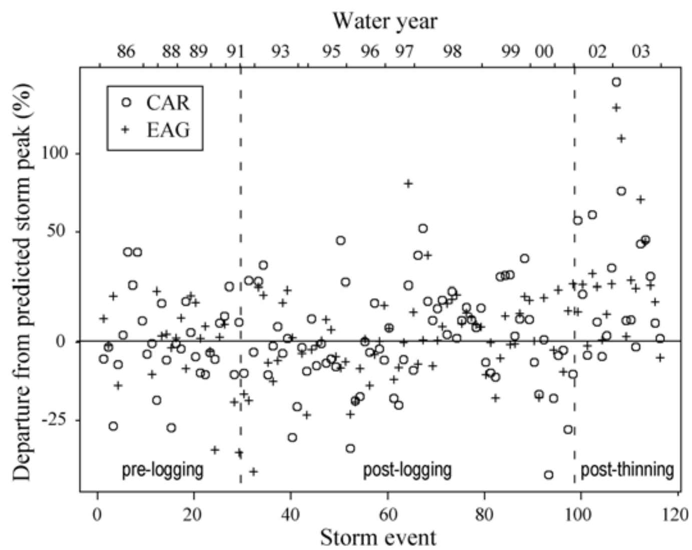

Figure 3—Departures from model (1) predictions of storm peak.

The thinning in watersheds CAR and EAG removed 68 and 84 percent of the crown volumes, respectively. The peaks model permits a test of whether these treatments were equivalent to clear-cutting the same percentage of the watersheds. For the calculations of *figures 3* and *4*, the variable t_{ij} was coded as 10 and 11 years, respectively, for CAR and EAG in HY2002, the winter following thinning. However, if we treat the disturbance as if 68 and 84 percent of the areas were clear-cut in the beginning of HY2002, the area-weighted mean cutting ages t_{ij} should be coded 3.2 for CAR and 1.8 for EAG in HY2002; and the ages in HY2003 should be 4.2 and 2.8 years. Based on this recoding of t_{ij}, the model predicts an average increase of 52 percent in peak flows, suggesting that thinning had half the impact on peak flows of an equivalent harvest by clear-cutting. Such a result is expected if evaporation and transpiration rates are elevated in a thinned stand because of lower aerodynamic resistance to the transport of water vapor as suggested by Calder (1990).

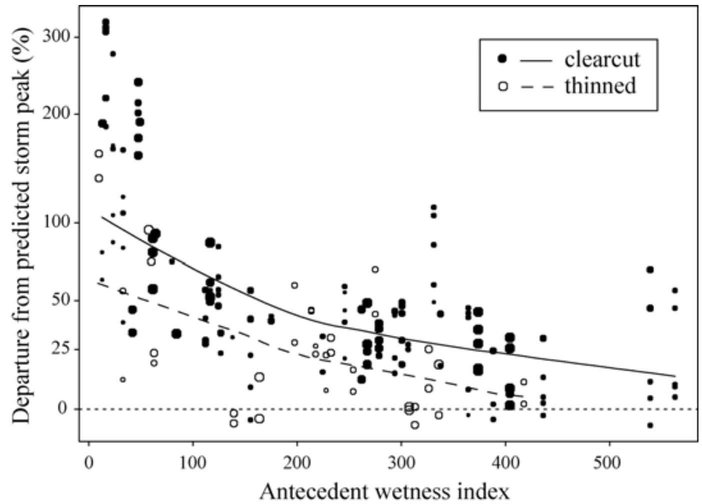

Figure 4—Relation to antecedent basin wetness of (a) clear-cut departures from pretreatment regressions (BAN, CAR, EAG, GIB, and KJE through HY1996), and (b) post-thinning departures from model (1) (CAR and EAG, HY2002-2003). Symbol sizes denote relative storm sizes.

Storm flow volumes

Storm flow volumes were analyzed using the same methods as for peak flows. The results through HY1996, reported by Lewis and others (2001) were similar to peak flow results. In clear-cut units, storm flows increased as much as 400 percent, but most increases were less than 100 percent. The largest increases occurred during early-season storms. As basin wetness increased, percentage increases declined. Under the wettest antecedent moisture conditions of the study, increases averaged 27 percent in clear-cut watersheds and 16 percent in partially clear-cut watersheds over the five to seven year period following harvest. Annual storm runoff volume (sum of storms) increased an average of 58 percent in clear-cut watersheds and 23 percent in partly clear-cut watersheds (the mean percentage harvested was 38 percent). As with peak flows, ongoing measurements show a return to pre-treatment flow volumes approximately 10 years post-harvest, followed by a response to the pre-commercial thinning *(fig. 5)*.

Model (1) also the fits the flow data well (r^2 = 0.94) with normally-distributed residuals and standard error equivalent to 21 percent of the predicted flow volume. The estimated recovery coefficient (*table 1*) suggests return of storm flows to pretreatment condition 10 years after logging, and is consistent with *figure 5*.

The flow model enabled quantification of the impact of pre-commercial thinning at CAR and EAG for 18 events in the two post-thinning years. The mean post-thinning departure from predicted flow volume was 26 percent (the 95 percent confidence interval is 15 to 38 percent) and the total storm flow volume was 19 percent greater than predicted by the model.

When the variable t_{ij} was recoded (as described above for peaks) to represent thinning as an equivalent harvest by clear-cut, the model predicts a mean increase of 53 percent and total increase of 44 percent in storm flow. Compared to an equivalent clear-cut, the mean effect of thinning on storm flows was about half (26/53) and the total effect on storm flows was 43 percent (19/44).

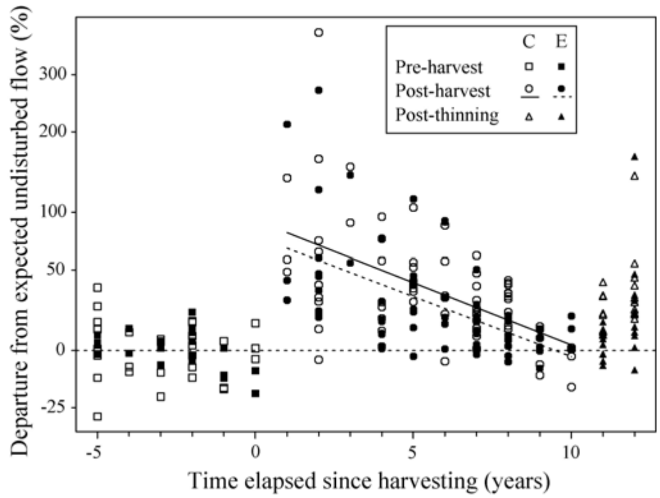

Figure 5—Storm flow volumes observed in North Fork clear-cut units C and E from HY1986 through HY2003. Expected undisturbed flow is based on log-log regressions of pre-harvest flows at CAR and EAG on the mean of the corresponding storm flows at control watersheds HEN and IVE.

Sediment Loads

Suspended sediment loads, summed over post-logging years through HY1996 increased 89 percent at the North Fork weir, primarily due to one landslide that occurred in the 1986 harvest area in 1995. Annual (sum of storms) suspended sediment loads in the years following logging decreased by 40 percent in one clear-cut watershed (KJE) and increased 123 to 238 percent in the other four clear-cut watersheds. Loads did not change significantly at most downstream sites, but at DOL increased by 269 percent. The median estimate of change in annual sediment load was +132 kg $ha^{-1}yr^{-1}$ for five clear-cut watersheds and –19 kg $ha^{-1}yr^{-1}$ for five partially clear-cut watersheds. Increases in sediment loads were greatest during those events with increased storm flows. In clear-cut watersheds where sediment loads increased, the correlations between departures from pretreatment sediment load and storm flow models were 0.66 (BAN to HY1995), 0.70 (CAR to HY2003), 0.62 (EAG to HY2003), and 0.86 (GIB to HY1995). Sediment increases at EAG have been greater than at CAR due to near-channel tunnel collapses. Storm event loads in EAG remained elevated a decade after harvest, while, at CAR, yields were close to the pretreatment level in year 10 (*fig. 6*). Suspended sediment levels from both subwatersheds, especially EAG, increased sharply in year 12 (HY2003), the first above-average runoff year since HY1999. Although sediment levels did not increase the first year after thinning, they certainly may have been influenced by the larger enhanced flows of HY2003. Prolonged impacts from logging in the South Fork (Keppeler and others, 2003) suggest that the episodic nature of sediment releases requires patience regarding conclusions about recovery.

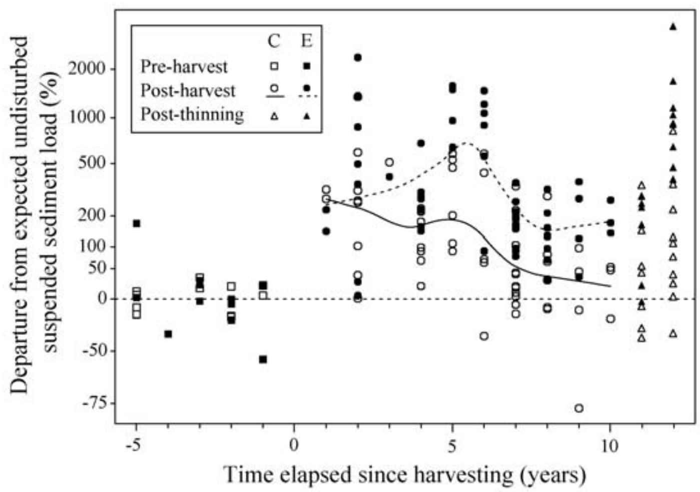

Figure 6—Sediment loads observed in North Fork clear-cut units C and E from hydrologic year 1986 through 2003.

Discussion and Conclusions

Although the variability is great, the impacts of clear-cut logging and forest regrowth on peaks and flows in the North Fork of Caspar Creek are fairly clear and quantifiable. Earlier analyses of selective logging in the South Fork of Caspar Creek (Ziemer 1981) had failed to show significant changes in peak flows, except in the smallest events at the beginning of the rainy season. Those results are not necessarily at odds with the North Fork study and may be attributable in part to differences in silvicultural methods (selective versus clear-cut logging). If thinning is a valid analog for selection cutting, our analysis suggests that the South Fork response should have been smaller than that in the North Fork. In addition, the North Fork analyses were more sensitive because multiple unlogged subwatersheds of the North Fork were available for use as controls. Low variability in the pretreatment relationship is critical to an effective watershed experiment, and the responses in North Fork watersheds slated for treatment were more closely related to North Fork subwatershed responses than to the South Fork response. In fact, the mean of two unlogged subwatersheds provided a better control than any individual subwatershed.

An empirical statistical model describes impacts on flow peaks and volumes in terms of antecedent basin wetness, proportion of area cut, time since logging, and event size. The effect of vegetation removal is greatest when the wetness index is low and diminishes as basin wetness increases. However, no conditions were observed under which the impacts were reduced to zero. The result is not unexpected given that effective rainfall is increased substantially by the loss of canopy interception throughout the rainy season (Reid and Lewis 2006).

A somewhat surprising result is that flow peaks and volumes 10 years after logging were similar to those in 100-year-old redwood forest. Further research will be necessary to understand this result, but it suggests that leaf area recovers very rapidly after harvest, and/or that evapotranspiration rates per unit leaf surface are much greater in younger forests. In fact, evidence suggests both may be true. Crown closure and maximum leaf area in one redwood plantation was attained within 15 years.[4] In riparian Douglas-fir forests of western Oregon, Moore and others (2004) found that a 40-year-old, rapidly growing stand used 3.3 times more water during the growing season than an old-growth stand.

Pre-commercial thinning resulted in smaller flow changes than would have been expected from equivalent clear-cuts. This may be partly related to the influence of canopy structure on evaporation rates. Calder (1990) reported that interception rates in mature spruce forest were almost unchanged after thinning one-third of the stand. He speculated that increased ventilation to lower levels of the canopy could increase evaporation rates. Reduced competition for soil water could also permit increased transpiration by vegetation that remains after thinning.

Variability in suspended sediment yield is much greater than variability in flow. Results are less consistent among clear-cut subwatersheds and much less predictable in downstream watersheds. One North Fork subwatershed that was clear-cut (KJE) experienced a decrease in sediment loads. The others experienced substantial increases. Of the two that are still being measured, neither has returned to pretreatment levels, and one (EAG) is yielding significantly more sediment than the other (CAR). One downstream site (DOL) had larger than expected sediment yields, apparently because of increased channel erosion, while those on the main stem have not experienced elevated sediment yields, apparently because of increased sediment storage. Unusual windstorms in combination with increased wind exposure in stream buffer zones resulted in blowdown that created many new sediment storage sites in the formerly wood-deprived main stem.

The sediment results are less directly extensible to other watersheds than the flow results, because they depend on events and conditions unlikely to be repeated in every coastal watershed. This is especially true as one moves downstream from first and second order streams to locations where channel complexity is greater. The results of the Caspar Creek sediment studies are probably not useful for making quantitative predictions, but they have helped us to understand many controlling factors and links among erosion, sediment delivery, and sediment transport. It has become clear that sediment impacts from regulated logging in the North Fork have been less severe than those from the tractor logging that took place in the South Fork (Keppeler and others 2003), and the research suggests opportunities for further reducing impacts. For example, limiting the rate of harvest in a given watershed would clearly limit increases in peak flows and flow volumes. Sediment yield increases in the North Fork were related to flow increases, so limiting harvest rates should also be effective in limiting sediment impacts. To further limit sediment yields in the North Fork would have required extending streamside protection zones farther upstream, but the incremental benefit of doing so is difficult to quantify, and it probably would not have greatly reduced sediment yields in DOL where much of the channel and bank erosion occurred downstream from the logged watershed (EAG).

Today much of the managed timber-producing area of north coastal California has been logged at least twice and may have experienced heavy impacts from tractor logging and road construction. The condition of the South Fork of Caspar Creek is probably more typical of areas being logged today than was the North Fork. It is becoming crucial for landowners, regulatory agencies, and the public to understand

[4] O'Hara, K.L.; Stancioiu, P.T.; Spencer, M.A. Manuscript in review. Understory stump sprout development under variable canopy density and leaf area in coast redwood. Canadian Journal of Forest Research.

the interactions between proposed future activities and prior disturbances. A third phase of Caspar Creek research is being initiated in the South Fork to examine the effects of re-entry on runoff and sediment production from previously tractor-logged redwood forests. Much remains to be learned about restoring impacted ecosystems and mitigating impacts from future harvests.

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