WATER RESOURCES RESEARCH, VOL. 18, NO. 3, PAGES 637–644, JUNE 1982

Streamflow Changes After Logging 130-Year-Old Douglas Fir in Two Small Watersheds

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Timber harvest in two small watersheds in western Oregon containing 130-yr-old timber increased annual water yield up to 42 cm. For 4 years after logging, yield increases averaged 38 cm at a 13.0-ha clearcut watershed and 20 cm at a 15.4-ha watershed where timber was shelterwood cut. Increased summer flows were indicated by much fewer low-flow days after logging, particularly at the clearcut watershed. During the 1977 drought year, only eight and two low-flow days occurred at the clearcut and shelterwood cut watersheds, respectively, compared to 143 and 135 low-flow days predicted by the calibration relationship. Neither the size nor the timing of peak flows changed significantly after logging at either watershed.

INTRODUCTION

Intensive management of even-aged stands of timber will become increasingly important as young forests approach rotation age. Partial cutting, such as shelterwood cutting to stimulate advance regeneration, is advantageous, particularly on south-facing slopes that are often difficult to reforest. This study was begun in 1963 to determine the effects of shelterwood cutting on streamflow characteristics of a south-facing watershed in western Oregon containing 130-yr-old Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and to compare these effects with those caused by clearcutting an adjacent, similar watershed.

That timber harvest activities can alter streamflow has been demonstrated in numerous studies throughout the United States [*Reinhart et al.*, 1963; *Hibbert*, 1967; *Hewlett and Helvey*, 1970; *Hornbeck*, 1973: and many others]. In the maritime climate of western Oregon, studies have shown that clearcut logging entire small watersheds in mountainous topography of the Coast and western Cascade Ranges can increase annual water yield up to 60 cm [*Rothacher*, 1970; *Harris*, 1973; *Harr et al.*, 1979], which is among the highest increases worldwide. In one study, however, annual water yields were unchanged at two watersheds logged in clearcut patches totaling 25% of watershed area, a result thought to be at least partly related to reduced fog drip after logging [*Harr*, 1980]. In absolute terms the greatest part of each annual increase has occurred during the fall-winter rainy season, but the largest relative increases (100–300% of predicted flows) have occurred during the summer [*Rothacher*, 1970, 1971; *Harr et al.*, 1979]. Where they have been detected, the relatively large summer increases have tended to diminish quickly as riparian vegetation has established; in one watershed, measured flows after logging have been slightly less than predicted by the prelogging flow relationship (i.e., decreased flow after logging), most likely because of greater consumption of water by newly established phreatophytic riparian vegetation [*Harr*, 1979]. In another case, summer flows were decreased slightly after logging, a result thought to be caused by reduced fog interception and drip after logging [*Harr*, 1980].

In western Oregon, as elsewhere in the United States where soil disturbance had been minimal, changes in storm runoff were restricted to those seasons when reduced evapotranspiration after timber cutting caused differences in water content of soil between logged and unlogged watersheds. Owing to their wetter soils, logged watersheds were hydrologically more responsive to rainfall and exhibited higher fall peak flows [*Rothacher*, 1973; *Harr et al.*, 1975].

Some studies in the Pacific Northwest reported changes in size and timing of peak flows that appear to have been related to factors other than wetter soils after logging. Peak flows during the winter were 20–48% larger after logging where soils on more than about 12% of total watershed area were compacted by roadbuilding, tractor yarding, or tractor windrowing of logging residue [*Harr et al.*, 1975; *Harr et al.*, 1979]. In two other studies, smaller, delayed peak flows after logging were attributed to changes in short-term snow accumulation and melt [*Harr and McCorison*, 1979] and to soil disturbance [*Cheng et al.*, 1975]. In the latter case, soil disturbance during high-lead yarding apparently disrupted water-transmitting pores sufficiently to slow down water movement through the soil profile.

Collectively, the foregoing studies indicate the variety of ways harvest activities might affect peak flows: peak flows may be larger, smaller, or unchanged after logging, depending on what part of the hydrologic system is altered and how much. This report summarizes a case history of changes in streamflow observed after harvesting in two small experimental watersheds. A third watershed was used as a control. This case study was the youngest of six experimental watershed studies begun in western Oregon in the late 1950's or early 1960's. Results of other experiments have been reported previously [*Rothacher*, 1970, 1971, 1973; *Harr*, 1979, 1980; *Harr and McCorison*, 1979; *Harr et al.*, 1975, 1979].

THE STUDY

Watershed Characteristics

The study area, located in the H. J. Andrews Experimental Forest, 72 km east of Eugene, Oregon, consists of three small watersheds designated HJA-6, HJA-7, and HJA-8 (Figure 1). The watersheds are located between the 865- and 1155-m elevations on the south aspect of Blue Ridge, the major divide between the Blue River drainage to the north and the Lookout Creek watershed which comprises the H. J.

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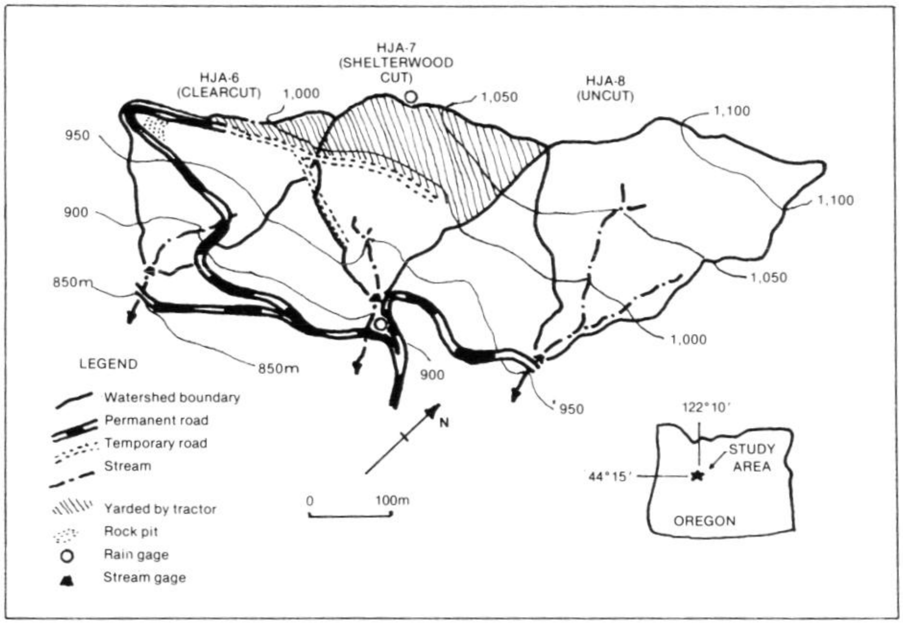

Fig. 1. Map of the study area.

Andrews Experimental Forest. Sideslope gradients generally range from 20 to 40%. Other physiographic characteristics are given in Table 1.

The experimental watersheds are underlain by two units of the Sardine Formation [*Swanson and James*, 1975]. The lower unit, which contains welded and nonwelded ash flows, underlies the middle portions of all three watersheds. The basalt and andesite lava flows of the upper Sardine unit are located along the upper boundaries of the watersheds and near the watersheds' outlets.

Four soil series are found in the experimental watersheds (C. T. Dyrness, and G. Hawk, unpublished report, H. J. Andrews Experimental Forest, 1972). The Carpenter series, which occupies about 55% of the area, has formed in deep andesitic landslide deposits. The Tidbits series, which occupies about 14% of the area, has formed from andesite and associated volcaniclastic rocks. Although generally shallower than the Carpenter series, the Tidbits soil has rooting depths in excess of 1 m. The Blue River series, found in the upper portions of all three watersheds, is derived from andesite residuum. This soil is generally less than 1 m deep and occupies about 19% of the area. The Budworm series is found primarily along the lower portions of the main stream channels in HJA-6 and HJA-8. Budworm soil is relatively stone-free and is generally 2–3 m deep. All soils are Typic Haplorthods except for the Tidbits soil, which is an Andic Cryumbrept.

Surface soils of all four series are sandy or silty loams of granular structure. Subsoils are loams or clay loams with structure that is subangularly blocky. Because the texture and structure of soils in watersheds HJA-6, HJA-7, and HJA-8 are nearly identical to those of soils studied more extensively in experimental watersheds at lower elevations in the H. J. Andrews Experimental Forest, the hydraulic properties of the soils should be nearly identical also. These lower elevation soils exhibit high porosities, relatively large amounts of macropore space, and wide ranges of pore sizes which result in both rapid movement of subsurface water during storms and sufficient retention of soil water for tree growth [*Dyrness*, 1969; *Harr*, 1977].

Prelogging vegetation occupied a transition zone between the western hemlock and Pacific silver fir zones, as defined by *Franklin and Dyrness* [1973]. As a result of fire, the experimental watersheds were forested primarily by Douglas-fir. Stands in HJA-6 and HJA-7 were made up of mainly 130-yr-old Douglas fir with scattered old growth about 450 yr old. Trees numbered 383/ha in HJA-6 and 334/ha in HJA-7. HJA-8 contains a higher proportion of old growth Douglas fir than did either HJA-6 or HJA-7 prior to logging. Primary understory vegetation included vine maple (*Acer circinatum* Pursh), rhododendron (*Rhododendron macrophyllum* D. Don ex G. Don), and salal (*Gaultheria shallon* Pursh).

Climate and Streamflow

The maritime climate of the study area is influenced greatly by the Pacific Ocean 160 km to the west. Annual

TABLE 1. Summary of Watershed Characteristics and Harvesting Activities

	Watershed		
	HJA-6	HJA-7	HJA-8
Area, ha	13.0	15.4	21.4
Elevation range, m	863–1013	908–1097	955–1190
Aspect	S	SSE	SSE
Area in permanent road, ha	1.2	0	0
Type of cut*	Clearcut	Shelterwood	Uncut
Area logged, ha	13.0	15.4†	0
Percent logged	100	100†	0
By tractor	10	60	0
By high lead	90	40	0
Residue disposal	Broadcast burn‡	Broadcast burn‡	Unburned

*Watersheds were logged during the summer of 1974.

†About 44 m^2 ha^{-1} or 60% of total basal area was removed in a shelterwood cut throughout the watershed.

‡Logging residue was burned in the spring of 1975.

TABLE 2. Annual Precipitation Near the HJA-7 Stream Gage and Annual Water Yields at Watersheds HJA-6, HJA-7, and HJA-8

Water Year	Annual Precipitation, cm	Annual Water Yield, cm		
		HJA-6	HJA-7	HJA-8
1964	204	132	95	115
1965	273	170	128	157
1966	172	104	68	88
1967	188	117	82	107
1968	216	110	72	100
1969	231	174	121	154
1970	199	125	89	115
1971	282	194	130	175
1972	281	231	162	190
1973	160	72	55	68
1974	290	253	171	214
1975	216	196*	126†	135
1976	257	209*	142†	148
1977	125	73*	47†	42
1978	244	192*	128†	135
1979	175	156*	97†	112
Mean	219			128

*All timber was clearcut in the summer of 1974.
†Sixty percent of basal area was removed in a shelterwood cut in the summer of 1974.

precipitation at the weather station near HJA-7 averaged 219 cm during the 1964–1979 water years, ranging from 125 cm in 1977 to 290 cm in 1972 (Table 2). On the average, about 80% of annual precipitation occurs in the October–March period, during relatively long-duration (12–72 hr), low- to moderate-intensity frontal storms associated with cyclones originating over the north Pacific Ocean (Figure 2). Amounts of 24-hour precipitation totaling at least 90 mm are common, having occurred 11 times in 16 years. Precipitation amounts totaling at least 120 mm in 48 hr and 150 mm in 72 hr have occurred 14 and 13 times, respectively. In a 120-hr period in each of December 1964 and December 1977, precipitation totaled 503 and 372 mm, respectively, and was partially responsible for the highest rates of streamflow measured at HJA-8.

Within the elevation range of the experimental watersheds, most precipitation falls as rain, but snow is common. Although snow may fall as early as late October, a snowpack generally does not develop until early December. In some years, pack depth may reach more than 225 cm and contain more than 85 cm of water equivalent at the time of maximum water equivalent. On the average, maximum water equivalent has been nearly one third of total annual precipitation in 1 of every 2 years. Rapid melting of snow during prolonged rainfall in winter has caused the maximum rates of runoff from these watersheds as well as from other watersheds in western Oregon [*Harr*, 1981].

Streamflow has been measured continuously with H flumes since October 1963. During the 1964–1974 prelogging period, annual streamflow averaged 143 cm at HJA-6, 121 cm at HJA-7, and 135 cm at HJA-8, the unlogged watershed. During these same periods, apparent annual evapotranspiration (annual precipitation minus annual streamflow) averaged 74 cm at HJA-6, 120 cm at HJA-7, and 92 cm at HJA-8. At HJA-6, annual streamflow averaged 67% of annual precipitation and 47 and 59% at HJA-7 and HJA-8, respectively. That the relatively high apparent annual evapotranspiration and annual streamflow were a low proportion of annual precipitation at HJA-7 is probably due to some water leaving the watershed as deep subsurface flow rather than as streamflow through the flume.

Relative amounts of interception and transpiration are unknown but probably were similar to those measured at the Willamette Basin Snow Laboratory [*U.S. Army Corps of Engineers*, 1956]. The Snow Laboratory, located in the upper Blue River drainage 3 km north, contained vegetation nearly identical to that in watersheds HJA-6, 7, and 8. Over a 4-yr period at the Snow Laboratory, precipitation minus streamflow equaled 84 cm, half of which was due to interception and half to transpiration.

On the average, maximum monthly precipitation has occurred in December (Figure 2), although maximum monthly precipitation frequently occurs in January and occasionally in February. Maximum monthly streamflow generally occurs in January or December. In most years there has been a secondary peak in the annual hydrograph during spring snowmelt, and in some years the spring peak equaled or exceeded the early winter peak (Figure 2). Both monthly precipitation and streamflow can vary greatly from year to year as illustrated by Figure 2.

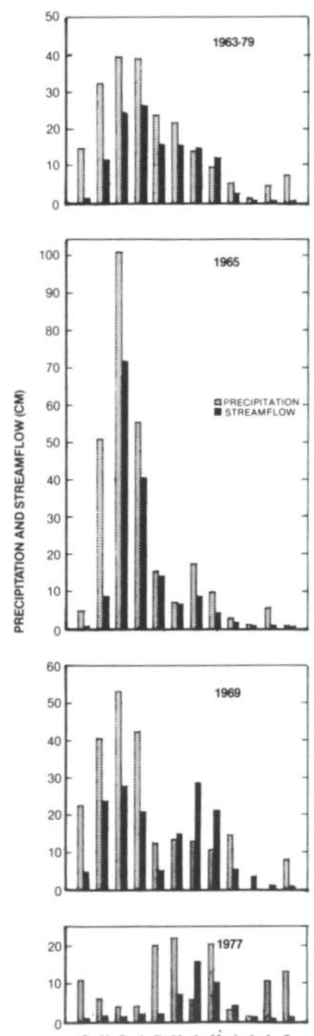

Fig. 2. Mean monthly precipitation near HJA-7 and mean monthly streamflow at HJA-8, 1963–1979. Variation in precipitation and streamflow is illustrated by plots of monthly precipitation near HJA-7 and monthly streamflow at HJA-8 for water years 1965, 1969, and 1977.

Watershed Treatments

The paired watershed technique was used to detect changes in streamflow in this study. Briefly, with this technique a hydrologic variable in one watershed is compared with that in another watershed during a pretreatment or calibration period to establish a relationship between watersheds for that variable over a range of climatic conditions. Then one watershed of a pair is treated or altered in some way by timber harvest activities, while the other remains an undisturbed control. Posttreatment measurements of the hydrologic variable are compared with a prediction of the variable based on the pretreatment relationship to evaluate changes caused by treatment. A control watershed is paired with each logged watershed to form two pairs of watersheds.

A permanent, all-weather road occupying 1.2% of total watershed area had been constructed through HJA-6 prior to the start of this study. Consequently, the calibration period also includes whatever hydrologic effects that were caused by the road.

Logging began in May 1974 and was completed in August 1974. All timber was removed in a clearcut in HJA-6 (Figure 3). Logs in 90% of the watershed were yarded uphill by a high-lead cable system; logs in the remaining 10% were yarded by tractor (Figure 1). Logging residue was broadcast burned in the spring of 1975, and the watershed was planted with Douglas fir seedlings in the spring of 1976.

In HJA-7, 60% of total basal area was removed in a shelterwood cut during the summer of 1974 (Figure 4). Temporary spur roads were constructed across the top of HJA-6 and into the middle of HJA-7 (Figure 1) and down the southwest ridge of HJA-7. Logs in the upper 60% of the watershed were yarded by tractor. Skid trails were not preplanned, but tractor operators were instructed for safety reasons to yard downhill. Consequently, soil compaction by tractors was limited to short segments of main skid trails immediately upslope from the upper spur road in HJA-7. Logs in the lower 40% were yarded partially suspended by a skyline cable system. Logging residue was broadcast burned only on the lower half of the watershed in the spring of 1975. HJA-8 has remained undisturbed.

Methods of Data Analysis

Streamflow data were analyzed to determine changes in annual yield, low flows, and instantaneous peak flows after timber harvest. Annual yields are expressed as a uniform depth of water (in centimeters) over a watershed, i.e., total streamflow volume divided by watershed area. Low-flow data are expressed as the numbers of days mean daily flow was less than 0.022 liters per second per hectare ($l\ s^{-1}\ ha^{-1}$), an arbitrary value, at each watershed. In annual yield and low-flow analyses, each postlogging year is considered separately because regrowth of shrub and herbaceous vegetation changes evapotranspiration drastically from year to year and precludes pooling postlogging data. Peak flow is the maximum instantaneous rate of streamflow attributable to a storm or snowmelt period and is expressed in $l\ s^{-1}\ ha^{-1}$. Nearly all storms included in these analyses occurred after soil water recharge so that differences between logged and unlogged watersheds were at a minimum. Because causes of peak flow changes tend to be relatively long lived, postlogging data, unlike annual yield and low-flow data, has been pooled.

Simple linear regression was used to obtain prelogging calibration equations and, for some analyses, postlogging response equations. Various flows at HJA-6 and HJA-7 were regressed against corresponding flows at HJA-8, the unlogged control watershed at common points in time. Although each regression analysis assumes that successive observations of a hydrologic variable are independent and random, strict independence does not always occur in this type of study.

In the analyses of annual water yield and low flows, the hypotheses were that there are no differences between

Fig. 3. All timber in HJA-6 was clearcut in 1974, and logging residue was broadcast burned in 1975. When this photograph was taken in May 1980, snowbrush ceanothus (*Ceanothus velutinus* Dougl. ex Hook), vine maple, various herbaceous species, and Douglas fir seedlings covered the watershed.

Fig. 4. In HJA-7, 60% of basal area was removed in a shelterwood cut. This view, 3 years after logging, is northward from the ridgetop spur road in HJA-7.

prelogging and postlogging yields. To test the hypothesis, a prediction limit was computed based on the standard error for estimating individual observations for the prelogging relationship. Prediction limit is given by (t) $(S_{\hat{Y}})$ where $S_{\hat{Y}}$ is sample standard error of $\hat{Y}$.

$$S_{\hat{Y}} = S_{y \cdot x}\left(1 + \frac{1}{n} + \frac{\chi^2}{\Sigma\chi^2}\right)^{1/2}$$

$S_{y \cdot x}$ is the sample standard error of the mean, n is the number of observations in prelogging regression, and $\chi = x - \bar{x}$, the corrected value at the point of comparison [*Snedecor and Cochran*, 1956, pp. 135–140]. Because timber harvest was expected to increase annual water yield and low flow, we used a one-tailed test for significance of changes after logging. If a postlogging value exceeded the prediction limit, the hypothesis was rejected in favor of the alternate hypothesis that the yield is significantly greater than a prelogging yield corresponding to that level of flow at the control watershed.

In the analysis of peak flow data, the hypothesis was that there is no difference between prelogging and postlogging regressions. This hypothesis was tested by the principle of 'extra sum of squares' [*Neter and Wasserman*, 1974, pp. 160–167]. All hypotheses were tested at the 0.05 level of probability.

RESULTS AND DISCUSSION

Annual Water Yield

During the calibration period, correlation of annual water yield between the control watershed and each of the two other watersheds was excellent. At HJA-6 and HJA-7, respective prediction equations are $\hat{Y} = -11.22 + 1.22X$ and $\hat{Y} = -5.10 + 0.83\,X$, where X is annual water yield at HJA-8, the control watershed. These prediction equations for the 11-yr calibration period explain over 98% of the variation in annual yield, as indicated by the r^2 values of 0.99 and 0.98 for HJA-6 and HJA-7, respectively. (Although timber was cut in late spring and early summer of 1974, the 1974 water year is included in the calibration period.)

Logging significantly increased annual yield in both logged watersheds (Figure 5). Increases were, as expected, larger at HJA-6, the clearcut watershed, where the first-year increase was 42 cm (27%), and increases averaged about 38 cm (30%) the first 4 years after logging. Yield increases averaged about 20 cm (22%) the first 4 years after shelterwood cutting in HJA-7. Yield increases in both watersheds were much smaller in 1979. All increases are statistically significant except for that of the 1979 water year at HJA-7. Increases in annual water yields appear to be decreasing, but because only 5 years have elapsed since logging, it is impossible to predict when annual water yields will return to prelogging levels.

Clearcutting a small watershed of 130-yr-old Douglas fir increased annual water yield nearly the same amount as did clearcutting a nearby watershed that contained 450-yr-old Douglas fir. The first-year 42-cm increase in annual water yield at HJA-6 was about 10 cm less than the first-year increase at watershed HJA-1 but nearly the same as increases 2 and 3 years after clearcutting at HJA-1, years *Rothacher* [1970] considered more representative of postlogging conditions. Elsewhere in western Oregon, clearcutting small watersheds caused first-year increases in annual water yield of 37 cm in the Oregon Coast Ranges [*Harris*, 1973] and 36 cm in southwestern Oregon [*Harr et al.*, 1979]. In the latter case, increases in subsequent years were less than the first-year increase, but in the former case, second- to fifth-year increases all were greater than the first-year increase, ranging from 47 cm to more than 60 cm.

Shelterwood cutting that removed 44 m^2 ha^{-1} or 60% of

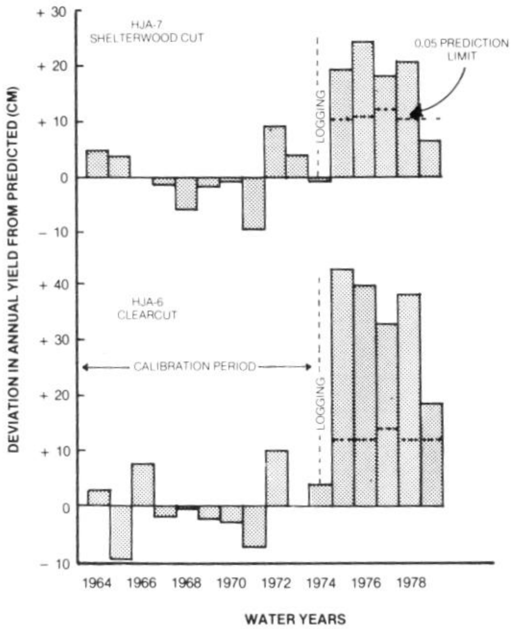

Fig. 5. Increases in annual water yield after logging.

basal area in a small watershed of 130-yr-old Douglas fir increased annual water yield nearly the same amount as did patch logging 30% of a nearby watershed that contained 450-yr-old Douglas fir. The 20-cm average increase in annual water yield the first 4 years after logging compares favorably with the 22-cm average at HJA-3 [*Rothacher*, 1970]. Elsewhere in western Oregon, partial cutting in small clearcuts or in a preparatory shelterwood cut that removed 50% of total basal area caused increases in annual water yield that averaged 8–10 cm the first 5 years after logging [*Rothacher*, 1970; *Harris*, 1973; *Harr et al.*, 1979].

It appears that harvest of second-growth forests in the future will increase annual water yields in small headwater drainages about the same amount as harvest of old growth timber does now. But where nearly identical areas of timber in a large drainage are harvested each year, increases in water yield—generally less than 1–2%—from recent logged areas in small headwater basins should not appreciably alter annual water yield at the mouth of the large parent watershed. In this latter case, flow increases from recently logged areas will be masked by normal flow from nonlogged areas and reforested areas [*Rothacher*, 1970; *Harr et al.*, 1979]. In most cases the increases in annual yield for the large watershed will be about the same size as the error in measuring streamflow in the large stream.

Low Flows

During the calibration period, number of low-flow days at HJA-6 and HJA-7 were moderately well correlated with number of low-flow days at HJA-8; prelogging prediction equations explain 92 and 72% of the variation in low-flow days at HJA-6 and HJA-7, respectively. Timber harvest resulted in fewer low-flow days in both logged watersheds in most years, i.e., streamflow during the summer low-flow period was increased. At HJA-6, the clearcut watershed, number of low-flow days was far outside the 0.05 prediction limit in 5 of 6 postlogging years (Figure 6). In 1977, by far the driest year on record in western Oregon, HJA-6 had only 8 low-flow days instead of the 143 low-flow days predicted by the prelogging relationship. At HJA-7, the shelterwood cut watershed, data points for 4 of 6 postlogging years fall outside the 0.05 prediction limit. In 1977, HJA-7 had only 2 low-flow days instead of 135 days predicted by the prelogging relationship. In 1978, precipitation during September, the primary low-flow month, totaled 12.2 cm, an amount sufficient to maintain relatively high summer streamflow and prevent mean daily flow from declining to the 0.022 $\mathrm{l\ s^{-1}\ ha^{-1}}$ at either logged watershed in September. Thus no low-flow days were observed in 1978.

Attempts were made to identify more closely the timing and volume of increased low flow, but no consistent relations were found. Variation in volume of flow during low-flow periods precluded any meaningful analyses of low-flow volumes.

Instantaneous Peak Flows

Both size and timing of instantaneous peak flows greater than 4.5 $\mathrm{l\ s^{-1}\ ha^{-1}}$ at HJA-8, the unlogged control watershed, and corresponding peak flows at each of the other watersheds were tabulated by water year. (According to a log Pearson type 3 frequency analysis, a peak flow of at least 4.5 $\mathrm{l\ s^{-1}\ ha^{-1}}$ would occur, on the average, at least once a year.) There were 17 such events during the 11-yr calibration period, and 8 and 7 during the postlogging period at HJA-6 and HJA-7, respectively. (The size of the eighth event at HJA-7 was omitted from data analysis because it was estimated after a streamgage malfunction.) Postlogging data

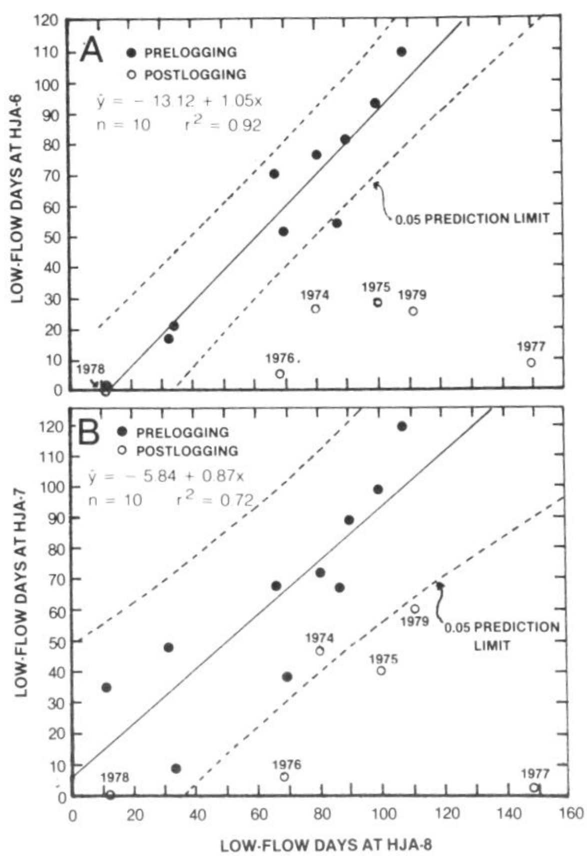

Fig. 6. Relationship of low-flow days between (*a*) clearcut watershed HJA-6 and unlogged HJA-8 and between (*b*) shelterwood cut watershed HJA-7 and unlogged HJA-8.

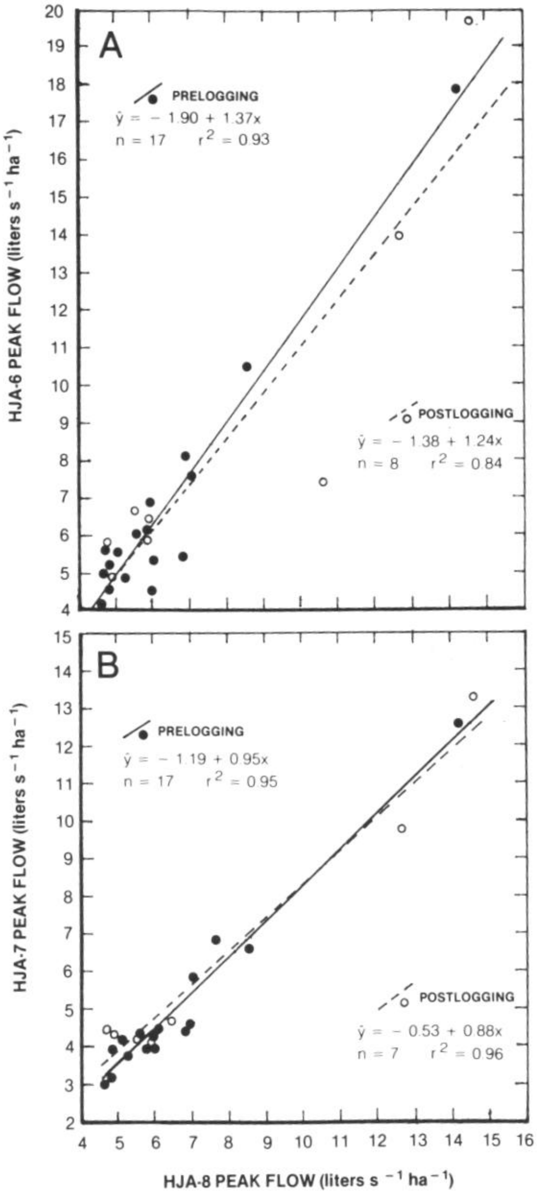

Fig. 7. Peak-flow relationships before and after logging in (*a*) clearcut HJA-6 and (*b*) in shelterwood cut HJA-7.

were then compared with prelogging data to determine if peak flow relationships had changed after logging.

In addition to size of peak flow, the difference between times of occurrence of peak flow at each watershed was determined for each storm runoff event. The time of peak flow at HJA-8 was subtracted from the time of the corresponding peak at HJA-6 and at HJA-7; the time was positive if HJA-8 peaked first and negative if HJA-6 or HJA-7 peaked first. Mean time difference for prelogging and postlogging periods was analyzed by an unpaired t test using a pooled mean-square estimate of variance [*Dixon and Massey*, 1957, p. 121].

Peak-flow size relationships between logged and unlogged watersheds are shown in Figure 7. There is no difference between prelogging and postlogging peak-flow relationships for peak flows greater than 4.5 l s^{-1} ha^{-1}; i.e., size of peak flows was not significantly changed by logging.

Changes in timing of peak flows greater than 4.5 l s^{-1} ha^{-1} are summarized in Table 3. Timing of peak flows was not changed significantly after logging in either HJA-6 or HJA-7.

TABLE 3. Change in Timing of Peak Flows After Logging in HJA-6 and HJA-7

	Prelogging		Postlogging		
Watershed	Number of Peaks	Mean Time Difference, h	Number of Peaks	Mean Time Difference, h	t
HJA-6	17	3.6	8	4.2	−0.371
HJA-7	16	−0.6	7	3.1	−1.530

Snowmelt

How clearcutting and shelterwood cutting have affected snowmelt in HJA-6 and HJA-7 is unknown. There are no data on either snowpack distribution or the meteorological variables that influence melt; the study was not designed to assess the effects of timber harvest on snowmelt.

Major runoff has been caused by rapid melting of snow during prolonged rainfall in late fall and winter. The study watersheds are located in the upper part of the zone of transient snowpacks where melt from shallow snowpacks during rainfall is most common [*Harr*, 1981]. Because convection and condensation are major sources of heat for this type of melt [*U.S. Army Corps of Engineers*, 1960] and both are directly related to windspeed and turbulence, greater exposure of the snow surface to moist, relatively warm air could increase rate of melt and cause higher peak flows. That such a condition could occur after timber harvest has been proposed by *Harr* [1981]. Data from the study described here, however, provide little information to help evaluate effects of timber harvest on rate of snowmelt during rainfall. Clearly, such information will come primarily from studies designed specifically to provide it, studies that relate melt to the meteorological and physiographic variables that influence melt rather than to the gross climatic data that are typically part of hydrologic studies.

SUMMARY

By reducing evapotranspiration, timber harvest increased annual water yield up to 42 cm. For 4 years after logging, yield increases averaged 38 cm at HJA-6, the clearcut watershed, and 20 cm at HJA-7, where timber was shelterwood cut. Increased summer low flow was reflected in much fewer low-flow days after logging; number of low-flow days was reduced more at HJA-6, the clearcut watershed. Neither the size nor the timing of peak flows changed significantly after logging at either watershed.

Acknowledgments. We gratefully acknowledge manuscript reviews by George W. Brown, John D. Hewlett, Charles A. Troendle, and J. D. Helvey and helpful discussions with Richard L. Fredriksen.

REFERENCES

Cheng, J. D., T. A. Black, J. de Vries, R. P. Willington, and B. C. Goodell, The evaluation of initial changes in peak streamflow following logging of a watershed on the west coast of Canada, *IAHS-AISH Publ.*, *117*, 475–486, 1975.

Dixon, W. J., and F. J. Massey, Jr., *Introduction to Statistical Analysis*, 2nd ed., 488 pp., McGraw-Hill, New York, 1957.

Dyrness, C. T., Hydrologic properties of soils on three small watersheds in the western Cascades of Oregon, *U.S. Dep. Agric. For. Serv. Res. Note PNW-111*, 1969.

Franklin, J. F., and C. T. Dyrness, Natural vegetation of Oregon and Washington, *U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. PNW-8*, 1973.

Harr, R. D., Water flux in soil and subsoil on a steep forested slope, *J. Hydrol.*, *33*, 37–58, 1977.

Harr, R. D., Effects of timber harvest on streamflow in the rain-dominated portion of the Pacific Northwest, in Proceedings of Workshop on Scheduling Timber Harvest for Hydrologic Concerns, 44 pp. U.S. Dep. Agric. For. Serv., Pacific Northwest Region, Portland, Oregon, 1979.

Harr, R. D., Streamflow after patch logging in small drainages within the Bull Run Municipal Watershed, Oregon, *U.S. Dep. Agric. For. Serv. Res. Pap. PNW-268*, 1980.

Harr, R. D., Some characteristics and consequences of melt from shallow snowpacks during rainfall in western Oregon, *J. Hydrol.*, *53*, 277–304, 1981.

Harr, R. D., and F. M. McCorison, Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon, *Water Resour. Res.*, *15*, 90–94, 1979.

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

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

Harris, D. D., Hydrological changes after clear-cut logging in a small Oregon coastal watershed, *J. Res. Geol. Surv.*, *1*, 487–491, 1973.

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

Hibbert, A. R., Forest treatment effects on water yield, in *International Symposium on Forest Hydrology*, edited by W. E. Sopper and H. W. Lull, pp. 527–543, Pergamon, New York, 1967.

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

Neter, J., and W. Wasserman, *Applied Linear Statistical Models*, 842 pp., Richard D. Irwin, Inc., Homewood, Illinois, 1974.

Reinhart, K. F., A. R. Escher, and G. R. Trimble, Jr., Effect on streamflow of four forest practices in the mountains of West Virginia, *U.S. Dep. Agric. For. Serv. Res. Pap. NE-1*, 1963.

Rothacher, J., Increases in water yield following clearcut logging in the Pacific Northwest, *Water Resour. Res.*, *6*, 653–658, 1970.

Rothacher, J., Regimes of streamflow and their modification by logging, in *Symposium on Forest Land Uses and Stream Environment*, edited by J. Morris, pp. 40–54, Continuing Education Publications, Oregon State University, Corvallis, Oregon, 1971.

Rothacher, J., Does harvest in west slope Douglas-fir increase peak flows in small forest streams? *U.S. Dep. Agric. For. Serv. Res. Pap. PNW-163*, 1973.

Snedecor, G. W., and W. G. Cochran, *Statistical Methods*, 5th ed., 534 pp., Iowa State University Press, Ames, Iowa, 1956.

Swanson, F. J., and M. E. James, Geology and geomorphology of the H. J. Andrews Experimental Forest, western Cascades, Oregon, *U.S. Dep. Agric. For. Serv. Res. Pap. PNW-188*, 1975.

U.S. Army Corps of Engineers, *Snow Hydrology*, 437 pp., U.S. Army Corps of Engineers, Portland, Oregon, 1956.

U.S. Army Corps of Engineers, Runoff from snowmelt, 75 pp., *Eng. Manual 1110-2-1406*, 1960.

(Received October 20, 1981;
revised January 25, 1982;
accepted February 10, 1982.)