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Changes in Storm Hydrographs After Road Building and Clear-Cutting in the Oregon Coast Range

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Changes in storm hydrographs after road building, clear-cutting, and burning were determined for six small watersheds in the Oregon Coast Range. Peak flows were increased significantly after road building, but only when roads occupied at least 12% of the watershed. Roads had no detectable effect on volumes of storm hydrographs. By reducing transpiration and interception, partial clear-cutting increased peak flow, quick flow, delayed flow, and total storm hydrograph volume of some streams. Most increases were largest in the fall when maximum differences in soil water content existed between cut and uncut watersheds. Maximum increases in storm flow occurred after a 175-acre watershed was 82% clear-cut. Here peak flow increased 16 $ft^3/s/mi^2$, quick flow 1.5 in., and total storm hydrograph volume 2.6 in. during the fall. The average increase in winter peak flows was smaller. The effect of roads on peak flows has significance for design of culverts and bridges in headwater areas, but probably does not influence downstream flooding. Increases in streamflow after clear-cutting should have no appreciable effect on either damage to bridges and culverts in headwater areas or downstream flooding. Caution must be used in extending results of this study to storm runoff events of low frequency and large magnitude.

Clear-cutting is the predominant method of harvesting timber in western Oregon. Each year, hundreds of miles of logging roads are constructed, and 500,000–700,000 acres are harvested by the clear-cut method. The visual impact of clear-cutting is great, and there has been continuing speculation about the influence of road building and clear-cutting on the magnitude and frequency of floods. Concern about the possible influence of logging activities on aquatic resources in Oregon led to initiation of the Alsea watershed study in 1958. Although watershed selection in this study was based largely on fishery considerations, the study did offer an opportunity to evaluate storm runoff response after road building and clear-cutting in the Oregon Coast Range.

In the 1950's, some increases in peak discharge resulting from forest cutting were shown [*Maruyama and Inose*, 1952; *Anderson and Hobba*, 1959], and in the past decade several studies have examined changes in storm hydrographs after forest cutting. The effects of commercial logging on streamflow were evaluated in a study at the Fernow Experimental Forest in West Virginia [*Reinhart et al.*, 1963]. After a 74-acre mountainous watershed was clear-cut, instantaneous peak flows increased an average of 21% during the growing season and decreased 4% during the dormant season. Storm flow volume increased an average of 6% during the growing season.

Hewlett and Helvey [1970] reported the effect of clear-cutting on the storm hydrograph of a mountainous watershed at the Coweeta Hydrologic Laboratory in North Carolina. After a hardwood forest on a 108-acre watershed was clear-cut, storm flow (quick flow) increased 11% overall, or 0.23 in. at the mean quick-flow volume of 2.1 in. Peak discharge increased 7%, or 6 $ft^3/s/mi^2$, at the mean peak flow of 92 $ft^3/s/mi^2$. Changes in time to peak, recession time, and quick-flow duration were not detected. Quick-flow increases occurred in all seasons of the year. The effects of clear-cutting on quick flow were greatest for larger storms; quick flow during a regional record flood (8.7 in. of quick flow) was increased 22%.

A study similar to the Coweeta study was conducted in the Hubbard Brook Experimental Forest in New Hampshire [*Hornbeck*, 1973]. All trees on a 38-acre watershed were cut and left where they fell. Herbicide application virtually eliminated vegetation during the experimental period. After clear-cutting, quick-flow increases averaged 0.51 in. during the growing season, but quick flow was not affected during the dormant season.

In the western Cascade Mountains of Oregon, *Rothacher* [1973] studied changes in peak flow after two watersheds were logged. On a 237-acre watershed completely clear-cut, average peak flow in the fall was increased 9 $ft^3/s/mi^2$, but high winter peaks were largely unchanged. A similar pattern of smaller increases was noted after a 250-acre watershed with 1.65 mi of road (8% of the watershed) was logged in three clear-cut units totaling 25% of the watershed.

STUDY

The three major study watersheds are located in the Alsea River basin in upper Drift Creek watershed about 8 mi south of Toledo and 10 mi from the Pacific Ocean (Figure 1). Mean annual precipitation is about 100 in., virtually all of which is rain. About 90% of annual precipitation falls between October and May during long-duration low-intensity frontal storms.

Elevation of the watersheds ranges from 440 to 1600 ft, with mean slopes of 35–40%. Soils are derived from the Tyee sandstone formation, 80% of the soils being included in the Bohannon and Slickrock series. Bohannon soils are stony, generally less than 24 in. deep, and derived from sandstone residuum. Slickrock soils are derived from sandstone

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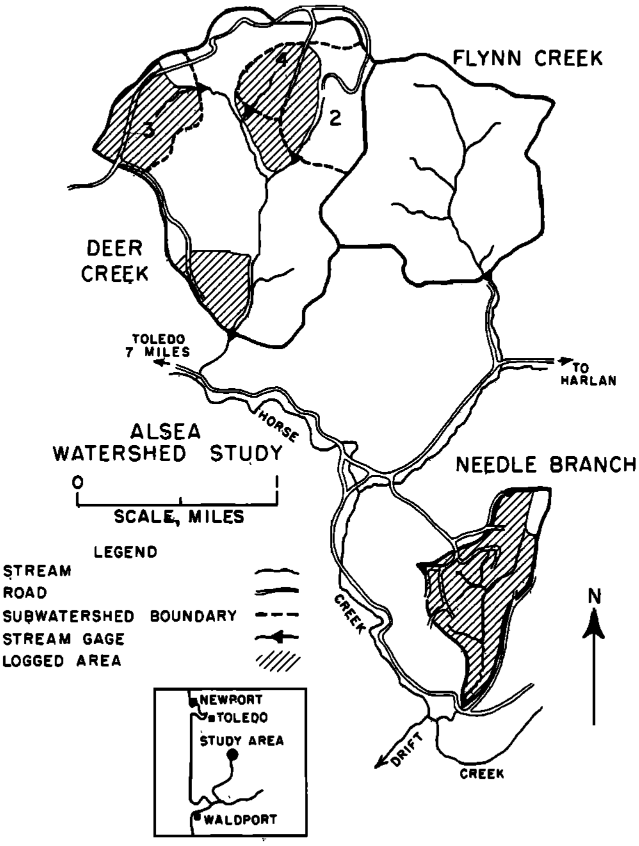

Fig. 1. Watersheds in the Alsea watershed study.

colluvium and range in depth to 55 in. Rates of infiltration and percolation are high, and overland flow on undisturbed forest soil has never been observed. Before logging began, the soils supported mixed Douglas fir and red alder. Watershed sizes are given in Table 1.

Deer Creek, Flynn Creek, and Needle Branch were calibrated for 7 yr (1958–1965), and the Deer Creek subwatersheds were calibrated for 3 yr (1963–1965). Logging roads were constructed into Deer Creek and Needle Branch between March and August 1965. Roads were separated from logging and burning as a treatment effect for only one season. Logging began in March 1966 and was completed by November 1966. High-lead logging predominated, but tractor skidding was done on part of Needle Branch. Slash on Needle Branch and on the lower clear-cut unit in Deer Creek was burned in October 1966. The 500-acre Flynn Creek watershed served as a control and remained undisturbed throughout the study. Watershed treatments are summarized in Table 1.

Storm events for the rainy seasons of 1965–1966, 1966–1967, and 1967–1968 were used to evaluate hydrograph changes after road building, clear-cutting, and slash burning, by a method of calibration described by *Bethlahmy* [1963]. With this method, relations are developed between parameters of the hydrographs for the control watershed and each watershed to be treated. Hydrograph parameters evaluated for change included instantaneous peak discharge, time to peak, and quick-, delayed, and total flow volumes for individual runoff events.

We followed simple linear regression techniques to obtain calibration and post treatment prediction equations for each hydrograph parameter. The significance of the difference between calibration and post treatment data was determined by the principle of 'extra sum of squares' [*Draper and Smith*, 1966, pp. 67–69] by testing the hypothesis that the two regressions are the same, i.e., $\alpha_1 = \alpha_2$ and $\beta_1 = \beta_2$, where α is the intercept of the regression line and β is the slope. First, the residual sum of squares of the calibration and post treatment regression are summed to give a sum of squares ($SS\Omega$) with $(n_1 + n_2 - 4)$ degrees of freedom. Next, a residual sum of squares ($SS\omega$) is determined by regression analysis of the pooled calibration and post treatment data. This sum of squares has $(n_1 + n_2 - 2)$ degrees of freedom. The difference between these sums of squares is the sum of squares due to the hypothesis and has $[(n_1 + n_2 - 2) - (n_1 + n_2 - 4)]$ degrees of freedom. Respective mean squares are compared with the F test:

$$F = \frac{(SS\omega - SS\Omega)/(n_1 + n_2 - 2) - (n_1 + n_2 - 4)}{SS\Omega/(n_1 + n_2 - 4)}$$

$$= \frac{SS\omega - SS\Omega/2}{SS\Omega/(n_1 + n_2 - 4)}$$

If the computed F value is less than the tabulated value, the effect of a particular watershed treatment is judged nonsignificant. If the computed F is greater than the tabulated value, the hypothesis is rejected in favor of the alternate hypothesis that the calibration and post treatment regressions are different.

Hewlett and Hibbert's [1967] method of hydrograph analysis was followed to separate volumes of quick and delayed flow. A line was projected at a slope of 0.05 $ft^3/s/mi^2/h$ from the point of initial rise until it intersected the falling limb of the hydrograph. That part of the hydrograph above the separation line represents quick flow, and that below is delayed flow.

TABLE 1. Summary of Treatment Areas in Alsea Watershed Study

		Deer Creek Subwatersheds				
	Deer Creek	2	3	4	Needle Branch	Flynn Creek
Total area, acres	750	138	100	39	175	502
Area in roads 1965, acres*	28	4	12		9	
Percent in roads*	4	3	12		5	
Logged area 1966, acres	187	41	65	35	143	
Percent logged	25	30	65	90	82†	
Burned area 1966, acres	58				143	
Percent burned	8				82	

*Includes landings, road cutbanks and fill slopes, and tractor skid trails.
†In the early 1950's, 32 acres in the headwaters of Needle Branch were logged.

Total flow of a storm hydrograph is the sum of quick and delayed flows.

Storm hydrographs that met certain criteria were selected for analysis. Because of special requirements of some hydrograph parameters, an individual runoff event was not used for analyses of changes in all hydrograph parameters. Single-peaked events were the principal events selected for peak discharge, but some complex hydrographs were used to increase sample numbers. Further details of data reduction are reported elsewhere [*Harper,* 1969; *Hsieh,* 1970].

During the rainy season in western Oregon, storm runoff occurs under conditions of both recharging (fall season) and recharged (winter season) soil moisture conditions. Because the largest effects of road building and clear-cutting on streamflow were expected to occur in the fall, the data for this season were separated from those of the remainder of the rainy season. Two methods of separation were followed. First was an arbitrary separation by date; September through November made up the fall season, and December through March the winter season for Needle Branch and Deer Creek 4. A less arbitrary method of separation based on antecedent moisture conditions was followed for subsequent analyses of data for Deer Creek and the other Deer Creek subwatersheds. In this later method, base flows antecedent to storm runoff events were plotted for each month of the year. The resulting curves showed a gradual rise in base flow to 3-4 $ft^3/s/mi^2$ after several storms in October and November, with a sharp rise occurring in either November or December. Therefore a base flow value of 3.5 $ft^3/s/mi^2$ was selected to separate the recharging and recharged periods. These periods correspond quite closely to the fall and winter periods of the Needle Branch and Deer Creek 4 analyses. Yearly data refer to a pooling of the seasonal data described above.

A flood-frequency analysis was made to set limits on the return period to which the results may apply. Because the Alsea watersheds have a streamflow gaging record of only 14 yr, three approaches were tried to obtain a flood-frequency relation. The first two, streamflow correlation between Flynn Creek and the Alsea River near Tidewater and correlation of precipitation data with those from stations with longer records, were abandoned because correlations were poor. The third approach was a partial series, flood-frequency analysis [*Linsley et al.,* 1958, pp. 247-249] performed on data from the 1959-1973 period at the control watershed. The occurrence of extreme runoff events of 175 and 178 $ft^3/s/mi^2$ on January 28, 1965, and January 11, 1972, made this flood-frequency analysis difficult. When these two events were plotted according to return period based on their high ranking among observed peaks, the resulting flood-frequency curve fitted the data poorly. Return period of the peak flow on January 28, 1965, at stations with long-term records approached 50-100 yr [*Rothacher and Glazebrook,* 1968]. If both extreme events are assigned arbitrarily a return period of about 50 yr, the flood-frequency curve fits the data quite well. Using this latter curve, we estimate the 2.33-, 10-, and 25-yr peak flows to be 84, 128, and 157 $ft^3/s/mi^2$, respectively.

RESULTS

Changes in peak discharge and hydrograph volumes that occurred after road building and clear-cutting are shown in Tables 2-5. The changes are based on differences in calibration and post treatment regression equations at the mean of the

TABLE 2. Effects of Road Building and Clear-Cutting on Peak Flows at Deer Creek, Deer Creek 2, and Deer Creek 3

Period	Number of Storms	Mean Peak Flow, $ft^3/s/mi^2$		r^2	Change at Mean of Calibration and Post Treatment Means for Control, $ft^3/s/mi^2$
		Control Watershed	Treated Watershed		
		Deer Creek			
Recharging					
Calibration	29	6	7	0.99	
After roads	8	9	9	0.96	-2
After cutting	9	8	9	0.99	-1
Recharged					
Calibration	64	29	30	0.99	
After roads	9	31	33	0.99	-1
After cutting	17	26	28	0.98	+1
		Deer Creek 2			
Recharging					
Calibration	9	3	2	0.78	
After roads	11	9	10	0.86	+1
After cutting	9	8	9	0.99	+1
Recharged					
Calibration	35	26	28	0.95	
After roads	7	34	44	0.98	-2
After cutting	17	26	35	0.91	+5
		Deer Creek 3			
Recharging					
Calibration	10	11	11	0.99	
After roads	11	9	13	0.88	+5*
After cutting	7	5	6	0.89	+3*
Recharged					
Calibration	37	24	24	0.99	
After roads	8	27	33	0.99	+5*
After cutting	16	26	39	0.99	+12*

*The change is significant at the 99% level of probability.

TABLE 3. Effects of Road Building and Clear-Cutting on Peak Flows at Deer Creek 4 and Needle Branch

Period	Number of Storms	Mean Peak Flow, $ft^3/s/mi^2$ Control Watershed	Treated Watershed	r^2	Change at Mean of Calibration and Post Treatment Means for Control, $ft^3/s/mi^2$
		Deer Creek 4			
Recharging					
Calibration	3	19	20	0.93	
After cutting	3	22	53	0.97	+27
Recharged					
Calibration	17	47	57	0.95	
After cutting	16	35	50	0.93	+10
		Needle Branch			
Recharging					
Calibration	39	14	20	0.95	
After roads	5	8	10	0.89	-3
After cutting	9	10	30	0.88	+16*
Recharged					
Calibration	39	37	44	0.95	
After roads	10	37	43	0.92	+0.0
After cutting	10	37	53	0.81	+10*

*The change is significant at the 99% level of probability.

TABLE 4. Effects of Road Building and Clear-Cutting on Hydrograph Volumes at Deer Creek, Deer Creek 2, and Deer Creek 3

Period	Number of Storms	Mean Volume, in. Control Watershed	Treated Watershed	r^2	Change at Mean of Calibration and Post Treatment Means for Control, in.
		Deer Creek			
Total flow					
Calibration	20	3.8	3.6	0.99	
After roads	6	4.5	4.4	0.99	+0.1
After cutting	10	4.1	3.8	0.98	-0.2
Quick flow					
Calibration	20	2.1	2.2	0.99	
After roads	6	2.4	2.5	0.99	0.0
After cutting	10	2.2	1.9	0.96	-0.3†
Delayed flow					
Calibration	20	1.7	1.4	0.97	
After roads	6	2.0	1.9	0.99	+0.1
After cutting	10	2.0	1.8	0.97	+0.2*
		Deer Creek 2			
Total flow					
Calibration	5	4.0	4.2	0.99	
After roads	3	2.4	2.2	0.98	-0.4
After cutting	9	4.0	3.8	0.95	-0.4
Quick flow					
Calibration	5	1.9	2.5	0.99	
After roads	3	1.5	1.5	0.99	-0.4
After cutting	9	2.0	2.1	0.98	-0.2
Delayed flow					
Calibration	5	2.1	1.7	0.87	
After roads	3	0.9	0.8	0.97	-0.1
After cutting	9	1.9	1.6	0.85	+0.1
		Deer Creek 3			
Total flow					
Calibration	4	2.6	3.2	0.52	
After roads	4	2.5	2.9	0.94	-0.2
After cutting	6	4.7	5.6	0.98	+0.8
Quick flow					
Calibration	4	1.1	1.5	0.94	
After roads	4	1.3	1.7	0.96	0.0
After cutting	6	2.5	3.0	0.99	+0.2
Delayed flow					
Calibration	4	1.2	1.2	0.56	
After roads	4	1.2	1.2	0.94	+0.1
After cutting	6	2.2	2.6	0.84	+0.6

*The change is significant at the 95% level of probability.
†The change is significant at the 99% level of probability.

TABLE 5. Effects of Road Building and Clear-Cutting on Hydrograph Volumes at Deer Creek 4 and Needle Branch

Period	Number of Storms	Mean Volume, in. Control Watershed	Mean Volume, in. Treated Watershed	r^2	Change at Mean of Calibration and Post Treatment Means for Control, in.
		Deer Creek 4			
Total flow					
Calibration	10	6.5	5.3	0.99	
After cutting	7	5.0	5.4	0.90	+0.4
Quick flow					
Calibration	10	3.9	4.3	0.97	
After cutting	7	2.8	3.3	0.96	+0.1
Delayed flow					
Calibration	10	2.6	1.0	0.37	
After cutting	7	2.2	1.2	0.70	+0.2
		Needle Branch			
Recharging					
Calibration	12	2.5	3.0	0.99	
After roads	2	0.4	0.6	1.00	0.0
After cutting	3	0.5	2.0	0.90	+2.6†
Recharged					
Calibration	13	6.8	6.8	0.99	
After roads	5	5.6	5.5	0.95	-0.3
After cutting	5	5.5	6.0	0.83	+0.4
Quick flow recharging					
Calibration	12	1.6	2.0	0.98	
After roads	2	0.2	0.3	1.00	-0.1
After cutting	3	0.3	1.3	0.91	+1.5*
Quick flow recharged					
Calibration	13	4.1	4.7	0.98	
After roads	5	3.4	3.2	0.88	-0.9*
After cutting	5	3.1	3.7	0.81	-0.1
Delayed flow recharging					
Calibration	12	0.9	1.0	0.98	
After roads	2	0.2	0.3	1.00	+0.1*
After cutting	3	0.1	0.6	0.90	+1.1†
Delayed flow recharged					
Calibration	13	2.7	2.1	0.76	
After roads	5	2.2	2.2	0.83	+0.6*
After cutting	5	2.4	2.4	0.86	+0.6†

*The change is significant at the 95% level of probability.
†The change is significant at the 99% level of probability.

calibration and post treatment means for the control watershed.

There were few storm events suitable for the analysis of effects of roads on peak flow, because roads were isolated from subsequent clear-cutting in only 1 yr. Consequently, results are variable (Tables 2 and 3), and a significant change in peak discharge was detected only at Deer Creek 3, where roads occupy 12% of total watershed area. There, average peak flow increased 5 ft^3/s/mi^2 in both the fall and the winter period.

Generally, peak discharge was increased after clear-cutting. Largest increases occurred in the watersheds that were clear-cut most extensively. Deer Creek 3, which had the highest road density and was 65% clear-cut, showed highly significant increases of 3 ft^3/s/mi^2 in the period of recharging soil moisture and 12 ft^3/s/mi^2 in the recharged period. These increases in peak flow continued those noted for the year after roads were constructed. After Deer Creek 4 was 90% clear-cut, average peak flow increased 27 ft^3/s/mi^2 in the fall period. Average peak flows at Needle Branch increased 16 ft^3/s/mi^2 in the fall and 10 ft^3/s/mi^2 in the winter after that watershed was 82% clear-cut. Both increases at Needle Branch were highly significant.

Changes in total volume in storm hydrographs after road building were variable. Although some changes were relatively large, not one was statistically significant because of statistical variance and the small number of hydrographs suitable for analysis. After clear-cutting, changes in total volume generally increased, with watersheds most extensively cut exhibiting the largest increases. Only the increases at Needle Branch were statistically significant, however. Here, total volume in fall storm hydrographs was increased 2.6 in. A significant change was not detected in the winter period.

Average quick-flow volume decreased after roads were built (Tables 4 and 5). Decreases ranged from <0.1 in. at Deer Creek for the combined fall and winter periods to 0.9 in. (significant at 95% level of probability) at Needle Branch during the winter period. Changes in quick-flow volume were more variable after clear-cutting and generally followed the same pattern as total storm hydrograph volume. Changes were significant on only two streams: a decrease of 0.3 in. at Deer Creek and an increase of 1.5 in. at Needle Branch, both during the fall period.

With one exception, delayed flow volume increased after roads were built. Statistically significant increases were noted only at Needle Branch, where average delayed flow increased 0.1 in. in the fall and 0.6 in. in the winter. In all instances, delayed flow increased after clear-cutting. The increases noted after road building at Needle Branch were sustained after clear-cutting. Here, average increases were 1.1 in. in the fall and 0.6 in. in the winter.

No consistent change in time to peak was noted among the watersheds.

DISCUSSION

Caution must be used in extending results of this study to storm runoff events of low frequency and large magnitude. The size distribution of peak flows at the control watershed for the calibration and post clear-cutting periods (Table 6) gives the magnitude of runoff events used in this study. For the full period (fall and winter combined) analysis of peak flow at Needle Branch, only two peaks at the control watershed in the calibration period were greater than 84 ft^3/s/mi^2 the estimated 2.33-yr peak flow at this watershed. Likewise, only two peaks were above 84 ft^3/s/mi^2 during the calibration period of the Deer Creek 4 analysis. No peak during the post clear-cutting period on Needle Branch or Deer Creek 4 exceeded the estimated annual peak of 84 ft^3/s/mi^2. Hydrograph analyses at Deer Creek and the other Deer Creek subwatersheds used runoff event data with size distributions similar to those shown in Table 6.

The construction of roads before the fall and winter runoff periods of 1965–1966 was expected to change storm hydrographs. A compacted surface reduces infiltration, and excess water is carried by a more efficient delivery system consisting of the road surface, ditches, and culverts. The cut slope can interrupt downslope movement of subsurface water and convert it to more rapid surface flow. Removal of trees from the right-of-way eliminates transpiration and provides a soil mass that is more moist and responsive to precipitation. This is of greatest importance in the fall when unvegetated soil has a higher moisture content than it did when it supported forest vegetation.

The proportion of a watershed in roads should govern the degree of hydrograph change. Among the four watersheds with roads, only one, Deer Creek 3, showed a significant increase in peak discharge. Roads occupy 12% of this watershed, a percentage above that of larger forested areas clear-cut in patches under normal management practices. In the other watersheds having roads the roads occupy only 3–5% of the watershed area. Changes in peak flows after road building in these watersheds were much smaller, inconsistent, and statistically nonsignificant. Conceivably, these smaller areas in roads were insufficient to exert much influence on storm hydrographs. Undoubtedly, experimental precision also contributed to the inconsistency and statistical nonsignificance of results. The 'least significant difference' method [*Snedecor and Cochran,* 1968, p. 272] was followed to test the ability to detect changes in peak discharge within the Deer Creek watershed at the 95% level of probability. This analysis showed the experimental precision was 6% at Deer Creek and 10% at Deer Creek 3. Because the increase in peak flow at Deer Creek 3 represents only about 3% of mean peak flow at the Deer Creek weir based on means of calibration and post road building regressions, and increase within the Deer Creek 3 subwatershed easily could have escaped detection at the Deer Creek outlet.

Some changes in hydrograph volumes after road building appear to be artificial, that is, created by errors in hydrograph separation. No consistent changes in total volume were observed, and no changes were statistically significant. Yet, quick flow decreased, and delayed flow increased on all but one watershed with roads. Changes were statistically significant only on Needle Branch. In this study, both quick and delayed flow were measured between the time of runoff initiation and the time an arbitrary hydrograph line intersected the recession limb of the hydrograph. We could find no physical reason why delayed flow would have increased and quick flow would have decreased. Errors in determining runoff initiation could have resulted in misplacement of the separation line and accounted for the changes noted for quick and delayed flow. But whatever the reason, changes in total hydrograph volume (the sum of quick and delayed flows) are most meaningful because this volume is less dependent on the subjectivity of hydrograph separation than the quick and delayed flows are.

The intensity of the combined treatments generally, but not consistently, governed the level of change in hydrograph parameters. Changes in fall peak flows were highest on Deer Creek 4 and Needle Branch, the watersheds most extensively clear-cut. Deer Creek 3, which was 65% clear-cut, showed the next greatest change in peak flow, followed by Deer Creek 2 (20% clear-cut) and Deer Creek (26% clear-cut). Increases in winter peak flow followed the same order except that Deer Creek 3 had the second largest change. The high density of roads and its influence on surface runoff most likely caused the large increases in winter peaks at Deer Creek 3.

Deer Creek 4 and Needle Branch had reasonably similar in-

TABLE 6. Size Distribution of Control Watershed Peak Flows Used in Analyses of Peak Flows at Needle Branch and Deer Creek 4

Peak Flow at Control, ft^3/s/mi^2	Frequency of Occurrence at Needle Branch: Calibration	Frequency of Occurrence at Needle Branch: Post Clear-Cutting	Frequency of Occurrence at Deer Creek 4: Calibration	Frequency of Occurrence at Deer Creek 4: Post Clear-Cutting
1-19	51 (29)	14 (7)	10	5
20-39	15 (4)	9 (2)	4	9
40-59	13 (4)	5 (0)	2	5
60-84	4 (0)	1 (0)	3	1
85-128	1 (1)	0 (0)	1	0
129-157	0 (0)	0 (0)	0	0
157+	1 (0)	0 (0)	1	0

Fall period data at Needle Branch are shown in parentheses. The 2.33-, 10-, and 25-yr peaks are 84, 128, and 157 ft^3/s/mi^2, respectively.

creases in both fall and winter peak flows after clear-cutting, although only Needle Branch contained roads and was burned after logging. Also changes in peak flow after road building in Needle Branch were small and variable. From this we could assume that the roads and burning had no major impact on the hydrograph at Needle Branch. Increases in hydrograph volumes were much larger (and statistically significant) at Needle Branch, however, the suggestion being that the runoff processes in this watershed were altered by the roads and the burning. Slash burning on Needle Branch was quite severe, and organic material in surface horizons in some areas was consumed. Consequently, pores in the unprotected surface soil could have been plugged with soil particles detached by raindrop impact, infiltration thus being reduced. Infiltration also could have been reduced by the formation of a hydrophobic surface layer during slash burning, as has been observed on some soils in California [*DeBano et al.*, 1967] and Montana [*De Byle*, 1973]. Overland flow observed locally in heavily burned areas on roads and in ditches in the Needle Branch watershed could have accounted for some changes in storm hydrographs, although it did not necessarily cause increases in peak flows above those noted on Deer Creek 4.

The substantial change in peak discharge during the fall recharging period as compared to the winter recharged period was most evident on the two most extensively clear-cut watersheds. Greater changes in the fall were not unexpected. That higher levels of soil moisture exist through the summer and into the fall after clear-cutting has been well documented [*Ziemer*, 1964; *Troendle*, 1970; *Patric and Reinhart*, 1971; *Rothacher*, 1973]. The wetter soil profile in a recent clear-cutting should respond to incoming precipitation more quickly than when it supported a forest that depleted soil moisture throughout the growing season.

Why an increase in peak discharge occurred during the winter on Deer Creek 4 and Needle Branch is unclear. Several causes of this increase are suggested. First, soil infiltration capacity could have been reduced by soil disturbance during the logging operation, surface runoff thus being caused. Although no systematic survey of soil disturbance was made on any of the study watersheds, soil disturbance from yarding alone probably was insufficient to have caused appreciable surface runoff, because soil disturbance during normal logging operations is light. *Dyrness* [1967], for example, found that compacted soil occupied only 9% of an area logged with the high-lead method in western Oregon. Needle Branch did contain logging roads, but comparing changes in peak flow after road building with changes after clear-cutting (Table 3) suggests roads had little influence on peak flow in this watershed.

Winter increases in peak flow can be explained best by changes in interception and soil moisture content resulting from removal of forest vegetation. Only part of a watershed contributes to storm runoff, and the size of this contributing area varies according to rainfall characteristics and water-transmitting properties of the soil [*Hewlett and Hibbert*, 1967]. For the small winter storms that are more representative of the data in this study, storm runoff is produced only near the stream channel. Thus the sum of the differences in both interception and soil moisture storage between such contributing areas on cut and uncut watersheds will determine the increase in storm runoff after clear-cutting. For storms approaching the sum of these differences in storage, differences in storm runoff will be similar to those observed in the fall. For larger storms, differences between cut and uncut areas become smaller, so that increases in storm runoff after clear-cutting would be smaller.

This explanation of winter increases in peak flow is supported by other analyses of peak flows in western Oregon. *Harris* [1973] evaluated changes in peak flow at Needle Branch using runoff events exceeding 50 $ft^3/s/mi^2$ at the control watershed. These peaks averaged 71 $ft^3/s/mi^2$ over the 1959–1969 period, and all occurred during what we termed the period of recharged soil moisture conditions (winter period) in our study. Harris found no significant increase in peak flow after clear-cutting. Conversely, our study, which included an additional 25 smaller runoff events in the calibration period and 5 in the post clear-cutting period, shows a highly significant increase in peak flows after clear-cutting, although adding these events increased statistical variance. Our peaks averaged 37 $ft^3/s/mi^2$, about half the size of the average peak used in Harris' analysis. In another study in western Oregon, the average of all peak flows over 10 $ft^3/s/mi^2$ was increased from 37 to 46 $ft^3/s/mi^2$ after a 237-acre watershed was completely clear-cut. Clear-cutting had only a minor effect on peak flows over 100 $ft^3/s/mi^2$ [*Rothacher*, 1973], however. Thus with increasing size of storm the differences between cut and uncut areas become less significant, and the two areas respond nearly alike hydrologically.

Generally, increases in quick flow, delayed flow, and total volume of the storm hydrograph were most notable at Needle Branch during the fall. These large increases and the smaller but significant increases during the winter again might be explained by differences in interception and soil moisture storage between cut and uncut watersheds. Of course, Needle Branch contained some roads and was burned severely after logging, and redistribution of hydrograph volumes after logging probably was affected by these factors. The necessary pooling of fall and winter events at Deer Creek 4 prevented evaluation of winter increases in hydrograph volumes on a watershed without roads or slash burning.

Certain increases in streamflow in this Alsea watershed study are comparable to those of previously described studies conducted at Hubbard Brook [*Hornbeck*, 1973], Coweeta [*Hewlett and Helvey*, 1970], and Fernow [*Reinhart et al.*, 1963]. At all these locations the effect of forest cutting on quick flow was detectable. Average increase in quick flow was 0.51 in. at Hubbard Brook, 0.23 in. at Coweeta, and 0.51 in. at Fernow. The average increase in quick flow at Needle Branch in the Alsea study was 0.38 in. During the winter period, when soil moisture was generally recharged, no significant change in quick-flow volume was detected after cutting on the Needle Branch watershed. *Hornbeck* [1973] similarly reported that forested and cleared watersheds in New Hampshire contribute to storm flow in the same way after soil moisture has been recharged.

Results of this study show storm flows from small watersheds in headwater areas of the Oregon Coast Range were changed by road building and clear-cutting. It is worthwhile to look at implications that these increases might have for design of culverts and bridges in these headwater areas and for downstream flooding.

Generally, attempts are made to design culverts and bridges to withstand at least the 25-yr peak flow in the coast range. If peaks of this size indeed are designed for, culverts and bridges are not likely to be damaged by an increase in storm runoff resulting from clear-cutting alone. Results of this study show that average winter peak flows can be increased up to 45% by clear-cutting, but the winter peaks to which these increases apply correspond to only 25–50 ft³/s/mi² at the control watershed (Tables 2 and 3), well below the estimated 25-yr peak of 157 ft³/s/mi². In the previously mentioned analysis of the largest peak flows at Needle Branch [*Harris*, 1973] the average increase in peak flow after clear-cutting was only 17%. Thus the percentage increase appears to decrease with increasing magnitude of the runoff event. That clear-cutting has little effect on large runoff events is supported further by results of a study on a 237-acre clear-cut watershed without roads in the H. J. Andrews Experimental Forest in Oregon [*Rothacher*, 1971]. Two 50- to 100-yr runoff events included in the post clear-cutting period produced peaks less than those expected on the basis of the calibration regression, well within normal variation.

Design implications, potential on-site damage, and damage to hydraulic structures resulting from the effects of roads on peak flows are much more serious than the implications and damages of clear-cutting because roads are more permanent than clear-cuttings and because, unlike the situation with clear-cutting, the differences between watersheds with roads and watersheds without roads probably will exist for even large runoff events. We can see the importance of the effects of roads on culvert and bridge design by applying the previously described flood-frequency analysis to streamflow at Deer Creek 3, where roads occupy 12% of total watershed area. We also must assume that similar increases in peak flow observed at Deer Creek 3 (20% increase) would occur on the Flynn Creek watershed if roads comprised 12% of its area and that the relative increases shown in Table 2 are reasonably applicable for larger storm events. Examination of the largest peak flows (>90 ft³/s/mi²) supports the latter assumption. Peak flows during the calibration period were nearly identical on the control watershed and the watershed with roads. Only one large peak flow occurred in the post road building period. This peak was about 25% greater on the watershed with 12% of its area in roads. Thus an estimated 10-yr peak of 128 ft³/s/mi² could be increased to 160 ft³/s/mi², slightly larger than the estimated peak of a 25-yr runoff event. Similarly, the estimated 25-yr peak of 157 ft³/s/mi² could be increased to 196 ft³/s/mi², a runoff event with a return period of about 90 yr. Thus a 25-yr runoff event on a watershed without roads could be a 90-yr event on a watershed with 12% of its area in roads. Of course, drawing this conclusion from such a small sample is tenuous, because there obviously are other influential factors, such as soil considerations, road placement, and road slope, that can affect storm hydrographs. Also the flood-frequency analysis most likely is inaccurate because of short-term record. These figures, however, do indicate that success or failure of a certain size culvert or bridge might depend heavily on the amount of roads that eventually will be built in the watershed whose outlet stream is to be contained within a culvert or bridge.

It is doubtful that normal clear-cutting practices in the headwater areas of the Oregon Coast Range have any appreciable effect on large low-frequency runoff events which have caused extensive downstream flooding. A similar conclusion was reached by *Rothacher* [1973] for the western Cascade Mountains of Oregon and by *Lull and Reinhart* [1972] and *Hornbeck* [1973] for forested watersheds of the eastern United States. These large events are wet mantle floods caused by such great amounts of precipitation that differences in soil moisture content and interception between cut and uncut areas become insignificant. If high-lead yarding is used, soil disturbance is light [*Dyrness*, 1967], and infiltration capacity is largely unchanged on the clear-cut area. Thus cut and uncut areas should respond nearly the same during these large precipitation events. In addition, whatever differences do exist are further masked downstream by water flowing from uncut areas. For example, about 1% of a typical large drainage in western Oregon is clear-cut each year under a 100-yr rotation. If one assumes that increases in storm flow do not disappear until 20 yr after clear-cutting and an initial increase in total storm flow of 10%, the increase in total storm flow at the outlet of the large basin would be, at most, only about 1% in any given year. For a rotation of 50 years, the maximum increase in total storm flow at the outlet would be about 2%. These examples are, of course, oversimplified. In reality, other factors, such as distance of clear-cuttings from the basin outlet and storm characteristics, would influence the relative times of arrival of water flowing from various clear-cuttings of different ages.

Results of this study also suggest that forest roads will not cause downstream flooding. Although peak discharge was increased significantly when roads occupied 12% of a watershed, no consistent changes in total storm flow were noted on this watershed or on any other watersheds containing roads (Tables 4 and 5).

The effects of clear-cutting on storm hydrographs have been detected readily in numerous watershed studies throughout the United States and have been summarized by *Lull and Reinhart* [1972]. This study and additional studies elsewhere have provided further evidence of changes in storm runoff after clear-cutting [*Harris*, 1973; *Hornbeck*, 1973; *Rothacher*, 1973]. Most of the storm events used in these studies, however, have been small. Few events of a magnitude sufficient to cause downstream flooding have been included, because of the infrequency of such events coinciding with watershed studies. Although analyses of the effects of clear-cutting on these large runoff events have not been statistically strong in any watershed study, the growing number of such analyses has provided considerable evidence that clear-cutting with only light soil disturbance has little effect on the magnitude of the large runoff events that cause downstream flooding.

Any slight effects of clear-cutting on storm runoff also may be overshadowed by the occurrence of other hydrologic phenomena that may be related indirectly to clear-cutting. Road failures can temporarily dam streams and cause extreme peak flows when the dam of soil, rock, and organic debris finally fails [*Fredriksen*, 1965]. Such dams also may result from natural failure of slopes or from the accumulation of natural organic debris in stream channels. Both logging debris and natural organic debris may plug culverts and cause them to fail during major runoff events, even though the culverts are adequate to carry the water produced in these runoff events [*Rothacher and Glazebrook*, 1968]. Thus additional storm runoff resulting from changes in evapotranspiration after clear-cutting becomes unimportant in causing on-site damage when it is compared with other causes of the damage.

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