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Storm Flow Response to Road Building and Partial Cutting In Small Streams of Northern California

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To assess the influence of road building and logging on storm flow response, a pair of watersheds were studied at Caspar Creek near Fort Bragg in northern California from 1963 to 1975. Selection cutting and tractor yarding of 85-year-old second-growth redwood and Douglas-fir forest did not significantly affect large peak streamflows. The first streamflow peaks in the fall, however, were increased about 300% after logging. These early fall storms produced small peaks, which had little, if any, hydraulic consequence. The effect of logging on peak flow was best predicted by a variable representing the percentage of the area logged divided by the sequential storm number within the year.

INTRODUCTION

Debate over the influence of forest management activities on storm runoff has been lengthy and, occasionally, heated. A number of paired watersheds have been studied in attempts to resolve this controversy.

Early studies at the Coweeta Hydrologic Laboratory in North Carolina found that clear-cutting hardwoods and leaving the trees where they fell increased annual streamflow volume from a 13-ha watershed but did not increase storm peak flows [*Hoover,* 1945; *Hewlett and Hibbert,* 1961]. In a similar clear-cutting experiment on a 44-ha watershed at Coweeta, *Hewlett and Helvey* [1970] found storm flow volume increased by 11% after cutting and most of the increase occurred in the recession phase. They recorded a 7% increase in peak discharge but decided that their data was inconclusive. A commercial clear-cut in a 30-ha watershed in the Fernow Experimental Forest in West Virginia produced a 24% increase in storm flow discharge during the growing season but only a 2.5% increase during the dormant season [*Reinhart,* 1964]. Maximum instantaneous peaks were increased by 2.5% during the growing season and decreased 4% during the dormant season. Clear-cutting a 15.6-ha watershed at Hubbard Brook, New Hampshire, produced results comparable to those from Coweeta and Fernow [*Hornbeck,* 1973].

In general, studies in the eastern United States indicate that increases in peak flow after logging are restricted principally to rainstorms that occur during the growing season. During the growing season, differences in soil moisture storage develop between the logged and unlogged watersheds. These soil moisture differences are the result of decreased evapotranspiration and interception loss in the logged watershed relative to the uncut watershed. Once the soil moisture differences between watersheds have been satisfied by rainfall, no increases in peak flow are expected. During the dormant season the differences in evapotranspiration and therefore in soil moisture storage between logged and unlogged watersheds are minor. Only small differences in winter storm flow between treated and control watersheds have been found.

These results do not necessarily apply to the western United States, where summers are characterized by long, rainless periods. Very little soil moisture recharge occurs during the growing season, and large soil moisture differences can develop between logged and unlogged watersheds during the summer. The soil begins to be recharged with moisture in fall with the onset of the rainy season, a period that also corresponds to the beginning of vegetative dormancy. In Oregon, *Rothacher* [1971, 1973] reported that the first storms of the fall produced streamflow peaks from a 96-ha clear-cut watershed in the H. J. Andrews Experimental Forest that ranged from 40% to 200% larger than those predicted from the prelogging relationship. In the Alsea watersheds near the Oregon coast, *Harris* [1977] found no statistically significant change in the mean peak flow after clear-cutting a 71-ha watershed or patch-cutting 25% of an adjacent 303-ha watershed. When *Harr et al.* [1975] included an additional 30 smaller early winter runoff events, a significant increase in peak flow was found after clear-cutting. These smaller runoff events reduced the size of the average peak used in Harris' study by about one half. Average peak flow was increased 30%, and average fall peak flow was increased 122% [*Harr,* 1976]. Large peak flows, which tend to damage stream channels and transport most of the sediment, were not significantly affected by logging in either the H. J. Andrews [*Rothacher,* 1973] or Alsea [*Harr,* 1976] studies.

Few studies have evaluated the effect of partially logging a watershed on hydrograph response. When 20% of a 43-ha Pennsylvania watershed was clear-cut, average peak discharge during the growing season rose by 351%, from 0.11 to 0.50 $(m^3/s)/km^2$ [*Partridge and Sopper,* 1973]. When 25% of a 101-ha watershed in the H. J. Andrews Experimental Forest was clear-cut in patches, *Rothacher* [1973] found no significant change in the slope of the before-logging and after-logging regressions. The adjusted mean peak flow, however, increased 10% from 0.30 to 0.33 $(m^3/s)/km^2$, after logging. This increase was highly significant. *Harr et al.* [1979] reported substantial peak flow increases after shelterwood harvesting a 69-ha watershed and clear-cutting a 50-ha watershed in southwestern Oregon. No significant change in peak discharge was found, however, after patch-cutting 30% of an adjacent 68-ha watershed. Only 14 peaks were used to calibrate these Coyote Creek watersheds, none of which exceeded a discharge of 0.64 $(m^3/s)/km^2$.

In the few studies where the impact of roads alone on peak flow has been evaluated, any changes following road construction have been variable and, in general, statistically nonsignificant. In the partially cut 101-ha H. J. Andrews watershed, a regression line for the period after road construction

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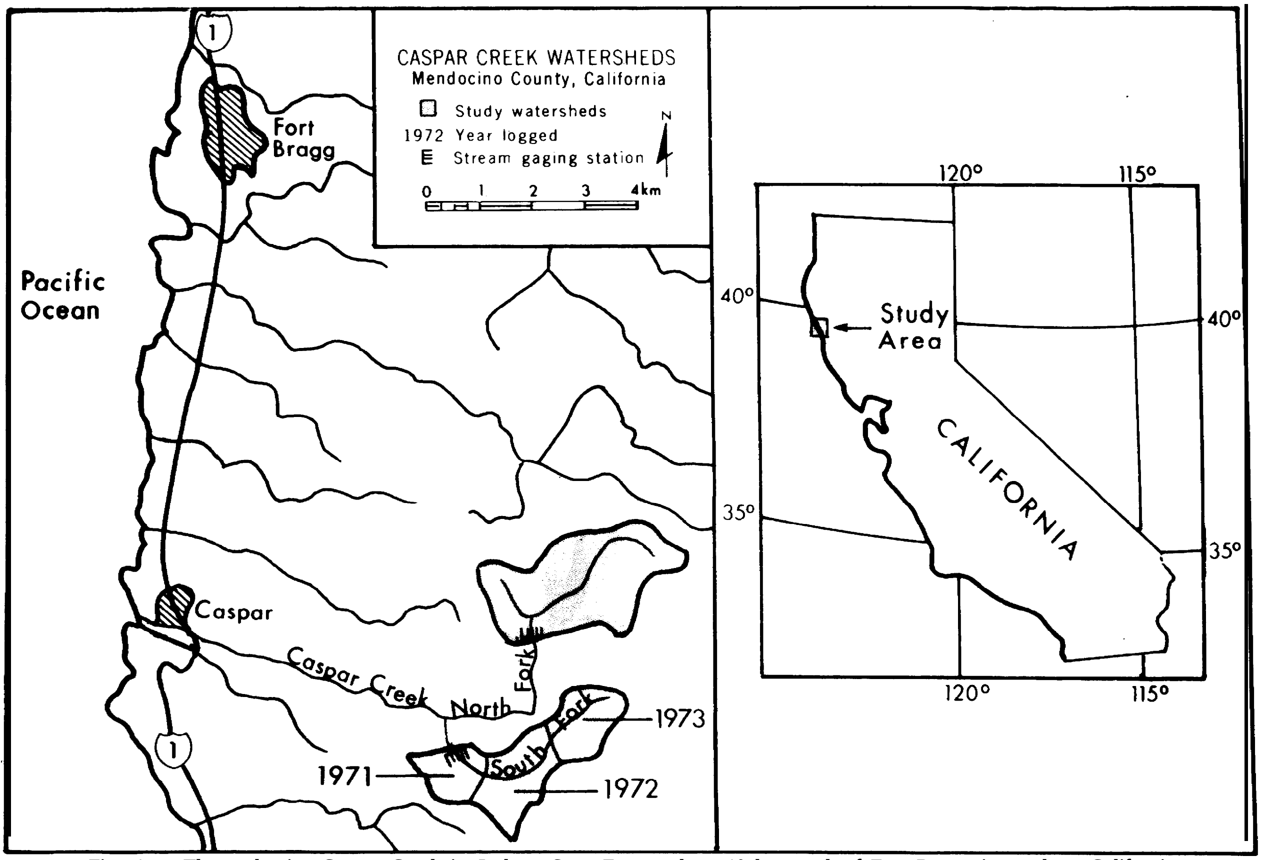

Fig. 1. The study site, Caspar Creek in Jackson State Forest, about 10 km south of Fort Bragg, in northern California.

had a significantly lower slope than the prelogging relation. *Rothacher* [1973] could find no logical reason why the peaks should be lower after building roads than they were before treatment. Peak flow appears to be increased when roads and other compacted areas occupy more than 12% of the total watershed area [*Harr et al.,* 1975]. The mechanism proposed is that peak increases result from increased surface runoff caused by compaction rather than any relationship to changes in evapotranspiration. The effects of roads on major storm peaks, however, has not been tested adequately. In the four watershed studies discussed by *Harr* [1971] the peak events used in the analyses were generally <0.33 $(m^3/s)/km^2$.

Within the past two decades, nearly all of the studies in the west have dealt with either clear-cutting or patch clear-cutting old-growth forests. None has addressed the effect the selective cutting a second-growth forest on storm flow from small watersheds.

In the early 1960's the Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, and the California Department of Forestry began an on-going cooperative study to evaluate the effects of road building and timber harvest on streamflow, sedimentation, and fish habitat. This paper reports the influence of selection cutting and tractor yarding an 85-year-old second-growth redwood and Douglas-fir forest on storm flow response of Caspar Creek in northern California. The influence of road building and logging on erosion and sedimentation has previously been reported by *Krammes and Burns* [1973], *Tilley and Rice* [1977], and *Rice et al.* [1979].

CASPAR CREEK

Caspar Creek is located in the Jackson State Forest about 10 km south of Fort Bragg, California (Figure 1). At Caspar Creek, streamflow from a pair of watersheds has been measured continuously since October 1962. A debris basin, which also serves as a stilling pond, with a surface area of about 0.1 ha is immediately upstream from each 120° V-notch weir.

The South Fork study area encompasses about 424 ha, and the North Fork about 508 ha. Elevation of the watersheds ranges from 37 to 320 m.

Slopes are relatively gentle. About 35% of the two experimental watersheds has slopes of <30%. The South Fork has slightly less of its area on steep slopes than the North Fork. About 7% of the North Fork slopes are >70%, whereas <1% of the South Fork slopes are this steep.

The soil on about 80% of the North Fork and South Fork watersheds is of the Hugo soil series. The remaining 20% of the North Fork is Mendocino soil and of the South Fork, Caspar soil [*Rice and Sherbin,* 1977]. Hugo and Mendocino soils are derived from sedimentary rocks of Cretaceous age. The parent material of Hugo soil is hard, coarse-grained sandstone and shale that is deeply shattered and moderately weathered. The standstone underlying Mendocino soil is highly weathered and is often streaked with clay lenses. Caspar soil is derived from weakly consolidated marine terrace deposits of sand and gravel of Pleistocene age.

The climate of the study area is typical of low-elevation Pacific coastal watersheds. Winters are mild and wet, and summers are warm and dry. Throughout the summer, coastal fog

TABLE 1. Timber Harvest in the South Fork of Caspar Creek (1967 Through 1973)

Year Logged	Area Harvested, ha	Average Total Stand Volume, m^3/ha	Average Harvest Volume, m^3/ha	Road Construction, ha	Skid Trails, ha	Landings, ha
1967*	19	993	993	19.0		
1971	101	815	483	2.0†	8.8	3.5
1972	128	731	502	0.5†	11.2	1.3
1973	176	598	386	0.7†	15.4	3.6
Average		708	471			
Total	424			22.2	35.4	8.4

*Road construction.
†Temporary roads.

often extends into the watersheds until late morning. Average annual precipitation is about 1190 mm but ranged from 838 to 1753 mm during the study. About 90% of the annual precipitation falls from October through April during low-intensity cyclonic storms. Snow is a rare event in these low-elevation coastal watersheds.

Both of the watersheds had been clear-cut and burned in the late 1800's, but when the study began in 1963 they supported fairly dense stands of second-growth Douglas-fir, (*Pseudotsuga menziesii* (Mirb.)Franco), redwood (*Sequoia sempervirens* (D. Don)Endl.), western hemlock (*Tsuga heterophylla* (Raf.)Sarg.), and grand fir (*Abies grandis* (Dougl. ex D. Don)Lindl.). Timber in the South Fork had been clear-cut 85 years ago, and in the North Fork, 65 years ago. Because of the difference in timber mechantability the South Fork was chosen as the watershed to be selectively harvested by tractor after calibration of the watersheds. The timber harvest and road location, design, and construction were to be of standards which, in 1971, were considered to be commercially acceptable practice by local contractors. Because only two watersheds were gaged, it was not possible to evaluate more than one logging practice or road-building method.

Streamflow was measured from 1963 to 1967, when both watersheds were in an undisturbed condition. (Water-years are used throughout this paper. Water-year 1963 began October 1, 1962, and ended September 30, 1963.) A main-haul logging road and main spurs were built in the South Fork watershed in summer 1967. The road right of way occupied 19 ha, from which 993 m^3/ha of timber was removed (Table 1). The effect of these roads on sedimentation was evalauted by *Krammes and Burns* [1973] and *Rice et al.* [1979].

The first of three stages of timber harvesting began in the South Fork drainage in March 1971 (Figure 1 and Table 1). During this stage, 59% of stand volume was selectively cut from 101 ha. During the second stage, summer 1972, 69% of stand volume was harvested from an additional 128 ha. During the third stage, surnmer 1973, 65% of timber volume on the remaining 176 ha was removed.

Greatest stand density was within the road right of way, which, generally, lay near the stream; second greatest stand density was in the 1971 harvest area located in the downstream third of the watershed. Lowest stand density was in the 1973 logged area that encompassed about 40% of the drainage area and lay near the headwaters of the South Fork drainage.

Overall, timber stand volume in the South Fork averaged 708 m^3/ha, of which 471 m^3/ha (about 67%) was removed. After road building and logging, about 22 ha were occupied by roads, 35 ha by skid trails, and 8 ha by landings. These data indicate that about 5% of the area was in roads and 10% in skid trails and landings, a total of about 15% of the land surface in relatively impervious areas.

HYDROGRAPH ANALYSIS

To evaluate the effects of road building and timber harvest on storm flow, data from all storm peaks with peak discharges in the North Fork control watershed of ≥ 0.08 m^3/s were tabulated from 1963 through 1975. These storm hydrographs were then compared to hydrographs of identical events occurring in the South Fork. If the hydrograph trace in either the North Fork or the South Fork was missing for a given event, that storm event was rejected from subsequent analysis. One of these paired events was missing for 16 out of 190 identified storm events; therefore 174 paired storm hydrographs were analyzed.

Data for seven basic variables were obtained from each hydrograph (Figure 2). These hydrograph variables together with variables expressing antecedent precipitation, storm sequence, area logged, and combinations of these variables are described in the notation section.

Peak Flow

A double-mass curve was constructed to compare cumulative peak flow in the South Fork with cumulative peak flow in the North Fork (Figure 3). The pretreatment relationship can

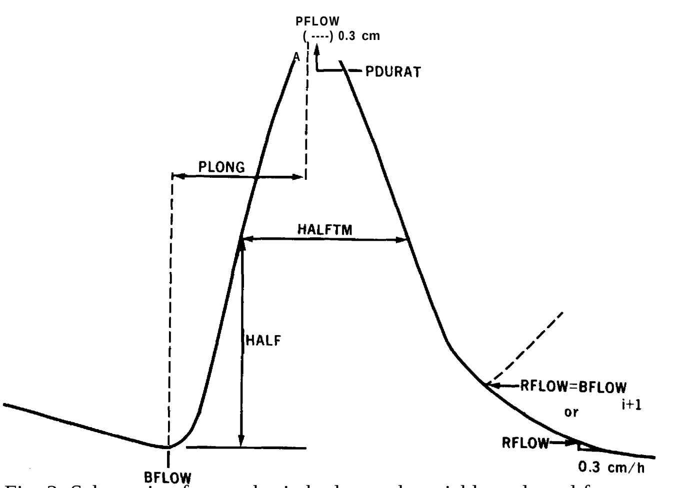

Fig. 2. Schematic of seven basic hydrograph variables selected for analysis. (Variables are defined in the notation section.)

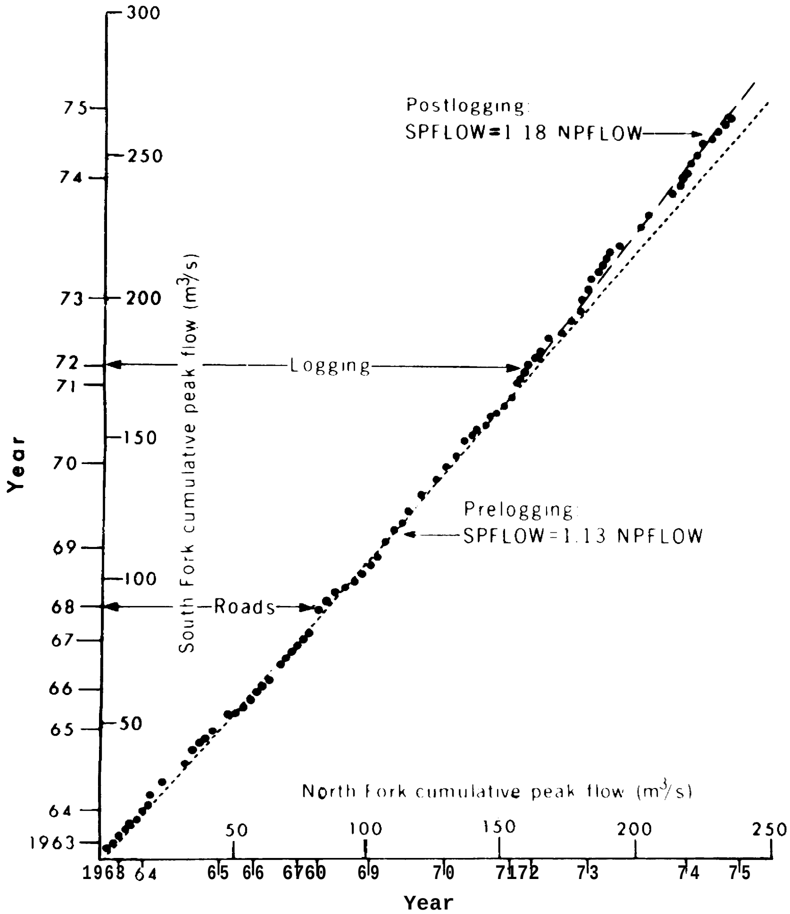

Fig. 3. Relation of cumulative peak flow in the South Fork of Caspar Creek to that of the North Fork.

be expressed as

$$SPFLOW = 1.13 \; NPFLOW$$

On the average, before logging, the South Fork produced a peak discharge that was 1.13 times the paired peak in the North Fork. A change in the slope of the pretreatment line would imply a treatment effect. Although no perceptible change in the slope of the line was associated with construction of the roads in 1967, a small deviation can be seen after logging in 1972 (Figure 3), and the posttreatment relationship is

$$SPFLOW = 1.18 \; NPFLOW$$

On the average, the South Fork produced peak flows about 4% larger after logging than before logging. The double-mass curve technique is a weak tool for assessing treatment effects and provides only a general assessment of trends.

Another approach to analyzing differences in peak flow before and after treatment is to use a least squares regression of the peaks observed in the North Fork control watershed against those observed in the South Fork both before and after logging (Figure 4).

The prelogging regression for the period from 1963 through 1971 was found to be

$$SPFLOW = 0.118 + 1.110 \; NPFLOW - 0.023 \; NPFLOW^2$$

and the postlogging regression, 1972 through 1975,

$$SPFLOW = 0.223 + 1.220 \; NPFLOW - 0.434 \; NPFLOW^2$$

To compare the regression lines, an analysis of covariance can be used [*Wilson*, 1978]. In this example, $F = 2.53$, with 3 and 168 degrees of freedom, which indicates that the two equations are not different, with a significance probability of 0.05. On the basis of this analysis I concluded that logging had no significant effect on peak flows. A similar analysis showed no difference in peak flows after road construction.

If the basic assumptions are met, regression gives the most precise unbiased estimates of the linear functions of the observations [*Daniel and Wood*, 1971]. The one assumption most often violated, however, is that the data are a representative sample from the entire range about which generalizations can be made. Often, when analyzing streamflow data, we do not have an adequate sample of the larger events, which are usually those events of principal interest. A close look reveals that the regression lines for before and after logging are each based on a reasonably well distributed data set, although only about one fourth of the observations lie above 1.98 m^3/s and only two observations in each set lie above 6 m3/s.

The lack of data and the influence of extreme events is not a unique problem. In fact, the data set of Caspar Creek has a better distribution of observations than several recent studies. *Harr et al.* [1979] compare changes in discharge for a peak flow of 1.1 $(m^3/s)/km^2$ on the basis of prelogging and postlogging regression lines. The postlogging regression was developed from a reasonably well distributed data set, although only one observation lay above 1.1 $(m^3/s)/km^2$. The prelogging regression was developed from 14 observations; how-

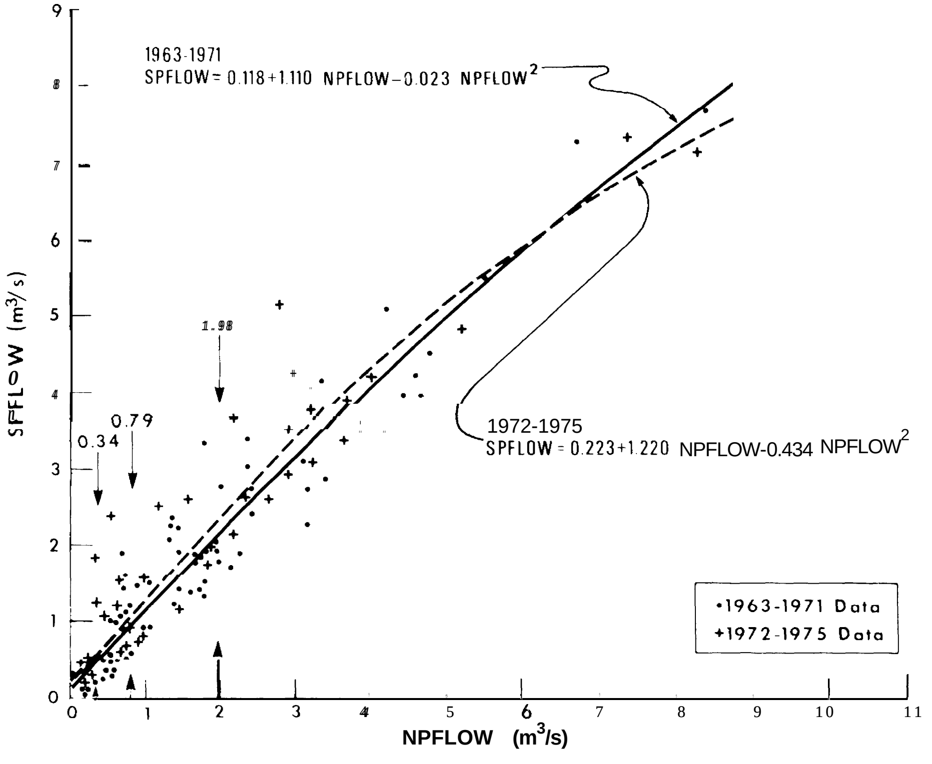

Fig. 4. Relationship between peak flows in the North Fork and South Fork of Caspar Creek before (1963-1971) and after (1972-1975) logging in the South Fork.

ever, none exceeded a peak flow of about 0.6(m^3/s)/km^2. To make such a comparison, the prelogging regression was extrapolated about 70% beyond the range of the observations. Such an exercise strongly violates the assumption that the data are a representative sample from the entire range about which generalizations can be made.

To study further the possibility of differences between the two watersheds, I chose to use the ratio of difference in the peak discharge between the South Fork and the North Fork, *PFLOWSFT*, in comparison to the North Fork peak flow, *NPFLOW*. A ratio between the two streams was used because ratios provide insight into relative change and, for this data set, about equal variances with increasing discharge. Another approach is simply to use the difference between the two streams. The variance of the difference increases rapidly with increasing discharge, however, and grossly violates the statistical assumption of homoscedasticity, or equal variance.

Data for *NPFLOW* were separated into four groups, shown by the three vertical arrows at 0.34, 0.79, and 1.98 m^3/s (Figure 4). Each group contained about the same number of peaks as required for Welsh's generalization of Student's t-test [Welsh, 1947]. Within the 0.08- to 0.33-m^3/s group (Table 2), 28 peaks were in the prelogging period, and 20 peaks were in the postlogging period. The mean value for *PFLOWSFT* before logging was about 0.42. After logging, the mean value increased to 1.49. The South Fork therefore produced a peak that was about 42% larger than that of the North Fork before logging, but after logging, the South Fork produced a peak that was about 149% larger than the comparable peak in the North Fork within the 0.08- to 0.33-m^3/s flow class. This represents an increase of 1.07 and is different from 0 at the 0.01 significance level.

Within the 0.34- to 0.78-m^3/s flow class, the value of *PFLOWSFT* before logging was 0.33 and after logging was

TABLE 2. Difference in ***PFLOWSFT*** Before and After Logging for Different Flow Classes of ***NPFLOW***

NPFLOW Class, m^3/s	Before Logging, 1963-1971: No. of Peaks	Mean	s.d.	After Logging, 1972-1975: No. of Peaks	Mean	s.d.	Difference: Mean	Pooled s.d.	d.f.	*t*
0.08-0.33	28	0.4198	0.3735	20	1.4915	1.0774	1.0717	0.2510	25	4.27*
0.34-0.78	29	0.3328	0.3846	16	0.7157	0.9653	0.3829	0.25 17	20	1.52†
0.79- 1.97	30	0.2051	0.3027	11	0.2628	0.3838	0.0577	0.1283	18	0.45†
≥1.98	24	0.0542	0.1889	16	0.1521	0.2821	0.0979	0.0804	27	1.22†

Here s.d. is standard deviation, and d.f. is degrees of freedom.
*Different from 0 at the 0.01 significance level.
†Not different from 0 at the 0.10 significance level.

TABLE 3. Percentages of the Time, Flow, and Suspended Sediment That Occur Above the Selected North Fork Discharge Classes

North Fork Discharge, m^3/s	Time, %	Flow, %	Suspended Sediment, %
0.08	20.0	83	99
0.34	6.0	54	97
0.79	1.5	33	90
1.98	0.5	13	68

0.72, an increase of 0.38. This increase, however, was not different from 0 at the 0.10 significance level. Similarly, for the 0.79- to 1.97- and >1.98-m^3/s classes, changes between the prelogging and postlogging effects on peak discharge also were not significantly different from 0.

To put the selected flow classes into perspective, the percentages of time, flow, and suspended sediment that were observed at discharges greater than each of the four classes must be considered (Table 3). For example, a stream flow discharge of >0.08 m^3/s is observed in the North Fork only 20% of the time. However, 83% of the annual flow volume occurs at a discharge of >0.08 m^3/s, and 99% of the suspended sediment is transported when the discharge is >0.08 m^3/s. No statistically significant difference was found in the prelogging and postlogging data for peak discharges of >0.34 m^3/s. Consequently, 54% of the flow and 97% of the suspended sediment is transported at discharge rates that were not significantly affected by logging. From a hydraulic standpoint, logging increased only the small peaks, and they have only a minor effect on in-channel erosion and sediment transport.

To better understand a possible seasonal influence of logging on peak flow, I plotted the sequence of *NPFLOW* (Figure 5a) and also *PFLOWSFT* (Figure 5b) storm peaks throughout the 13-year study. During the calibration period, *PFLOWSFT* ranged from about -0.25 to 1.20. After construction of roads in summer 1967, no significant change was observed in *PFLOWSFT.* In 1972, however, after about 24% of the area had been logged, the first storm of the year produced a *PFLOWSFT* of about 2.40, almost twice the maximum value observed previously. Subsequently, *PFLOWSFT* values in 1972 returned to within the prelogging range. In 1973, after 54% of the area had been logged, the first four storm events produced values of *PFLOWSFT* larger than those of the prelogging period.

After the entire drainage was logged in 1974, *PFLOWSFT* values for the first three storm events for the next 2 years were 4.60, 2.30, and 1.20 (for 1974) and 3.20, 2.10, and 1.15 (for 1975). The dominant influence of the logging occurred within the first few storm events of the year. Occasionally, large *PFLOWSFT* values were observed later in winter, but most of

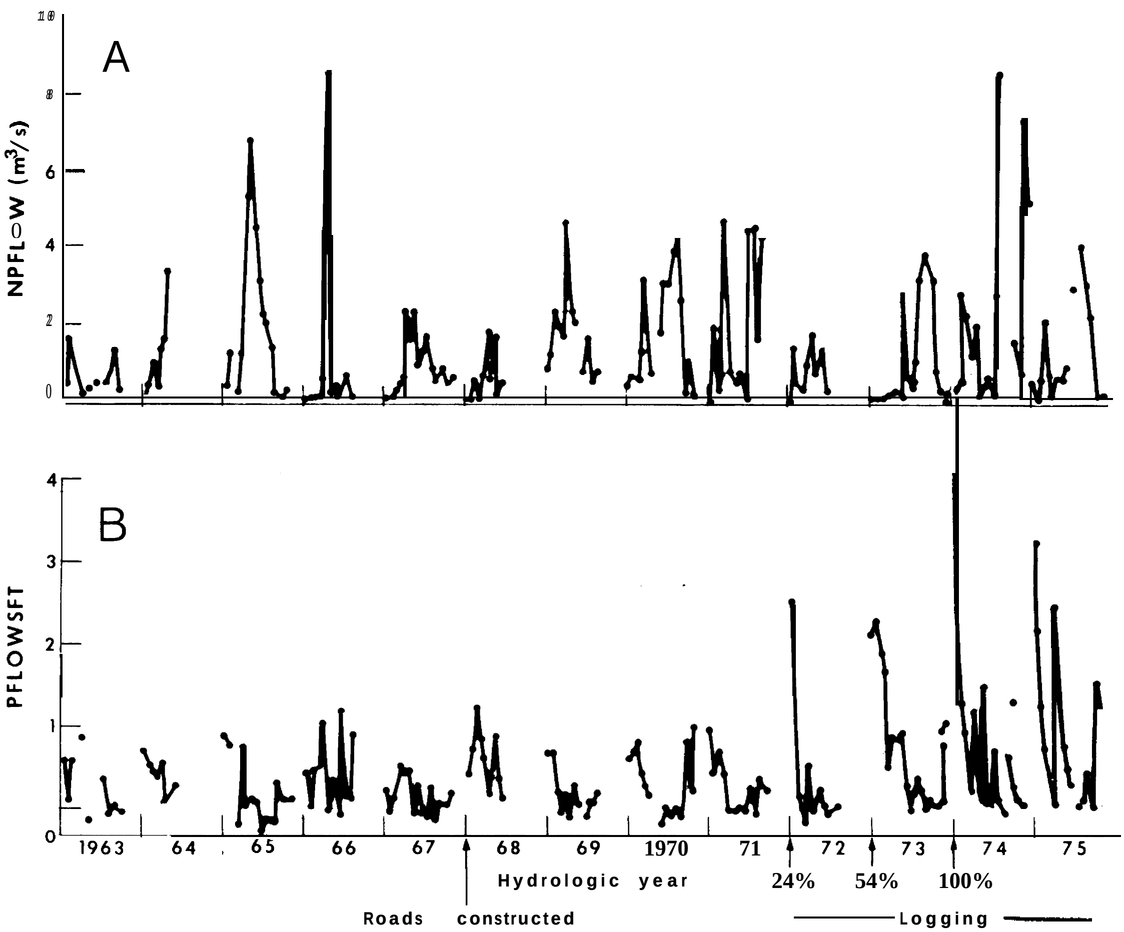

Fig. 5. (a) Sequence of peak flow in the North Fork of Caspar Creek from 1963 through 1975. (b) Sequence of the difference between the South Fork and North Fork peak flows expressed as a ratio of the North Fork peak flows *(PFLOWSFT)* during the 1963-1975 period.

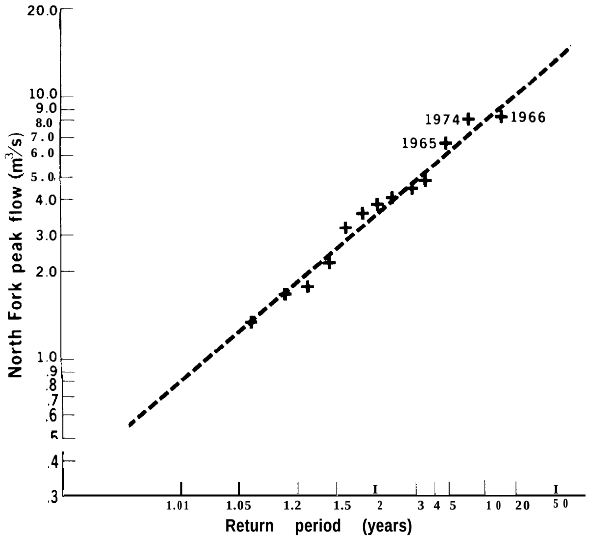

Fig. 6. Analysis of peak flow frequency for the North Fork control watershed, 1963-1975.

these were associated with small storms. This observation is supported by analysis (Table 2).

This pattern of major change in storm peak flow after logging observed during the first small storms of the wet season probably resulted from differences in partitioning of rainfall between soil moisture recharge and streamflow within the logged and control watersheds. Because evapotranspiration was greater in the uncut control watershed than in the logged watershed, a smaller proportion of the first fall rains were required to recharge the more moist soil in the logged watershed than in the drier uncut watershed. Also, canopy density, and therefore interception loss, was less in the logged watershed, thereby allowing more rainfall to reach the ground. During a small storm more rainfall was available for streamflow in the logged than in the unlogged watershed. Once soil moisture was recharged in both watersheds, differences in streamflow were related to differences in interception between the logged and unlogged watersheds. During large storms the relative importance of interception becomes an insignificant factor affecting runoff patterns.

In 1965 and in 1966, peak discharges of 6.77 and 8.50 m^3/s were observed in the North Fork, and after logging in 1974, two additional peaks of 8.41 and 7.43 m^3/s were observed. These are large peak discharges for the North Fork of Caspar Creek (Figure 6). No significant difference in *PFLOWSFT* for these large peaks before or after logging was observed (Table 4). In fact, for large peaks the larger drainage area of the North Fork generally produced a higher peak than the South Fork before, as well as after, logging, although the reverse is true for the smaller peaks. If the effect of logging was to alter the infiltration rate in the South Fork substantially, so that a larger proportion of rainfall became surface runoff, we would expect to see an increase in the size of the larger peaks, or an earlier arrival of the peak at the gaging station, or both. None was found.

To understand which variables are most useful in predicting *PFLOWSFT,* I screened 12 variables by using all possible regressions and partial *F* tests (Table 5). Five of these significantly increased the explained variance (R^2) of the regression: The most important variable was *LOG/SEQ*. The standardized coefficient had a value of 0.65. (Standardized coefficients are regression coefficients that have been scaled so that the absolute value of the coefficient indicates the relative importance of that variable in the regression.) The greater the area of the watershed logged, and the earlier the storm in the year, the greater the predicted value of *PFLOWSFT.* The next most significant variable was *NPFLOW*. The standardized coefficient had a value of -0.28. The larger the peak flow in the North Fork, the smaller the difference between the North Fork and the South Fork. The third most important variable was *PPTWK*. The standardized coefficient had a value of -0.20. The larger the precipitation between 24 hours and 7 days before the peak, the smaller the difference between the North Fork and the South Fork. The fourth variable was *NPDURAT*. The longer the duration of the peak in the North Fork, the smaller the differences in the magnitude of the peaks between the North Fork and the South Fork. The last significant variable was *NPLONG*. The longer the time from the initiation of the hydrograph rise until the peak in the North Fork, the smaller the differences between the North Fork and the South Fork. These variables are consistent with the analyses discussed previously.

In summary, all of the analyses of the effect of logging on peak discharge seem to be internally consistent. First, the double-mass curve showed a relatively minor increase in the slope of the relationship between the North Fork and the South Fork after logging. Second, an analysis of covariance on least squares regressions of the North Fork peak flow versus South Fork peak flow showed that the regressions before and after logging were not different at the 0.05 significance level. Third, logging increased significantly only those peaks in the flow class 0.08-0.33 m^3/s. Peak discharges of >0.34 m^3/s were not significantly different before and after logging. Fourth, a plot of time sequence versus peak discharge showed that there were important differences in *PFLOWSFT* that were correlated with the first small storms of each year after logging began. Fifth, the multiple regression analysis showed that *LOG/SEQ* was the most important variable and correlated positively with *PFLOWSFT.* The other four variables, *NPFLOW, PPTWK, NPDURAT,* and *NPLONG,* which describe the magnitude of the storm event, correlated negatively with *PFLOWSFT,* further illustrating that larger storm events produce smaller differences between the North Fork and the South Fork than do the smaller storm events.

Storm Discharge

The variable *HALFQ* was selected as an analog of the volume of water produced by the storm event. *HALFQ* was calculated by multiplying *HALF,* the mean discharge between *BFLOW* and *PFLOW,* by *HALFTM,* the amount of time between the beginning and the end of that discharge. The hydraulic im-

TABLE 4. Impact of Logging on the Peak Flows From the Largest Storms Observed (From 1963 to 1975)

Year	*NPFLOW*, m^3/s	*SPFLOW*, m^3/s	*PFLOWSFT*
Before Logging			
1965	6.77	7.38	0.0901
1966	8.50	7.75	-0.0882
After Logging			
1974	8.41	7.23	-0.1403
1974	7.43	7.39	-0.0054

TABLE 5. Results of All Possible Subsets Regression Where *PFLOWSFT* is the Dependent Variable

Variable	Regression Coefficient	Standard Error	Standardized Coefficient
Intercept	0.89729	0.08207	1.313
LOG/SEQ	0.03238	0.00208	0.648
NPFLOW	-0.11970	0.02048	-0.278
PPTWK	-0.02438	0.00542	-0.201
NPDURAT	-0.04438	0.01146	-0.178
NPLONG	-0.01078	0.00315	-0.145

R^2 = 0.733, standard error estimate is 0.3583, n = 174, and F = 92.23. Other variables considered were *STORM, LOGGED, NBFLOW, PPTDAY, PPTMO, WEEKLY*, and *MONTHLY.*

pact of a particular streamflow event in terms of channel erosion is a function not only of the magnitude of flow but also of the duration of the flow at that discharge. *HALFQ* should give some insight into the volume of water that passed during the upper portions of the storm hydrograph. As with the peak flow, least squares regressions between the North Fork and the South Fork were calculated for the periods before and after logging (Figure 7). The 'best' regression for the before-logging period indicates a linear equation

$$SHALFQ = 0.638 + 0.842\ NHALFQ$$

The best regression after logging is a quadratic equation

$$SHALFQ = 2.118 + 0.519\ NHALFQ + 0.005\ NHALFQ^2$$

After logging, the addition of the $NHALFQ^2$ term reduced the unexplained variance at the 0.05 significance level. The two equations are different by definition. The postlogging regression lies above the prelogging regression for values of *NHALFQ* of <5.10 (m^3/s) h and below the prelogging regression for values of >5.10 (m^3/s)h. This implies that the impact of logging was to increase the volume of discharge at low flows and reduce the volume at high flows. As before, three vertical arrows indicate the division points of flow classes that contain about an equal number of observations.

Within the flow class ≤5.09 (m^3/s)h the mean *HALFQSFT* increased from 0.29 before logging to 0.95 after logging (Table 6). This increase of 0.66 is greater than zero at the 0.01 confidence level. Within the two flow classes from 5.10 to 16.70 (m^3/s)h the values of *HALFQSFT* before and after logging were not significantly different. Within the flow class ≥16.71 (m^3/s)h the mean *HALFQSFT* before logging was -0.15 and after logging was -0.30. This decrease of -0.15 was significant at the 0.05 level. The least squares regression analysis implies that the effect of logging was to increase the volume of flow of the small peaks and decrease the volume of flow from the large peaks.

As before, a multiple regression analysis identified those variables which best predict *HALFQSFT* (Table 7). Three of the 13 independent variables significantly improved the prediction The most significant was *LOG/SEQ,* and next most important was *NHALFQ,* which was correlated negatively with *HALFQSFT.* The third significant variable was *NPDURAT,* the duration of the peak flow in the North Fork, which was correlated negatively with *HALFQSFT.* Additional variables did not significanlty improve the equation.

The three analyses on the effect of logging on *HALFQ* are consistent. The least squares regressions of *NHALFQ* and *SHALFQ* before and after logging and the analysis of variance on the four flow classes show that logging results in larger values of *HALFQ* in the South Fork relative to the North Fork for the small storm events but smaller values of *HALFQ* for the largest events. The multiple regression showed that *LOG/SEQ* explained most of the variance of the difference between the North Fork and the South Fork and that the larger the storm event, expressed by *NHALFQ,* and the longer the peak lasted, expressed by *NPDURAT,* the less the difference between the two watersheds.

CONCLUSIONS

Results of this study are consistent with those of other paired watershed studies in which storm flow from small streams originates from rainfall rather than snowmelt. A common caveat given in watershed studies is that each watershed is unique in its storm flow response and that results from one area can be applied to other watersheds only with extreme caution. However, some general mechanisms of storm flow response to logging and road building are becoming more clear.

Construction of roads in the South Fork of Caspar Creek resulted in no change in any of the storm flow parameters measured. Becuase roads occupied only 5% of the watershed area, this result was not unexpected. In other studies, no increases in peak flow were found until roads and other impermeable areas occupied more than 12% of the watershed [*Harr et al.*, 1975; *Harr,* 1976]. The peak events used in Harr's Oregon analyses, however, were generally <0.33 (m^3/s)/km^2. After road construction, but before logging in Caspar Creek, five

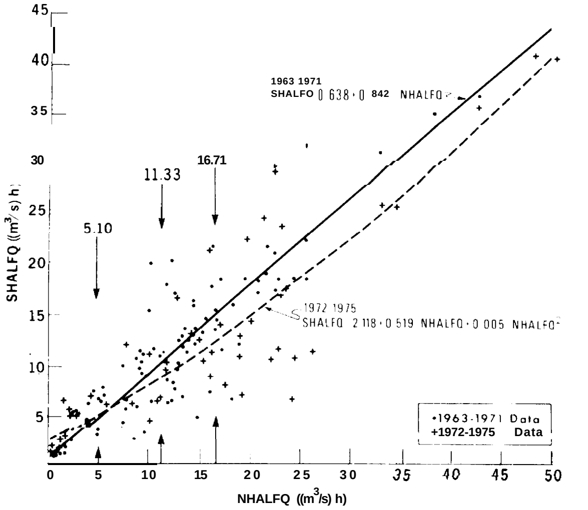

Fig. 7. Relationship between half-volume discharge in the North Fork *(NHALFQ)* and South Fork *(SHALFQ)* of Caspar Creek before and after logging the South Fork.

TABLE 6. Difference in *HALFQSFT* Before and After Logging for Different Flow Classes of *NHALFQ*

NHALFQ Class, $(m^3/s)h$	*HALFQSFT*									
	Before Logging, 1963-1971			After Logging, 1972-1975			Difference			
	No. of Peaks	Mean	s.d.	No. of Peaks	Mean	s.d.	Mean	Pooled s.d.	d.f.	t
≤5.09	25	0.2911	0.4573	21	0.9514	0.7388	0.6603	0.1854	35	3.56*
5.10-11.32	30	-0.0264	0.3500	8	-0.0629	0.3617	-0.0365	0.1429	14	−0.26†
11.33-16.70	27	-0.1305	0.2900	13	-0.1762	0.2266	-0.0457	0.0841	34	−0.54†
≥16.71	29	-0.1524	0.2074	21	-0.3026	0.2661	-0.1502	0.0697	40	-2.15‡

Here s.d. is standard deviation, and d.f. is degrees of freedom.
*Different from 0 at the 0.01 significance level.
†Not different from 0 at the 0.10 significance level.
#Different from 0 at the 0.05 significance level.

of the peaks were >1.0 $(m^3/s)/km^2$, or 4.24 m^3/s. Even these moderate peaks were not affected by road construction.

Roads and landings may be expected to modify storm flow peaks by two principal mechanisms: compaction of road surfaces may reduce infiltration and allow rapid surface runoff, and roads may intercept subsurface flow as well as capture surface runoff and channel it more directly to streams. When the surface area of roads is small in relation to watershed area, these effects remain undetected.

The Caspar Creek study is unique in the west in reporting storm hydrograph response after selective logging of a second-growth forested watershed. Other partial logging studies have reported the effects of patch clear-cutting and shelterwood cutting old-growth forests. *Rothacher* [1973] reported a 10% increase in adjusted mean peak discharge from a 25% patch-cut watershed in the Oregon Cascades. At Caspar Creek, after logging the mean peak discharge in the South Fork relative to the North Fork control watershed also increased about 10% from 0.37 to 0.40 $(m^3/s)/km^2$. Changes in relative mean peak discharge between two watersheds can result from a change in the distribution of storm size as well as from logging-induced changes, and so attributing a causal relationship should be made with caution. A double-mass curve analysis of the Caspar Creek data suggests that the South Fork has peaks 4% larger, on the average, than the North Fork after logging compared to those before logging. The double-mass curve technique, however, should only be used to assess general trends. Formal statistical tests are not appropriate to double-mass analysis, and so a statement of the significance of observed differences is not possible. The regression relationships of the South Fork and North Fork peaks before and after logging (Figure 4) were not different with a significance probability of 0.05. Although each of these analyses addresses a different question, each consistently indicates only minor changes, if any, in average peak flow related to logging. A more detailed view may be necessary, however, to uncover the basic mechanisms operative on the response of storm flow to logging.

TABLE 7. Results of All Possible Subsets Regression Where *HALFQSFT* is the Dependent Variable

Variable	Regression Coefficient	Standard Error	Standardized Coefficient
Intercept	0.38029	0.07051	0.708
LOG/SEQ	0.01789	0.00221	0.455
NHALFQ	-0.02331	0.00318	-0.415
NPDURAT	-0.03888	0.01088	-0.198

R^2 = 0.497, standard error estimate is 0.3847, n = 174, and F = 55.88. Other variables considered were *STORM, LOGGED, NBFLOW, NPFLOW, NPLONG, PPTDAY, PPTWK, PPTMO, WEEKLY,* and *MONTHLY.*

Tractor logging may modify storm flow peaks by several mechanisms. Compaction of skid trails and landings may reduce infiltration and thereby contribute to direct surface runoff. The influence of skid trails on runoff is different from that of roads because skid trails generally are less compacted than roads. Infiltration may be somewhat greater in the skid trails. Skid trails usually are aligned along the slope, and roads are aligned across the slope. Rain that falls on a skid trail has an opportunity to flow downslope along the skid trail. However, water bars should be constructed on the skid trails at close intervals to divert runoff to noncompacted land where the infiltration rate is high. The net result is that well-constructed skid trails may have minimal effect on direct runoff to stream channels as long as such trails occupy only a minor part of the watershed. In Caspar Creek, skid trails occupied about 8% of the watershed area. The effect of compaction on peak flow would be expected to continue independent of season; that is, if fall peaks are increased, winter and spring peaks would be increased equally. In Caspar Creek, only the fall peaks were increased after logging; consequently, compaction and reduced infiltration there did not play a significant role.

Logging can modify the soil water budget by reducing the rate of soil moisture depletion through evapotranspiration. Also, a greater proportion of annual precipitation is available for moisture recharge in the logged area because interception loss is reduced. Interception becomes less important as the size of the storm increases. Once the canopy is wetted, additional rainfall cannot contribute to interception. We would not expect canopy interception to play a role in anything but the smallest storm flow peaks, and this effect would be found in all small peaks, independent of season. In Caspar Creek, only the smallest one fourth of the observed peaks were significantly increased by logging. Peaks of >0.33 m^3/s (0.08 $(m^3/s)/km^2$) were not affected by logging at the 0.10 significance level. Evapotranspiration during the growing season, however, can produce substantial soil moisture differences between logged and unlogged watersheds which, in turn, can cause increased peak flow in the wetter, logged watershed. Once the soil moisture has been recharged in the uncut watershed to equal that in the logged watershed, subsequent storms would be expected to produce similar peak flow responses from both drainages until soil moisture differences again develop. During the dormant season the rate of evapotranspiration is greatly reduced, and the interval between storms is short. Consequently, soil moisture differences between logged and unlogged watersheds would be expected to be small during the late fall and winter. This was the case in Caspar Creek. These effects had the greatest effect on the first storms of the fall season, which also consistently produced small peak flows in Caspar Creek. These early fall effects increased as the amount of the watershed that was logged increased.

The most significant variable explaining differences between the logged and unlogged watersheds was the annual storm number divided by the amount of the watershed logged. The Oregon studies have yielded similar logging effects. For example, *Rothacher* [1971, 1973] found that the first storms of the fall produced storm peak flows from the clear-cut H. J. Andrews watershed up to 200% higher after logging than before logging. *Harr* [1976] reported that average fall peak flow from the Alsea watersheds increased 122% after clear-cutting. Large peak flows were not significantly increased by logging in either the H. J. Andrews or the Alsea studies. Differences in peak flow between the logged and unlogged Caspar Creek watersheds correlated negatively with amount of rainfall and size and duration of the runoff event. If a major storm had occurred as the first storm of the fall, we may have seen an increase in large peaks after logging. Large storms, however, were always preceded by several early season small storms in each of the 13 years of the study. The potential impact of logging on storm flow peaks of a size to be a hydraulic significance to the channel or sediment transport was moderated by early storms of minor importance.

Values for the variable selected as the analog to storm flow volume, *HALFQ*, were decreased after logging for the largest storms. Such a finding is contrary to expected physical conditions. These results may be an artifact of the definition of the variable and do not necessarily imply that the total storm runoff for large events decreased after logging. More appropriately, because the discharge at the beginning of the storm *(BFLOW)* and the peak discharge *(PFLOW)* for large storms were not increased by logging, and the total large-storm runoff would not be expected to change after logging, a decrease in *HALFQ* may imply a change in hydrograph shape during the recession phase. If recession time was increased after logging, as reported by *Hewlett and Helvey* [1970], and the total storm flow volume remained constant, it follows that a downward shift in the discharge that separates one half of the storm flow volume would occur. This shift would be reflected in a decrease in *HALFQ* as defined. Such a mechanism has not been investigated, however, and must be regarded as conjecture.

NOTATION

BFLOW discharge at the initiation of the peak, identified as the beginning of the hydrograph rise, m^3/s.

HALF discharge, defined as (*BFLOW* + *PFLOW*)/2 or (*RFLOW* + *PFLOW*)/2, whichever is larger, m^3/s.

HALFQ quantity of flow, defined as *HALF* × *HALFTM*, $(m^3/s)h$.

HALFQSFT ratio of change in half discharge between the South Fork and the North Fork, equal to (*SHALFQ* − *NHALFQ*)/*NHALFQ*.

HALFTM duration of flow greater than or equal to *HALF*, hours.

LOGGED percentage of the watershed area that had been logged.

LOG/SEQ *LOGGED/STORM*.

MONTHLY precipitation within 30 days of the peak, equal to *PPTDAY* + *PPTWK* + *PPTMO*, cm.

PDURAT duration of the peak, the time for the peak to rise and fall 0.3 cm of stage, hours.

PFLOW discharge at the peak, m3/s.

PFLOWSFT ratio of change in peak discharge between the South Fork and the North Fork, equal to (*SPFLOW* − *NPFLOW*)/*NPFLOW*.

PLONG time from initiation of rise until the peak is reached, hours.

PPTDAY precipitation within 24 hours before the peak, cm.

PPTMO precipitation between 7 and 30 days before the peak, cm.

PPTWK precipitation between 24 hours and 7 days before the peak, cm.

RFLOW discharge on recession limb when either a new rising limb occurs, then $RFLOW_i = BFLOW_{i+1}$, or recession continues and Δ stage is less than or equal to 0.3 cm/h, m^3/s.

STORM sequential storm number within a year, beginning with the first peak greater than or equal to 0.08 m^3/s in the North Fork.

WEEKLY precipitation within 7 days before the peak, equal to *PPTDAY* + *PPTWK*, cm.

YEAR hydrologic year of observation.

N or *S* preceding the above variable names refers to the North Fork control watershed or the South Fork treated watershed, respectively.

REFERENCES

Daniel, C., and F. S. Wood, *Fitting Equations to Data*, John Wiley, New York, 1971.

Harr, R. D., Forest practices and streamflow in Western Oregon, Gen. *Tech. Rep. PNW-49*, 18 pp., U.S. Dep. of Agric., Forest Serv., 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* (3), 436-444, 1975.

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

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

Hewlett, J. D., and J. D. Helvey, Effect of clear-felling on the storm hydrograph, *Water Resour. Res., 6*, 768-782, 1970.

Hewlett, J. D., and A. R. Hibbert, Increase in water yield after several types of forest cutting, *IAHS AISH Publ., 6*, 5-17, 1961.

Hoover, M. D., Effect of removal of forest vegetation upon water yield, *Eos Trans. AGU, 6*, 969-977, 1945.

Hornbeck, J. W., Storm flow from hardwood-forested and cleared watersheds in New Hampshire, *Water Resour. Res., 9*(2), 346-354, 1973.

Krammes, J. S., and D. M. Bums, Road construction on Caspar Creek watersheds--10-year report on impact, *Res. Pap. PSW-93*, 10 pp., U.S. Dep. of Agric., Forest Serv., Berkeley, Calif., 1973.

Partridge, D. B., and W. E. Sopper. Effects of partial forest removal on storm hydrographs, *Res. Briefs 7*(1), pp. 23-26, School of Forest Resour., Penn. State Univ., University Park, 1973.

Reinhart, K. G., Effect of a commercial clearcutting in West Virginia on overland flow and storm runoff, *J. For., 62*(3), 167-171, 1964.

Rice, R. M., and S. A. Sherbin, Estimating sedimentation from an erosion-hazard rating, *Res. Note PSW-323*, 4 pp., U.S. Dep. of Agric., Forest Serv., Berkeley, Calif., 1977.

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., U.S. Dep. of Agric., Forest Serv., 1979.

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

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

Tilley, F. B., and R. M. Rice, Caspar Creek watershed study-A current status report, *State Forest Notes 66*, 15 pp., Calif. State Dep. of For., Sacramento, 1977.

Welsh, B. L., The generalization of "Student's" problem when several different population variances are involved, *Biometrika, 34,* 28-35, 1947.

Wilson, A. L., When is the Chow test UMP?, *Am. Stat., 32*(2), 66-68, 1978.

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