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Logging Effects on Streamflow: Storm Runoff at Caspar Creek in Northwestern California

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The effects of road building and selective tractor harvesting on storm runoff were assessed for a small (424 ha) coastal watershed in northern California. Road building alone did not significantly affect the storm runoff. After road building and logging, lag time was decreased approximately I .5 hours, and the very small storm volumes (less than 1209 m^3) and storm peaks (less than 566 L/s) were increased by about 132 and 111% respectively. Storm volumes and peaks of large storms (occurring less frequently than eight times a year) were not significantly increased by either roads or logging. even though more than 15% of the watershed was compacted in roads, skid trails, and landings. Although a decrease in lag time showed that the average storm hydrograph was shifted forward in time. only the small storm hydrographs were changed in shape. We speculate that the rate of delivery of water to the stream channel during large channel-forming flows was governed by infiltration and subsurface flow rates on the 85% of the watershed that was unaffected by roads. landings. or skid trails. From these findings we conclude that, in a rain-dominated hydrologic environment. logging and forest road construction (as carried out in this study) are not likely to change the flow regime of a stream adversely.

INTRODUCTION

The effects of timber harvesting on streamflow have been the subject of many studies, often with conflicting results. That area of research is becoming increasingly important as forested watersheds become more intensively managed and attempts are made to minimize adverse impacts.

The analysis of storm flows and lag times contribute to a better understanding of streamflow processes and how they can be affected by timber management practices. We defined hydrograph lag time as the difference between the time when half the rainfall of a storm had fallen and the time coordinate of the centroid of resulting quick flow. Lag time represents the time required for 50% of the input into the watershed to produce 50% of the output. Lag time reflects the efficiency of the subsurface flow network and basin channels to deliver runoff to a downstream point. If the efficiency of delivering water to the stream system is increased, then storm volumes and peak flow would likely be increased. An increase in the large channel-forming flows or volumes would increase channel scour and bank erosion.

This paper reports a study to determine whether road building and selective harvesting at Caspar Creek in northwestern California increased total storm volumes, quick flow volumes, or peak flows or altered the lag times.

EARLIER STUDIES

Ziemer [1981] did a similar analysis of Caspar Creek streamflow to determine the effects of road building and logging on the storm flows. Ziemer used an indirect variable as a proxy for storm volume, whereas we determined actual storm volumes using a method described by ***Hewlett and Hibbert*** [1967], and we also analyzed lag times. We used the hydrograph separation technique described by ***Hewlett and Hibbert*** [1967] to separate quick flow volume and delayed volume. Our methods yielded a data set somewhat different from Ziemer's. The storm hydrograph parameters used in this paper are similar to parameters used in the Alsea watershed study by ***Harr et al.* [1975].**

Construction of a road network in forested watersheds can alter subsurface flow and influence the storm hydrograph [***Reinhart***, 1964: Megahan, 1972]. Heavy logging equipment can compact the soil surface on skid trails and landings, significantly reducing the infiltration capacity [Munns, 1947: ***Reinhart, 1964; Johnson and Beschta,*** 1980]. Other analyses have shown increases in bulk density and a conversion of macropore space to micropore space [Campbell et al., 1973; ***Dickerson,*** 1976; ***Froehlich,*** 1978; ***Cafferata,*** 1983]. The impact of tractor logging on soil surfaces is well documented, but the effects these alterations have on the generation of streamflow are not well understood. Researchers have reasoned, however, that impacts on the storm hydrograph could include a shortened response time and increased peak flows, due to a faster streamflow reaction to precipitation ***[Harr et al.***, 1975, 1979; ***Leopold, 1981].***

Rothacher [I971] suggested that normal logging activity may not sufficiently compact the soil to reduce the infiltration capacity below the rate of precipitation. Because of high infiltration rates and relatively low precipitation intensities in the Pacific Northwest there may be no large-scale change from subsurface to surface ***flow. Harr et*** al. [1975] reported that no consistent change in time to peak was found in three partially clearcut watersheds in the Alsea Watershed Study in the Oregon Coast **Range.** Other researchers report that lag time may be increased after timber harvesting ***[Chamber/in. 1972: Cheng et al.,*** 1975; ***DeVries and Chow,*** 1978]. They

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suggested that during a storm on an undisturbed site a significant proportion of infiltrated water tends to bypass the soil matrix as a result of conduction through decayed root channels. Disturbance of the forest floor by logging could close off a significant number of root channels, causing a greater percentage of the infiltrating water to move through the soil matrix. This would result in slower water movement and a longer lag time.

There have been numerous studies on the effects of timber harvest and road building on storm flows in the Pacific Northwest, many with seemingly conflicting results (Table 1). Most studies have found increases in the small early season storm flows after timber harvest ***[Rothacher,*** 1973; ***Harr er al.,*** 1975, 1979; ***Harris,*** 1977; ***Ziemer,*** 19811. But on the H.J. Andrews (HJA) Experimental Forest, in Oregon, ***Harr et al.*** [1982] and ***Harr and McCorison*** [1979] found that none of the peak flows had been increased significantly. On HJA-10 a 10.2-ha watershed which was 100% clearcut logged using a cable yarding system and left unburned, ***Harr and McCorison*** [1979] found that the size of annual peak flows was reduced 32%. Most studies have shown that larger storm flows are not increased as a result of road building and timber harvest ***[Rothacher,*** 1973; ***Harr et al., 1982; Harr and McCorison, 1979; Harris,*** 1977; ***Ziemer,*** 1981] But some studies have found increases in the largest peak flows when roads, landings, and skid trails occupy 12% or more of the watershed area ***[Harr et al.,*** 1975, ***1979; Krygier and Harr,*** 1972].

STUDY AREA AND TREATMENTS

The study watersheds (North and South Forks of Caspar Creek) are located in the Jackson Demonstration State Forest, 11 km southeast of Fort Bragg, California and about 7 km from the Pacific Ocean (Figure 1). The North and South Forks of Caspar Creek drain watersheds having areas of 483 and 424 ha, respectively. The elevation of the watersheds ranges from 37 to 320 m. Topography of the North and South Fork watersheds runs from broad, rounded ridge tops to steep inner gorges. About 35% of both watersheds have slopes less than 30%. The South Fork has about 1% of its area steeper than 70%, whereas about 7% of the North fork is steeper than 70%. The soils in both watersheds were formed in residuum derived predominately from sandstone and weathered coarse-grained shale of Cretaceous Age. Soils are well drained, having high saturated and unsaturated hydraulic conductivities ***[Wosika,*** 1981). The climate is Mediterranean, having dry summers with coastal fog. Summer temperatures are mild, ranging from 10” to 25” C. Winters are mild and wet, with temperatures ranging between 5” and 14” C and a rainfall average of about 1200 mm per year ***[Ziemer,*** 1981]. Caspar Creek does not receive any appreciable snowfall.

The North and South Forks of Caspar Creek were originally clearcut logged and burned in the late 1800s, the North Fork about 15 years after the South Fork ***[Tilley and Rice,*** 1977]. Since then, fairly dense stands of second-growth redwood (Sequoia se***mpervirens*** (D. Don) Endl.) and Douglas fir ***(Pseudotsuga menziesii*** (Mirb.) Franco) developed, with some associated western hemlock ***(Tsuga heterophylia*** (Ref.) Sarg.) and grand fir ***(Abies grandis*** (Dougl.) Lindl.). At the onset of the study, timber volume on both watersheds was estimated at about 700 m^3/ha ***[Krammes and Burns,*** 1973]. The North Fork was selected as the control watershed because its timber was younger. Road location and construction and timber harvest practices in the South Fork were designed to meet standards which were considered “state of the art” but also considered commercially acceptable by the local timber contractors.

Construction of stream gauging stations on both forks was completed in the summer of 1962. Flow was measured with compound weirs consisting of a 6.1 m x 0.91 m rectangular sharp crested weir superimposed upon a 0.61 m 120” v notch weir. Precipitation was estimated from four weighing rain gauges (Figure 1).

Both watersheds were monitored in an undisturbed condition during hydrologic years (October-September) 1963-1967. Road construction in the summer of 1967 was monitored through hydrologic year 1971 when logging began. Logging effects were followed through hydrologic year 1976 for the flow analyses and through 1981 for the lag time analysis.

Of the total 6.8 km of roads constructed in the South Fork watershed during the summer of 1967, 6 km were within 61 m of the stream. Coarse debris, resulting largely from right-of-way clearing, was removed from the stream and from along the stream banks after road construction ***[Krammes and Burns,*** 1973]. The roads (including cut and fill slopes) occupied 19 ha (4.5% of the total watershed area) from which 993 m^3/ha of timber was removed (Table 2).

About 110 m of streambed were disturbed by tractor operation directly in the stream. These areas were primarily around bridge crossings, landings, and in a stretch of stream cleared of debris which had been deposited there from the road construction. All fill slopes, landings, and major areas of soil exposed by the road building activities were fertilized and seeded with annual ryegrass in September 1967. The grass was well established before the first rains in November ***[Jackman and Stoneman, 1973].***

Logging, which began on the South Fork of Caspar Creek during the summer of 1971, continued over a 3-year period. The South Fork watershed was divided into three sale areas. Selective cutting started at the weir and progressed up the watershed on successive years (Table 2; Figure 1). All logging was done by tractor, but many of the skid trails did not have adequate cross drains installed. By the completion of logging, over 15% of the watershed was in roads, landings, and skid trails and considered heavily compacted (Table 2).

METHODS

The criteria used to select storm hydrographs and the methods of data analysis for lag times were slightly different than those used for storm volumes and flows. This is because the analysis of the lag time and the analysis of peak flows and volumes were conducted independently ***(Sendek*** [1985] analyzed lag times and ***Wright*** [1985] analyzed storm volumes and peak flows). When selecting storm flows for the lag time analysis, Sendek selected 100 paired hydrographs, whereas Wright selected 128. Wright analyzed the effects of logging on large storm hydrographs versus small storm hydrographs in addition to overall effects, while Sendek primarily analyzed average and seasonal changes in lag time after logging.

Analysis of Flow Volumes and Peak Flows

The criteria used to select storm hydrographs for the storm volume and peak flow analysis were the following: (1)

TABLE I. Summary of Paired Watershed Studies on the Effects of Road Building and Logging on Stormflows in the Pacific Northwest

Watershed	Area, ha	Annual Rainfall, cm	Logging System	Silviculture Treatments*	Area Compactedi	Minimum Flow Analyzed, L/(s ha)	Roading Effects on Peak Flows	Logging Effects on Peak Flows, Flow Change, L/(s ha), %	Reference
H.J. Andrews Watershead 1	95	233	cable	cc-100% BB-100%	...	1.1	not tested	fall peaks increased up to 7 (200%); larger winter peaks, ns	***Rothacher*** [1973]
H.J. Andrews Watershed 3	101	233	cable	cc-25% BB-25%	10%	1.1	decreased	mean increase 0.33 (10%); data on larger peaks lost	***Rothacher*** [1973]
H.J. Andrews Watershed 6	13	219	10% tractor 90% cable	CC-100% BB-100%	...	4.5	not tested	no significant change in peak flows or timing of peak flows	***Harr et al. [*** 1982]
H.J. Andrews Watershed 7	21	219	60% tractor 40% cable	SC-6095 BB-100%	...	4.5	not tested	no significant change in peak flows or timing of peak flows	***Harr et al.*** [1982]
H.J. Andrews Watershed 10	10	230	cable	CC-100% YUM-100%	19%	2.2	not tested	annual rain on snow peaks decreased 4.4 (36%); annual rain fall peaks ns	***Harr and McCorison [1979]***
Coyote Creek Watershed 1	6Y	123	tractor	SC-SO% UT	13%	2.2	not tested	mean peaks increased 0.85 (30%); larger peaks (9-year return period) increased 3.2 (48%)	***Harr et al. [*** 1979]
Coyote Creek Watershed 2	68	123	14% tractor 16% cable	cc-30% TP-14% YUM-16%	5%	2.2	not tested	no significant change in peak flows	***Harr et al.*** | 1979]
Coyote Creek Watershed 3	49	123	23% tractor 77% cable	cc- 100% TP-23% YUM-77%	12%	2.2	not tested	mean peaks increased I.5 (44%); larger peaks (Y-year return period) increased 3.0 (35%)	***Harr et al.*** | 1979]
Needle Branch	70	248	10% tractor 72% cable	CC-82% BB-82%	5%	5.5 and 0.03 0.03	ns	large peaks > 5.5 ns; peaks > 0.03: fall peaks mean increase 1.7 (50%) and winter peaks mean increase 1.1 (19%)	***Harris [1977]*** ***Harr et al.*** | 1975)
Deer Creek	303	247	cable	cc-26% UT	4%	5.5 and 0.03 0.03	ns	no significant change in peak flows	***Harris*** [1977]
Deer Creek subwatershed	40	247	cable	CC-65% UT	12%	0.03	increased 0.55	fall peaks mean increase 0.33 (50%); winter peaks mean increase 1.3 (30%)	***Harr et al.*** [1975]
Deer Creek subwatershed	16	247	cable	cc-90% UT	...	0.03	not tested	fall peaks mean increase 3.0 (51%); winter peaks mean increase 1.1 (20%)	***Krygier and Harr [1972]***
South Fork Caspar Creek	424	1010	tractor	SC-60% UT	16%	0.19 and 4.7	ns	peaks 0.19-0.78 increased 0.52 (107%); large peaks > 4.7, ns	***Ziemer*** | 198 I]

No significant change detected, ns.

* CC-lOO%, clearcut logged over 100% of the watershed; SC-60%, shelterwood harvest removing 60% of the basal area; BB-l00%, broadcast burned 100% of the watershed; TP-23%, tractor piled 23% of the watershed; YUM-77, slash was cable yarded over 77% of the watershed; UT, slash nontreated.

† Includes roads, landings, skid trails and, in some cases, areas compacted by tractor piling of slash.

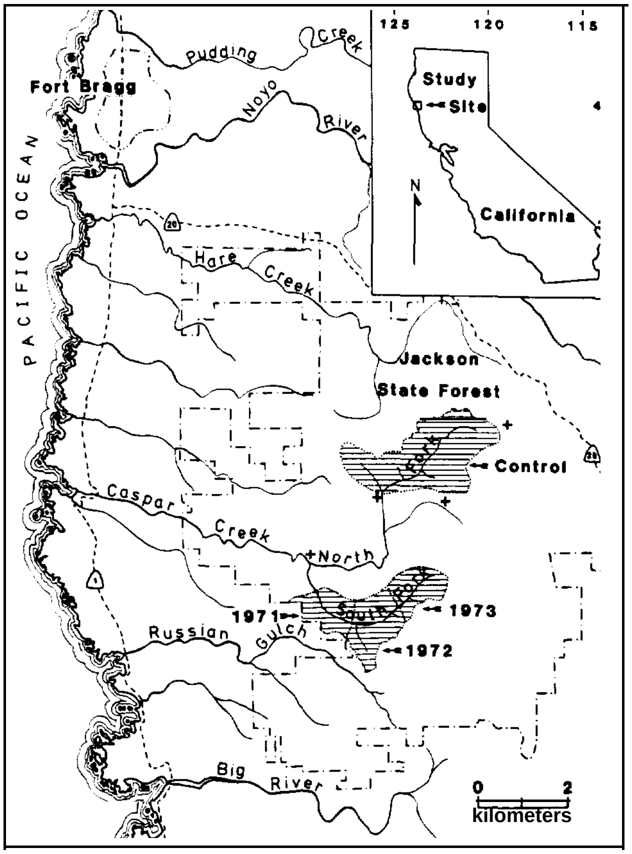

Fig. I. Caspar Creek experimental watersheds: North Fork (control) and South Fork (areas logged each year are shown and rain gauge locations are indicated with a plus symbol).

A peak flow of at least 28.3 L/s (0.056 L/(s ha)) on the North Fork, (2) complete records for both the control and treated watersheds for the variable being measured, (3) storm pairs that approximately corresponded in time, and (4) storm flows possessing an initial rise greater than 0.0055 L/(s ha h). These criteria led to the selection of about nine storms per year, producing sample sizes of 128 for the volume analyses and 129 for the peak flow analysis. Precipitation records were also examined for localized differences in storms, but none were identified. For each storm hydrograph we determined the initial, peak, and ending flow and calculated the total volume and quick flow volume.

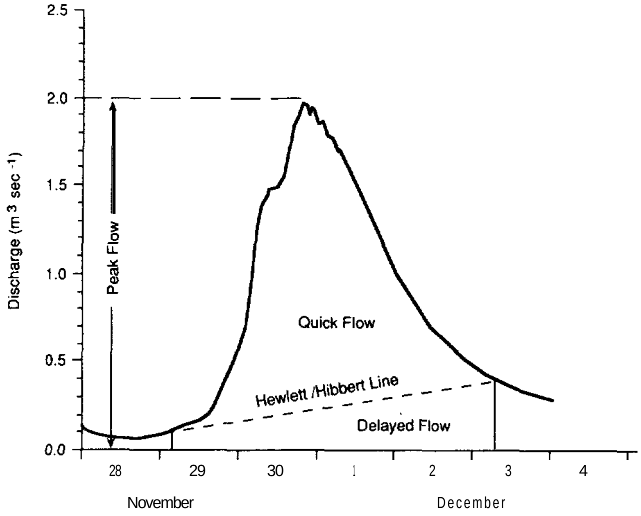

Fig. 2. Hydrograph separation applied to runoff from the North Fork of Caspar Creek between November 29, 1973, and December 3, 1973 (adapted from *Krygier and Harr [1972]*).

Hydrograph separation into quick flow volume (that part of runoff which enters the stream promptly after the rainfall) and delayed volume (the sustained fair-weather component of the runoff) was based on the method described by *Hewlett and Hibbert* [1967]. A line that projected from the initial rise, at a slope of 0.0055 L/(s ha h), until it intersected the falling limb of the hydrograph divided the storm hydrograph into quick flow volume and delayed volume. Although no in-depth analysis of this method of hydrograph separation was conducted, inspection of plots of all the hydrographs indicated that it was performing satisfactorily. Peak flow and total volume were also determined for each of the hydrographs selected (Figure 2). A least squares regression [*Dixon and Jennrich*, 1981] was used to determine if the peak flow, total volume, or quick flow volume were altered after road building or logging. The total volume, quick flow volume, and peak flow regression equations for the calibration period were fit to a logarithmic form. Other multiple regression models were tried, but the logarithmic model best met the assumption of homoscedasticity and gave the best distribution of data points along the entire range of the regression [*Daniel and Wood*, 1971]. The form of the regression equation was

TABLE 2. Summary of Treatments in the South Fork of Caspar Creek

	Year					
Parameter	1967	1971	1972	1973	Average	Total
Area harvested, ha	19*	101	128	176		423.7
Average stand volume, m^3/ha	993	815	731	598	708	
Volume harvested, m^3/ha	993	483	502	386	471	
Volume harvested. %	100	59	69	65	67	
Road construction, km	6.8	0.7	0.2	0.2		7.9
Road construction, ha	19.0	2.0	0.5	0.7		22.2
Skid trails, ha	0	8.8	11.2	15.4		35.4
Landings, ha	0	3.5	1.3	3.6		8.4
Area compacted (roads, landings, and skid trails). %	4.5	7.8	10.9	15.6		15.6

* Road construction right-of-way area.

$$\text{Log (SFvar)} = b_0 + b_1 \text{ Log (NFvar)} \qquad (1)$$

where (SFvar) was the South Fork hydrograph variable, and (NFvar) represents the same variable on the North Fork.

We hypothesized that the regression equation for the calibration period is still valid for the treated period and tested ($p = 0.10$) this, utilizing a procedure described by Chow [1960]. We chose Chow's test because it is more powerful than analysis of covariance when the assumptions of regression analysis are violated [*Wilson,* 1978]. The 10% significance level was chosen to reduce the risk of committing a type II error (i.e., where the test would not show a change in storm volumes or flows when there actually was a change). Considering the potential impacts which could occur from increasing storm volumes or flows, we preferred to take a higher risk of committing a type I error (i.e., determining that storm volumes or flows were increased when in fact they were not).

Analysis of Lag Time

A different suite of hydrographs was used in this analysis because some storms were deemed unacceptable for lag time calculations. A total of 100 pairs of storm hydrographs were analyzed.

The hydrograph separation method of ***Hewlett and Hibbert*** [1967] was again used to delineate quick and delayed flow. Each hydrograph was plotted to visually check the fit of the separation line. In most cases, separate storm events were easily discernible, as the separation line usually intersected the falling limb before the next storm started. In those situations where the recession limb did not quite reach the separation line before rising again the lower end of the recession limb was graphically extrapolated to the point of intersection. This adjustment was based on the determination that both watersheds varied little in the configuration of the tail end of their recession limbs. In about 15% of the hydrographs we extrapolated the data but only in cases where less than 15% of the quick flow volume occurred during the extrapolation. If continuing rainfall produced long, flat hydrographs with two or more inseparable peaks, the hydrographs were considered unsuitable for analysis and were discarded.

After each hydrograph was separated, the time coordinate of the quick flow centroid was determined. Because only the time coordinate of the quick flow hydrograph centroid is needed to calculate lag time, the "partial areas" were approximated by narrow vertical trapezoids having bases equal to the elapsed time between tabulated points on the hydrograph (linking approximately straight line segments) and sides with heights equal to the quick flow discharges at the boundaries of the intervals. Denoting these partial areas by m_j, and the time coordinates of their midpoints by c_j, the time coordinate of a hydrograph centroid C is approximated by

$$C = \sum_j c_j m_j \Big/ \sum_j m_j \qquad (2)$$

Applied to a hydrograph, this equation was expressed in a computer program algorithm:

$$C = \sum_n \left(\frac{T_n + T_{n+1}}{2}\right)\left(\frac{D_n + D_{n+1}}{2}\right)(T_n - T_{n+1}) \cdot \left[\sum_n \left(\frac{D_n + D_{n+1}}{2}\right)(T_n - T_{n+1})\right]^{-1} \qquad (3)$$

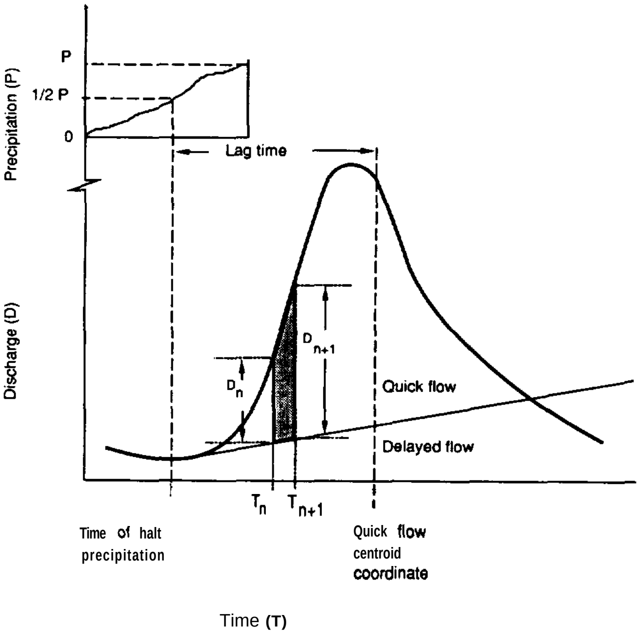

Fig. 3. Hydrograph lag time was determined by relating the time of occurrence of 50% of the rainfall to the centroid of quick flow.

where T_n and T_{n+1} were the time in minutes at the start and end of the nth interval and D_n and D_{n+1} were the corresponding quick flow discharges in liters per second (Figure 3). The centroid time coordinate is given in minutes from the beginning of the rainfall that produced the hydrograph. The time was recorded when one half of the rainfall for that storm had fallen and is referred to as the precipitation midpoint (Figure 3). The lag time for each hydrograph was measured as the time separation between the occurrences of the precipitation midpoint and the time coordinate of the quick flow runoff centroid (Figure 3).

Each hydrograph was separated at the peak in order to determine if a change in lag time after logging was restricted to either the rising or falling limb of the hydrograph. The time coordinates of the quick flow centroid of the rising and falling limbs were established by using equation (2) over the respective limbs of the hydrograph. These lag times were also computed from the precipitation midpoint.

The data were analyzed for three time periods: calibration (hydrologic years 1963–1967), postroad building (1968–1971), and postlogging (1972-1981). The South Fork (the treated watershed) lag time was regressed on the North Fork (the control watershed) lag time for each of the three periods. The data were checked for inconsistencies and examined using Chow's test (alpha = 0.05) to decide if significant differences in lag time occurred after treatment [Chow, 1960].

A ratio (LAGSHIFT) was used to examine changes that occurred seasonally and with time after treatment. LAGSHIFT was defined as

$$\text{LAGSHIFT} = \frac{\text{North Fork lag time} - \text{South Fork lag time}}{\text{North Fork lag time}} \qquad (4)$$

Six variables were screened to determine which were most useful in predicting the ratio LAGSHIFT. Mallows' C_p

TABLE 3. Regression Coefficients R^2, Sum of Squared Residuals, and Chow's F Test Showing Which Regressions Were Significantly Different From the Calibration Period Regression, for Each Hydrograph Parameter

Regression	n	Regression Coefficients* b_0	b_1	R^2	Sum of Squared Residuals	Chow's F Test
Total volume						
Calibration	49	0.258	0.883	0.982	0.466	
Calibration and road	86	0.263	0.882	0.984	0.728	0.71 ns
Calibration and log	91	0.424	0.817	0.953	2.112	3.951
Quick flow volume						
Calibration	49	0.393	0.834	0.972	0.936	
Calibration and road	86	0.386	0.841	0.975	1.392	0.62 ns
Calibration and log	91	0.531	0.778	0.945	3.076	2.56†
Peak flow						
Calibration	49	0.241	0.951	0.968	0.492	
Calibration and road	86	0.299	0.933	0.968	0.856	0.94 ns
Calibration and log	92	0.476	0.886	0.927	2.074	3.51†

Calibration, calibration period; road, roaded period; log, logged period; ns. not significant (at p greater than 0.10).

* The b coefficients represent regressions of the form $\mathrm{Log}(\mathrm{SFvar}) = b_0 + b_1 \mathrm{Log}(\mathrm{NFvar})$.

† Significant (p less than 0.01).

[Daniel and *Wood,* 1971] was the screening criterion using an all possible subsets regression program [*Frane*, 1981]. C_p is used to compare regression equations having different numbers of independent variables or different sets of variables. It adjusts its value to the number of variables being used to counteract the tendency for larger models to automatically appear to fit the data better. The six variables were North Fork peak flow (NPFLOW), storm sequence number within hydrologic year (SEQNO), storm size (SIZE), the cumulative proportion of the area that had been logged prior to each hydrologic year (PROPLOG), antecedent precipitation index (API), and the ratio of the proportion of area logged to the storm sequence number (LOGSEQ).

RESULTS AND DISCUSSION

Effects of Road Construction

Chow's test failed to detect a significant change in the regressions for total volume, quick flow volume, peak flow, or lag time after road building (Tables 3 and 4; Figures 4 and 5). These results are consistent with those of other similar studies. Roads occupied 4.5% of the land surface in the South Fork drainage. This proportion is notably lower than 12%, a value often taken as the threshold at which significant impacts begin to occur (based on results reported by *Harr et al.* [1975]).

Road systems can alter streamflow by reducing infiltration on road surfaces, intercepting subsurface flow, and quickly conveying water to the stream in ditches. Although these effects most likely occurred to some degree in the study area, they were not large enough to statistically significantly change the parameters analyzed here. The absence of a detectable change may be due to 88% of the 6.8-km road mileage being within 61 m of the main channel of the South Fork. Consequently, the routing of precipitation was probably unchanged throughout most of its path to the stream. These results suggest that road construction did not appreciably affect the streamflow regime of the South Fork watershed. In analyzing peak flows, Ziemer [1981] arrived at a similar conclusion.

Effects of Logging

In the total volume, quick flow volume, and peak flow analyses there was a significant (p less than 0.01) difference between the calibration and the combined calibration plus postlogging regressions for all three dependent variables (Table 3). In comparing the plotted regressions for the calibration and logged period total storm volumes (Figure 5) it appears that the small storm volumes are increased after logging (agreeing with *Ziemer* [1981]). However, the regression lines converge and cross as storm size increases,

TABLE 4. Regressions of South Fork Lag Time on North Fork Lag Time

Regression	Intercept	Coefficient	r^2	n	F*	p*
Hydrograph						
Calibration	0.936	0.791	0.94	29	...	...
Postroading	1.402	0.697	0.86	27	1.28	0.27
Postlogging	2.736	0.589	0.77	44	2.46	<0.01
Rising Limb						
Calibration	0.002	0.758	0.90	29	...	...
Postlogging	0.029	0.523	0.59	44	2.31	<0.01
Falling Limb						
Calibration	0.580	0.828	0.96	29	...	...
Postlogging	3.327	0.611	0.71	44	4.42	<0.01

*Critical F and significance probability p values refer to Chow's test regression comparisons.

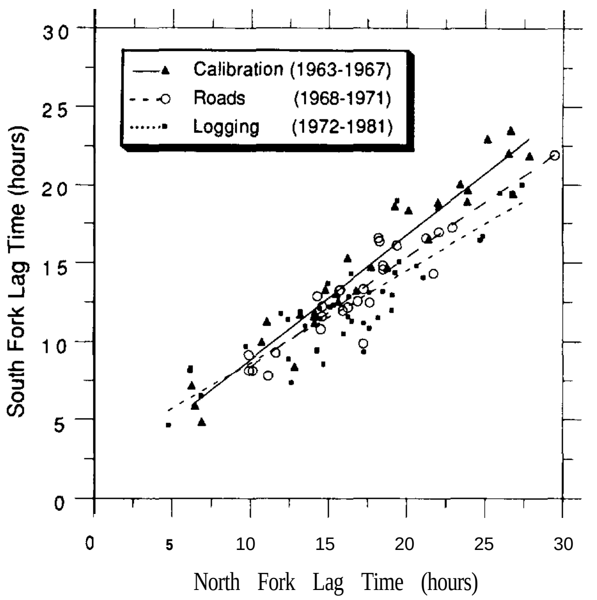

Fig. 4. Regression of South Fork on North Fork lag times for calibration (1963–1967), postroading (1968–1971), and postlogging (1972-1981) hydrologic years.

indicating that the larger storm volumes were not increased after logging (we presume that the crossing of the regression lines is an artifact of using simple linear regressions and does not indicate that large flows were reduced by logging). The plotted regressions for peak flow and quick flow volume (not shown) were very similar to the storm volume regressions.

When analyzing the larger storms (events occurring about eight times each year) separately from the small storms, *Wright* [1985] found that after logging the larger storm volumes or peak flows were not significantly increased (p greater than 0.10) after either road building or logging. Only the increases of the smallest peak flows (less than 566 L/s) and storm volumes (less than 1209 m^3) were statistically significant. The South Fork total storm volumes, quick flow volumes, and peak flows in the flow class of less than 566 L/s increased relative to the North Fork by 132, and 170, and 111%, respectively, after logging. Wright found that during the roaded period the smallest peak flows were increased approximately **20%** (p less than 0.10), although regression analysis using all the storm hydrographs and Chow's test failed to detect a significant difference. The increases in the smaller storm volumes or peak flows after logging could have been caused by either reduced evapotranspiration and reduced interception from the removal of the trees or from compaction by the roads, skid trails, and landings.

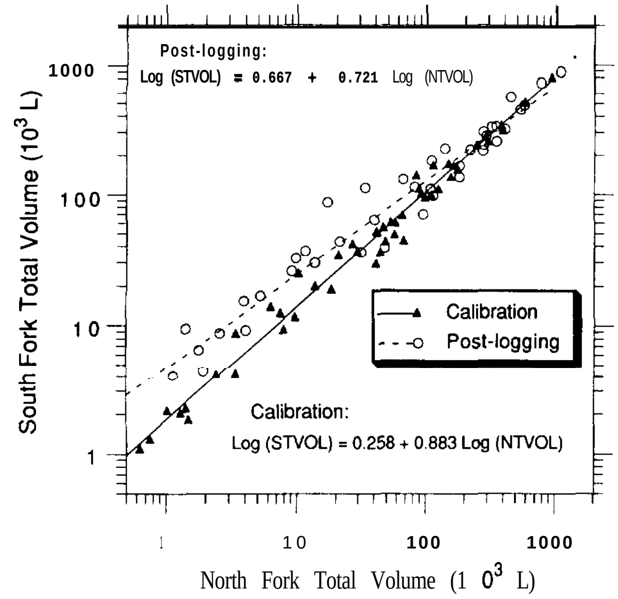

Fig. 5. Relationship between total storm volumes on the South Fork (STVOL) and North Fork (NTVOL) of Caspar Creek during the calibration period and logged period.

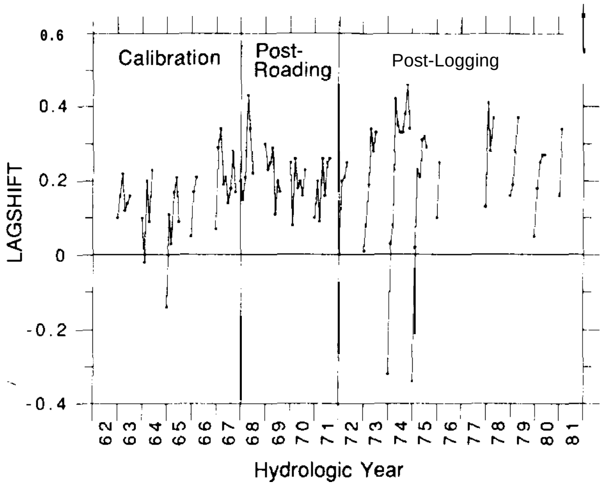

Fig. 6. LAGSHIFT (the relative change in the South Fork lag time) within each hydrologic year during the study.

After logging of the South Fork, lag time was significantly (p less than 0.01) changed from undisturbed conditions (Table 4; Figure 4). The average lag time decreased about 1.5 hours. We found similar decreases in lag time for the rising limb, falling limb, and entire storm hydrograph.

Multiple regression analysis, with the ratio LAGSHIFT (equation (4)) as the dependent variable, indicated that the two most important variables among those screened were the proportion of area logged (PROPLOG) and the ratio LOGSEQ, which was PROPLOG divided by storm sequence number (SEQNO). LOGSEQ was the more important of the two, indicating seasonal trends in LAGSHIFT. Similarly, *Ziemer* [1981] found that LOGSEQ was the most important variable in his peak flow analysis of Caspar Creek. The values for PROPLOG in various hydrologic years were 0.04 (1968–1971), 0.28 (1972), 0.59 (1973), and 1.00 (1974-1981).

The ratio LAGSHIFT for each storm was plotted in time sequence to graphically display changes of hydrograph lag times seasonally and with time (Figure 6). The effects of logging appear to be the most pronounced in the years immediately after logging, and the ratio appears to follow a seasonal pattern, being lowest early in the hydrologic year.

Evapotranspiration and Interception Effects

Evapotranspiration differences during the growing season can produce substantial differences in soil moisture between logged and unlogged watersheds. This, in turn, can cause increased storm runoff in the wetter, logged watershed. The

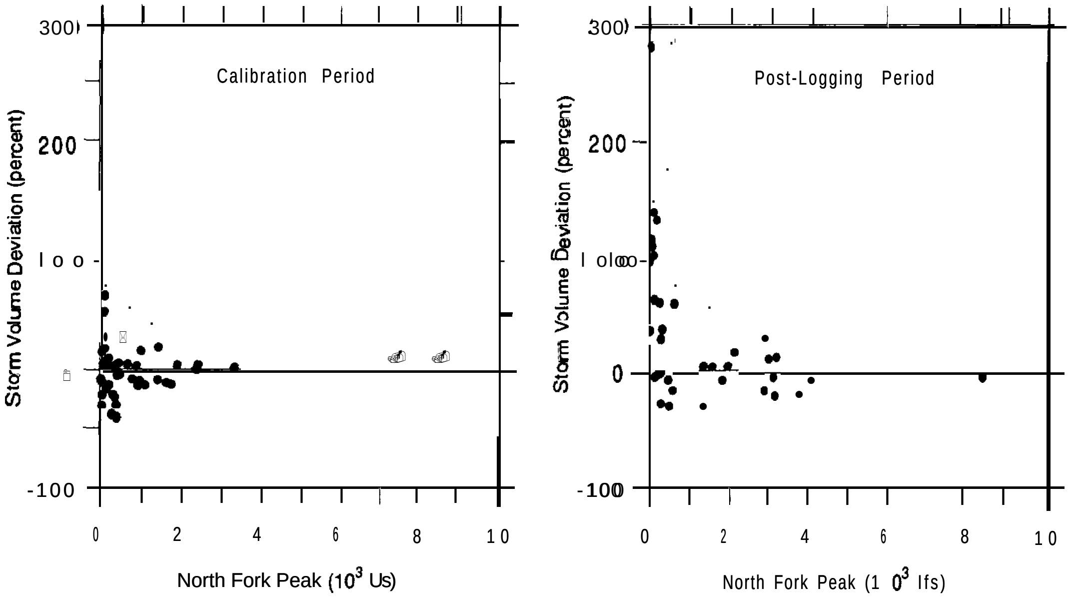

Fig. 7. Deviation of observed South Fork storm volumes from predicted volumes during the calibration and logged periods as a function of peak flow in the North Fork.

increased storm volume could also increase lag times because the centroid of larger hydrographs would tend to be shifted back in time. After fall storms have satisfied the soil moisture deficit in the North Fork (control) watershed the relative responses of the North and South Fork would be expected to be similar to what it had been during the calibration period with respect to both the volume of storm runoff and peak flows. This is, in fact, what Ziemer [1981] found. Evapotranspiration is reduced during the winter months and the intervals between storms are short. Therefore soil moisture differences generally do not become significant again until spring or summer.

Interception is another variable that is changed by timber harvesting and could affect storm runoff. *Rothacher* [1963] found that interception during storms of 50-100 mm on the H. J. Andrews Experimental Forest in the Cascade Mountains of Oregon averaged 6-12 mm in old growth Douglas fir. Assuming the redwood canopies on Caspar Creek had similar water-holding capacities, interception would have been an important factor only in small storms. Many of the small storm flows on Caspar Creek were in response to less than 25 mm of rainfall. Assuming that the logging removed 60% of the canopy, the storm volume from a 25-mm rainfall event could have been increased by approximately 20% due to the reduced interception. For larger storms, interception would be less significant because the canopy quickly reached its water-holding capacity of 6-12 mm. The largest storm flows were in response to over 220 mm of rainfall. Removal of 60% of the canopy could have increased the total storm runoff volume no more than about 2% over the untreated watershed (ignoring evaporation from interception storage).

The larger storms occurred during midwinter when both watersheds had high soil water levels. This, combined with the reduced effects of interception for larger midwinter storms, caused logging to have insignificant effects on large storm peaks or volumes. The increases from logging decreased as the storm size increased (Figures 7 and 8). The small storm volumes were increased up to 290% after logging, and the very largest storms were not increased. The peak flows were also increased up to 240% for the smaller storms after logging but not for the larger storms.

The storms which showed increases in lag time were generally the early fall storms, presumably occurring before soil moisture recharge was completed in the logged watershed. The most marked increases occurred in the years during and immediately following logging. A plausible explanation for the increased lag time of small early fall storms can be based on the increased volume of runoff of those storms shifting the hydrograph centroid back in time. From the appearance of Figure 4, however, we are inclined to believe that the "increase" in lag time is an artifact of the regression analysis. Current studies in the North Fork of Caspar Creek may indicate if there is a physical explanation for increased lag time of small storms [Ziemer and *Albright*, 1987].

After soil moisture recharge had occurred and if soil moisture differences between the watersheds were small, the lag time generally decreased in the South Fork drainage. These results imply that the hydrologic regime was altered in such a way that runoff reached the stream gaging station more quickly after logging than before it. The entire hydrograph was moved on the time axis to a faster response time. No increase was seen in total volume, quick flow volume, or peak flows of large winter storms, therefore it appears that hydrograph response time was shortened but hydrograph shape did not change appreciably.

Compaction Effects

Compaction of the watershed may have also contributed to the increase in the peak flow, total volume, and quick flow volume for the smaller storms and caused their lag times to be shortened.

The soils of Caspar Creek have high infiltration rates [*Wosika*, 1981]. Consequently, overland flow on the natural forest floor rarely occurs. Skid trails, landings, and roads

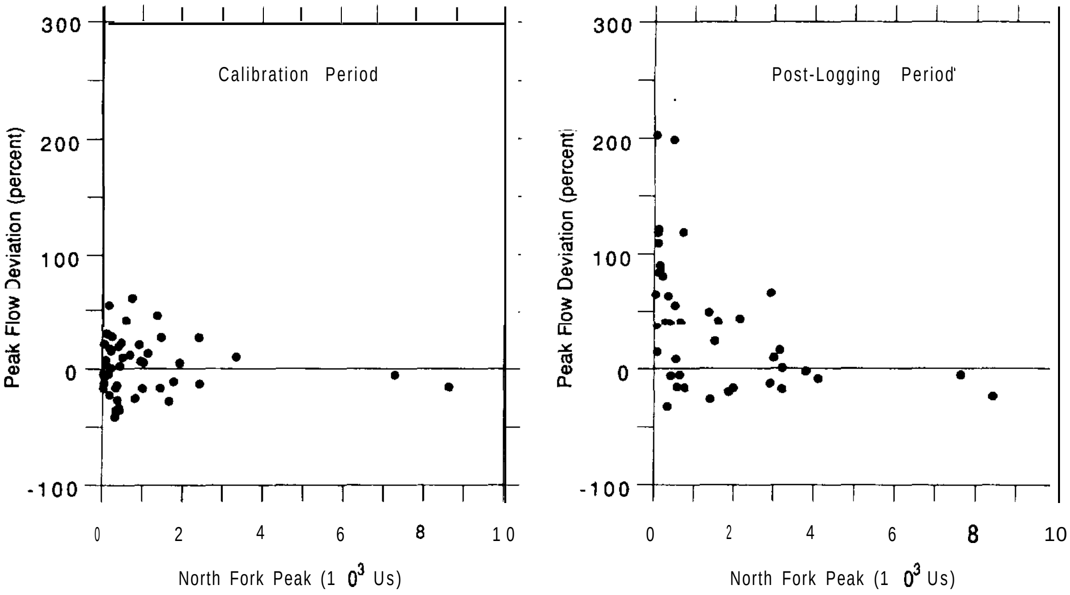

Fig. 8. Deviation of observed South Fork peak flows from predicted peaks during the calibration and logged periods as a function of peak flow in the North Fork.

compacted the soil, promoting surface runoff. This may have created a direct, more efficient route for water to reach the stream. All areas of compacted and disturbed soil do not contribute equally to increased runoff. It is hypothesized that runoff on a ridge top road would more likely be dispersed and infiltrate into the soil. Midslope roads have the greatest potential for affecting runoff by intercepting subsurface flow as well as rainfall and dumping it into side channels. Roads near the stream have less effect since the flows they intercept are almost to the stream anyway (R. Beschta, personal communication, 1986). Most of the roads and landings in the South Fork watershed are adjacent to the stream. The skid trail pattern in the South Fork watershed could efficiently transmit water to the stream. The skid trails converged downhill and were not well water-barred. The effects of skid trails on increasing storm runoff would be less than a similarly oriented road, since the infiltration is presumably higher on skid trails. No in situ measurements were made of infiltration or compaction, but the road and landing operating surfaces appeared nearly impervious. Overland flow on the skid trails was evidenced by their rill erosion rate of 20.9 m^3/ha.

We do not believe that compaction significantly increased the larger storm volumes or flows. During small midwinter storms of less than 35 mm, only 1–5% of the rainfall ran off as quick flow on the control watershed. The compacted areas (15% of the South Fork watershed) might increase the proportion of the rainfall that runs off another 5–10% in these small storms because of the more efficient transmission of water to the stream. During the major storms, over 75% of the rainfall ran off as quick flow in the control watershed. Although little overland flow occurred during the major storms, the translatory flow, or flow by displacement through the soil, becomes more efficient as the soil approaches saturation [*Harr*, 1976]. Consequently, the effects of compaction on the hydrograph become less apparent as an appreciable proportion of a watershed approaches saturation. The "more efficient" overland flow on compacted areas may be masked by the more efficient translatory flow from the recharged watershed. Since the larger storm volumes and peak flows appear unaffected, we agree with *Ziemer's* [1981, p. 915] conclusion that "compaction and reduced infiltration did not play a significant role."

After logging, subsurface flow may have been intercepted by roads, skid trails, or landings and directed into roadside ditches. However, the rate of delivery to these higher-velocity portions of the slope (the 15% in roads, landings, and skid trails) was governed by the rates of infiltration and subsurface flow on the remaining 85% of the watershed. The effect was an earlier start of quick flow and quicker hydrograph response which shifted the hydrographs forward in time but left them unchanged in shape.

COMPARISON WITH OTHER STUDIES

Our results are contrary to those reported by ***Harr et al.*** [1975, p. 436], who concluded that "peak flows were increased significantly after road building, but only when roads occupied 12% of the watershed." ***Harr et al.*** [1979], reporting studies on the Coyote Creek watersheds in southwestern Oregon, concluded that logging and road building increased the largest storm flows as well as the small storm flows and that the increases were related to compaction of the watershed by roads, landings, and skid trails. Coyote Creek watershed 1, which showed the greatest increase in peak flows, was treated similarly to Caspar Creek. Both were logged removing approximately the same percent of the volume by tractor and compacting about the same proportion of their watersheds (Table 1). In the South Fork of Caspar Creek, roads and landings were usually near the streams, and the skid trails were oriented such that they should have been effective in delivering the water to the stream when runoff occurred.

One of the problems common to paired watershed experiments is obtaining storm flows that are well distributed, particularly in the larger flow classes. The distribution of the

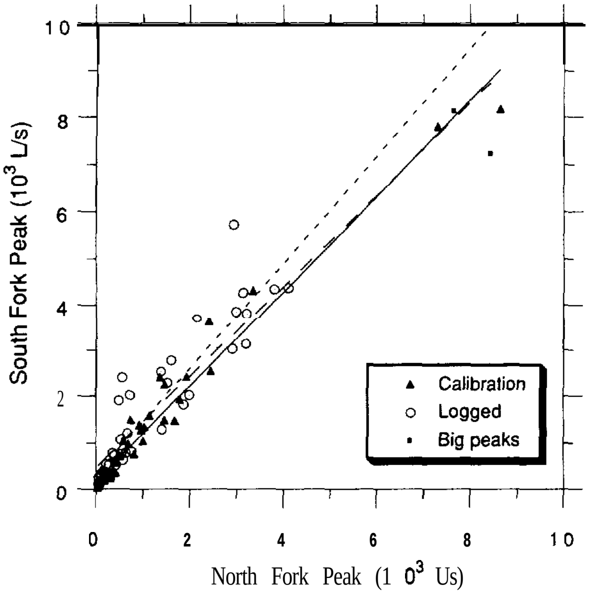

Fig. 9. Relationship between peak flows on the South Fork (SPFLOW) and North Fork (NPFLOW) of Caspar Creek during the calibration period, logged period, and logged period with the two largest postlogging storms excluded from the regression analysis.

large storm flows was a problem in the Coyote Creek and Alsea studies. The Coyote Creek study did not have any large storm flow data for the calibration period because the large storms that occurred during the calibration period filled the weir ponds with sediment so that discharge could not be measured accurately [*Harr et* al., 1979]. In the Alsea study, no peaks on either Needle Branch of Deer Creek 4 exceeded the estimated annual peak of 9.2 L/(s ha) during the postclearcutting period. Caspar Creek had four large storm flows, all fairly close in size (ranging from an estimated 12- to 25-year return period). We were fortunate that two occurred during the calibration period and two occurred during the postlogging period.

We altered our data to test the hypothesis that the differences between our results and those of ***Harr et al.*** [1975, 1979] were caused by the absence of data from large storm flows in either their calibration periods or after logging. We also did not use a logarithmic transformation of our data since neither the Alsea or Coyote Creek studies used logarithms. When we removed the two highest peaks from our calibration data, the results suggested a reduction in the higher peak flows after logging. It was only when we retained the two largest prelogging peaks and omitted the two largest peaks during the postlogging period from our data that the regressions were then more like the regressions for the Alsea and Coyote Creek studies (Figure 9). The regressions showed that both small and large peak flows increased after logging. Conclusions based on these regressions would be similar to the conclusions made in the Alsea and Coyote Creek studies. This exercise illustrates the sensitivity of regression analyses to the distribution of the data, especially extreme values. It supports our hypothesis that the differences between our results and those from the Alsea and Coyote Creek studies may be caused by the lack of large flow data on the Alsea and Coyote Creek studies, which created a need to extrapolate the regressions to estimate treatment effects.

SUMMARY AND CONCLUSIONS

Road building on 5% of the watershed and selectively removing 67% of timber volume by tractor logging significantly increased runoff volumes and peak flows only in the very smallest storms (those with peaks less than 566 L/s). The large flows in this study were not increased even though over 15% of the watershed was compacted in skid trails, landings, and roads. Although a decrease in lag time showed that the storm hydrographs were shifted forward in time, their shapes were unchanged.

From these results we conclude that logging or forest road construction that causes no more ground disturbance than we observed is unlikely to change a watershed's streamflow regime adversely in a rain-dominated hydrologic environment. Therefore watershed management based on the assumption that large channel-forming flows are increased by timber management may be erroneous in an environment similar to Caspar Creek's Other studies have reported increases in the larger peak flows from roading and logging related compaction of the watershed [***Harr et al., 1975,*** 1979]. But those studies were lacking in data for the higher flows, either during the calibration period or after treatment. We believe that the lack of those data, not hydrologic changes, were responsible for the "observed" increase in large peak flows. In this study, with a reasonable distribution of data in the higher flows in both periods and with over 15% of the watershed compacted, no significant increase in the major channel-forming flows was detected.

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