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Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon

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Abstract. This study quantified long-term changes in streamflows associated with clear-cutting and road construction and examined alternative hydrologic mechanisms to explain stream hydrograph changes in the Cascades Range, western Oregon. We examined differences in paired peak discharges for 150 to 375 storm events for five basin pairs, using 34-year records from two pairs of 60-to-101-ha experimental basins in the H. J. Andrews Experimental Forest, and 50-to-55-year records from three pairs of adjacent basins ranging from 60 to 600 km^2. Forest harvesting has increased peak discharges by as much as 50% in small basins and 100% in large basins over the past 50 years. These increases are attributable to changes both in flow routing due to roads and in water balance due to treatment effects and vegetation succession.

Introduction and Background

Forest harvesting has been conducted since the turn of the century in the Cascade Range of Oregon. Logging began in the 1930s, and a pattern of roads and distributed patch cuts of 20 to 40 ha now covers up to 25% of public national forest lands, which occupy over half of the western Cascades. A number of small paired basin experiments were established on public lands in the early 1950s in western Oregon to examine the influence of forest harvesting on streamflow, especially water yield [*Hibbert*, 1967; *Rothacher*, 1965]. Comparable paired basin experiments have been conducted in many different parts of the United States and abroad [e.g., *Blackie et al.*, 1979; *Callaham*, 1990; *Wright et al.*, 1990; *Ziemer*, 1981], in basins ranging from 0.1 to 1.0 km^2.

Early studies from small paired experimental basins showed that clear-cutting and road building increased only some peak storm discharges [*Rothacher*, 1970, 1973; *Wright et al.*, 1990; *Ziemer*, 1981]. In the Pacific Northwest, increases were greater for small, early wet season storms, but "there has been no appreciable increase in peak flows for the largest flood-producing storms" [*Rothacher*, 1970, p. 656, 1973]. Thus *Rothacher* [1971, p. 46] concluded that "logging . . . does not significantly increase major floods" in forested basins of the western Cascades. However, subsequent studies [*Harr*, 1986; *Wright et al.*, 1990] have questioned the validity of the regression method used by *Rothacher* [1971] and others [e.g., *Harr et al.*, 1982].

Evidence of peak flow response to forest harvest over several decades in basins larger than 5 km^2 is mixed. Some studies around the United States have shown significant relationships between higher peak discharges and logged or deforested conditions in basins ranging up to 20,000 km^2 [*Anderson and Hobba*, 1959; *Potter*, 1991; *Trimble and Weirich*, 1987]. *Christner and Harr* [1982] and *Lyons and Beschta* [1983] inferred that in the western Cascades of Oregon, peak discharges increased with greater cumulative area of forest harvested in basins ranging from 60 to over 600 km^2. However, other studies in Washington State have not found peak discharges to be related to forest harvest [*Duncan*, 1986; B. A. Connelly et al., unpublished manuscript, 1993].

Several theoretically possible water balance mechanisms might operate to produce observed changes in peak discharge in response to specific treatments and climate-vegetation associations. Evapotranspiration is a major determinant of streamflow in forested basins, so suppression of evapotranspiration by forest harvest can be expected to increase water yield and peak discharges. However, the magnitude of this response may vary by season. For example, seasonal fluctuations in soil moisture storage in the Mediterranean climate of Oregon may produce different responses for peak discharges in fall versus winter or spring. Also, streamflow response to forest harvest may be confounded by changes in water balance components other than evapotranspiration. For example, fog and cloud water interception and snowpack accumulation and melt are important water balance components in western Oregon, so changes in these components could mitigate or counteract evapotranspiration-related increases in peak discharges [*Harr*, 1982, 1986; *Harr and Coffin*, 1992; *Harr and McCorison*, 1979].

Forest roads, constructed to access harvest sites, further complicate the hydrologic mechanisms operating in harvested basins in western Oregon. In these basins, soil infiltration capacity is high and hillslope flow is dominantly subsurface, so roads have the potential to both increase surface runoff and intercept subsurface flow [*Wemple*, 1994]. Roads have been shown to increase, decrease, or not affect peak discharges in various studies in the Pacific Northwest [*Wright et al.*, 1990; *Ziemer*, 1981; *Harr et al.*, 1975, 1979; *King and Tennyson*, 1984].

The objective of this study is to quantify long-term changes in storm hydrograph behavior associated with clear-cutting and road construction and to examine alternative hydrologic mechanisms to explain stream hydrograph changes in western Oregon. We are especially interested in understanding the following: (1) the magnitude and duration of peak discharge

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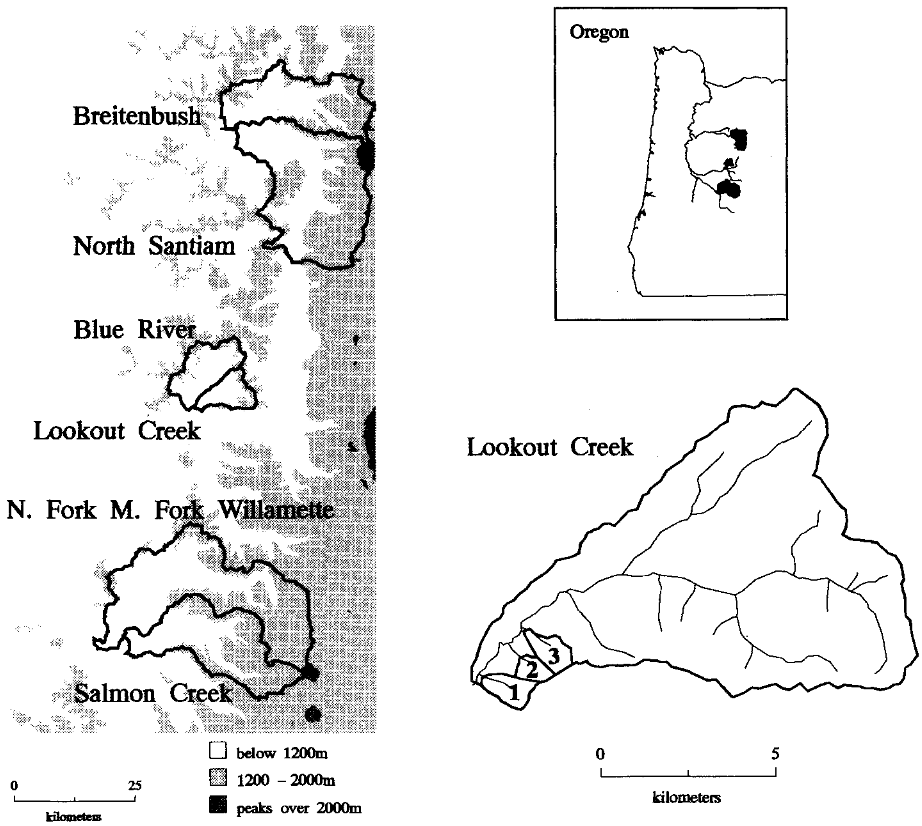

Figure 1. Locations of six large basins in the western Cascades, Oregon, and Watersheds 1, 2, and 3 in the H. J. Andrews Experimental Forest (Lookout Creek basin).

responses associated with clear-cutting alone, roads alone, or clear-cutting with roads; (2) how the size, season, and type (rain versus rain on snow) of streamflow event influences the magnitude of response; and (3) how well small-basin response to forest harvest predicts large-basin response.

Methods

Approach

We examined 34-year records from two pairs of experimental basins, ranging from 60 to 101 ha, in the H. J. Andrews Experimental Forest, and 50-to-55-year records from three pairs of adjacent basins ranging from 60 to 600 km^2 in the western Cascades (Figure 1, Table 1). The small basins (Watersheds 1, 2, and 3) were a paired basin experiment, with clearly defined pretreatment and post-treatment periods, two unreplicated treatments, and a control (Table 1). In "station pair" unreplicated experiments such as this, *Eberhardt and Thomas* [1991] recommend that statistical analyses examine the difference between the logarithms of the response variable at the "impacted" and control stations and how this variable changes as a function of treatment. We examined changes in peak discharge between the treated and control basins for paired events, as a function of time before and after treatment. This procedure meets statistical assumptions of identity and independence of data required for analysis of variance. The widely used regression-intersection method for paired basin studies violates the assumptions of normally distributed data and uniformly distributed residuals.

Our analysis of small-basin streamflow differed in several respects from previous studies of Watersheds 1, 2, and 3 [*Rothacher*, 1973]. We used a much longer data record (34 years) and included data on stormflow peaks as small as 0.03 m^3 s^{-1} km^{-2}, producing large sample sizes (over 350 storm peaks), whereas *Rothacher* [1973] examined roughly 40 peak flows exceeding 0.4 m^3 s^{-1} km^{-2} over a 5-to-10-year post-treatment period for the same basins. We compared five or six 5-year post-treatment periods to the pretreatment period, whereas early studies lumped all post-treatment data. We transformed our data before analysis, following *Eberhardt and Thomas* [1991], and classified peak discharges by season, size, and type (rain versus rain on snow). Also, we used categorical data analysis to examine changes in the shape of the hydrograph, including timing, peak flows, and volumes.

The analytic approach for the large basins was more complicated. No large basins in the western Cascades were unharvested throughout this period, so no control basin was available. Also, forest harvest treatments (patch clear-cutting and roads) were imposed progressively through space and time. However, the three pairs of large basins did have contrasting land use histories. Therefore we were able to use the same response variable, that is, the difference in peak discharge for each paired event between the more harvested and less harvested basin, and we related this variable to the magnitude of the difference in harvest area between the basins.

Our analysis of large-basin streamflow differed in several respects from previous studies of large basins. No prior studies have examined differences in paired peak discharges. *Christner and Harr* [1982] conducted the first study of these basins, but they did not assess the magnitude or the statistical significance

Table 1. Summary of Characteristics of Small and Large Basins in This Study in the Western Cascades of Oregon

Basin	Area, km^2	Elevation, m		Type and Duration of Treatments: Cutting		Roads		Hydrologic Record Used	
		Minimum	Maximum	%	Years	km km^{-2}	Years	Duration, years	Number of Paired Events
Small Basins									
Watershed 1	1.0	460	990	100	1962–1966	0	n/a	1955–1988	352
Watershed 2	0.6	530	1070	0	n/a	0	n/a	1955–1988	352, 377
Watershed 3	1.0	490	1070	25	1963	2.7	1959	1955–1988	377
Large Basins									
Upper Blue River	119	400	1600	25	1957–1991	1.9	1957–1990	1949–1991	148
Lookout Creek	62	400	1600	22	1949–1991	1.9	1949–1990	1949–1991	148
Salmon Creek	313	350	2400	20	1930–1991	···	···	1935–1990	171
N. Fork Middle Fork Willamette River	637	350	2400	16	1910–1991	···	···	1935–1990	171
Breitenbush River	280	400	2800	14	1910–1991	···	···	1932–1987	191
North Santiam River	559	400	3200	12	1940–1991	···	···	1932–1987	191

Ellipses indicate data not used in this study; n/a, not applicable.

of the relationship between area cut and changes in peak discharges. Moreover, our analysis used streamflow records of 50 to 55 years compiled from original U.S. Geological Survey (USGS) strip charts, whereas *Christner and Harr* [1982] used a 25-year USGS record of published peaks that omitted numerous storms, we discovered. We determined cumulative harvests directly from U.S. Forest Service (USFS) cutting records and recorded them in a geographic information system, whereas *Christner and Harr* [1982] used USFS estimates of area cut. Details of the methods are presented below.

Study Site Description

The small basins, Watersheds 1, 2, and 3, are tributaries of Lookout Creek in the H. J. Andrews Experimental Forest near Blue River, in the western Cascades of Oregon. Lookout Creek is one of the six large basins, all of which are within the Willamette National Forest (Figure 1, Table 1). The basins span elevations from 400 to 3200 m and have slopes of 60 to 100%. The small basins are described in many publications [e.g., *Adams et al.*, 1991; *Dyrness*, 1965, 1969, 1973; *Grant and Wolff*, 1990; *Halpern*, 1989; *Harr*, 1976a, b, 1986; *Harr et al.*, 1975, 1982; *Hicks et al.*, 1991; *Rothacher*, 1965, 1970, 1973].

Mean annual precipitation in the western Cascades ranges from 2300 mm at lower elevations to more than 2500 mm at higher elevations [*Greenland*, 1994]. Over 80% of precipitation falls from November to April, typically as rain below 400 m and as snow above 1200 m. Elevations between 400 and 1200 m may alternately receive snow or rain and thus have been termed the "transient snow zone" [*Harr*, 1981, 1986]. All of the small basin area and more than 75% of the Blue River/Lookout Creek basins is in the transient snow zone below 1200 m, but between 30 and 55% of the upper elevations of the Salmon Creek/North Fork Willamette Middle Fork River and Breitenbush River/North Santiam River basin pairs is in the seasonal snow zone (Figure 1).

The study area is underlain by Tertiary and Quaternary volcanic rocks, primarily andesites and basalts, with some glacial deposits [*Sherrod and Smith*, 1989]. All of the small basins and more than 75% of the Blue River/Lookout Creek basins are underlain by highly weathered, deeply dissected volcanics [*Swanson and James*, 1975]. One third to one half of the two largest basin pairs are above 1200 m and underlain by <2-million-year-old, relatively permeable lava flows of the High Cascades [*Ingebritsen et al.*, 1991]. Soils are weakly developed with thick organic litter horizons, deeply weathered parent materials, and high stone content. Although the <2-mm soil fractions are mostly clay loams, moisture storage and transfer is characterized by high porosity, infiltration rates, and percolation rates [*U.S. Forest Service*, 1973; *Dyrness*, 1969]. Before treatment, the vegetation of these basins consisted of mainly 100- to 500-year-old Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) in closed canopy stands, with increasing amounts of Pacific silver fir (*Abies amabilis*) above 800 m.

Forest Harvest History and Data Collection

Roads were constructed prior to clear-cutting in small basins except in Watershed 1, which has no roads. Small basin treatments occurred in the late 1950s and early 1960s. In 1959, 2.7 km of roads (6% of basin area assuming a road right-of-way width of 25 m) were constructed in Watershed 3. Watershed 1 was 100% clear-cut from 1962 to 1966 and broadcast burned in 1966. In 1963, 25% of Watershed 3 was clear-cut, and the three patch cuts were broadcast burned (Table 1). Both basins were replanted after burning and now support 25-plus-year-old stands of Douglas fir.

The precise history of forest harvest and road construction in the six large basins was not known when this study began. Roads were constructed concurrently with clear-cutting in large basins. Therefore, geographic information system (GIS) data layers showing the date and location of clear-cuts were compiled from USFS records, historical maps, and aerial photographs. Each cut was outlined on 1:24,000 orthophotos, and these polygons were digitized and stored as a GIS layer. Each polygon was given attributes indicating the year and type of timber harvest (e.g. clear-cut), based on USFS Timber Resource Inventory and Mature and Over-Mature Stand data bases obtained from the Blue River, Oak Ridge, and Detroit Ranger Districts and the Supervisor's Office of the Willamette National Forest. Numerous cuts had conflicting or unavailable data. Information for these polygons was supplemented by consulting aerial photographs or the District silviculturalist.

Data on road networks were compiled for Lookout Creek and Blue River basins only. The current road networks were video digitized; 1:100,000 black-and-white aerial photographs obtained in 1991 and the digitized lines were stored as a GIS layer. Each road segment was assigned a decade of construction based on historical maps and aerial photography and a year of construction corresponding to the year prior to the date of the nearest adjacent clear-cut.

Basin boundaries and proportions of area by elevation were calculated from digital elevation data using Arc/Info GIS software. The area cut and the length of road constructed by year and by elevation in each basin were calculated from clear-cut and road layers overlaid on the elevation data. This GIS analysis indicates that clear-cutting began as early as the 1900s (railroad logging in the N. Fork Willamette) and as late as 1950 (Blue River). By 1990 cumulative clear-cuts represented between 12% (N. Santiam River) and 25% (Blue River) of basin area (Table 1).

Streamflow Monitoring and Data Collection

Continuous hydrographs were obtained from the gaging station for each basin. In the small basins the recording stations were installed in 1953 and, apart from a modification of the Watershed 1 flume early in the pretreatment period (1957), neither the calibration method nor the rating curves was changed over the period of record. Continuous records in the large basins began as early as 1928, and rating curves were periodically updated by the USGS.

Storm hydrographs were extracted from the small-basin records based on the following criteria. Storms began when gage height rose more than 3.7 cm (0.12 ft) and ended when either gage height fell to 20% of the peak value or 24 hours elapsed with steadily declining flow. Secondary storm peaks were defined as a gage height rise of 2.7 cm (0.09 ft) within 12 to 24 hours of a primary peak. Five descriptive statistics were obtained for each primary hydrograph: cumulative volume, instantaneous peak discharge, and time at beginning, peak, and end of each storm.

Storm hydrographs for the large basins were collected manually from stage height records (from the original A-35 strip charts or digital records) and the corresponding rating curves for each water year housed in the USGS archives. The discharge, date, and time of the peak were recorded for all storms during the period of record whose peak exceeded the original peak discharge threshold (1.1-year return interval calculated by *U.S. Geological Survey* [1993]) in either of the paired basins. Original records were examined in preference to USGS published records because criteria used to construct the latter have changed over the period of record. For example, in some basins only the single highest peak discharge was recorded in the early years. For five of the six gages the base flow used by the USGS to report peak discharges had been revised upward at some time during the record. Because of these various factors, our resulting data set contained events with recurrence intervals as low as 0.1 year, implying that in some basins the original 1.1-year event had been reduced to as frequent as a 0.1-year event.

Matched storm hydrograph data sets were created for the following five basin pairs: Watershed 1 versus 2, Watershed 3 versus 2, Blue River versus Lookout Creek, Salmon Creek versus North Fork Willamette Middle Fork River, and Breitenbush River versus North Santiam River (Table 1). Storm hydrographs were considered matched if primary peaks occurred within 12 hours of each other. Seventy-five percent of matched peaks in the small basin pairs were within 4 hours. Each matched peak flow data set contained the date, time, peak discharge, begin date/time, peak date/time, and total volume as continuous variables along with categorical variables including the month, season, and recurrence interval for each paired event (Table 1).

Peak Discharge Event Classification

Peak discharge events were classified according to time period, season, size, and event type. Time periods were defined as six or seven roughly 5-year periods before, during, and after treatment in small basins, and by decade (e.g., 1930s) in large basins. Three seasons were defined: fall (August through November), winter (December through February), and spring (March through July). Size categories were defined based on the four quartiles (for small basins) and thirds (for large basins) of the cumulative distribution of events. Recurrence intervals for each size class were defined using a nonparametric event-ranking procedure (i.e., the tenth largest event recorded in a 10-year record is given a recurrence interval of 1 year) [*Haan*, 1977]. The small-basin peak discharge record included on average 10 storms per year, so 90% of the small-basin events had a <1-year return period. The smallest event category had <0.125-year return periods, while the largest event category had return periods from 0.4 to 100 years. In contrast, the large-basin peak discharge record included on average three to five storms per year, so 70 to 75% of the events had a <1-year return period. The smallest event category had <0.5-year return periods, while the largest event category had return periods from 1 to 100 years. More large events occurred in all basins in the 1950s and 1970s, decades that had generally higher precipitation in this region [*Greenland*, 1993]. Despite different periods of record and distances of as much as 75 km between the northern and southernmost basin pairs, nearly 70% of the matched storms occurred in all six large basins.

Storm event types (rain versus rain on snow) were classified for matched events in the small basins and in the Blue River/Lookout Creek large-basin pair. Small-basin events were classified by (1) classifying precipitation for each event into rain or snow with a break point at 0°C, and (2) determining the amount of snowpack present at the time of the storm based on a distributed-parameter hydrologic model (MMS [*Leavesley et al.*, 1983]). Large-basin events were classified based on minimum and maximum daily temperatures, the average daily hydrograph, and an antecedent precipitation index (API) over a 2-week period preceding each storm, following *Harr* [1981, 1986]. API was calculated from daily precipitation data at Lookout Creek, following *Fedora and Beschta* [1989]. Hydrographs at the other two large-basin pairs which had dates corresponding to peaks at Blue River/Lookout Creek were classified as rain on snow according to their classification at Blue River/Lookout Creek. This ad hoc classification should be viewed as approximate because of differences in geography and elevations among the large basins.

Statistical Analysis

Changes over time in the shape of the hydrograph were examined using categorical data analysis. Four properties were examined: peak discharge, volume, begin time, and time of peak. For each hydrograph property, the mean difference was calculated for the period of record, and counts of hydrographs falling above/below this number were obtained for each time period. For each period, observed (post-treatment) counts were compared to expected (pretreatment) counts using a X^2

test of significance with 1° of freedom [*SYSTAT, Incorporated*, 1992]. The expected count was defined as the pre-treatment count for the small basins, and the average count for the whole period of record for the large basins. In this analysis, expected counts ranged from 9.5 to 41.5, producing a comparatively strong X^2 test [*Hosmer and Lemeshow*, 1989; *SYSTAT, Incorporated*, 1992, p. 564]. Because multiple observed counts were compared to expected counts, probabilities were conservatively adjusted to α/k using a Bonferroni procedure where α is the desired level of significance (0.05), and k is the number of comparisons (5 or 6) [*Miller*, 1980; *Neter et al.*, 1990; *SYSTAT, Incorporated*, 1992].

Changes in the average magnitude of peak discharges in the small basins in response to treatment (broken down by time period, season, size, and type) were examined using analysis of variance (ANOVA) followed by post hoc tests of effects using multiple comparisons procedures [*Miller*, 1980; *Neter et al.*, 1990; *SYSTAT, Incorporated*, 1992]. Because multiple post-treatment periods were compared to the pretreatment period, probabilities were conservatively adjusted using Tukey's highest significant difference test to guarantee an overall protection of $\alpha = 0.05$ [*Miller*, 1980; *Neter et al.*, 1990; *SYSTAT, Incorporated*, 1992]. Data were tested for independence, equality of variance, and normality before analysis. Small-basin peak discharges and simple differences or ratios of peak discharges were lognormally distributed. This was corrected by using the difference in log-transformed peak discharges between the treated and control basins for each paired event as the variable of interest, following *Eberhardt and Thomas* [1991].

Changes in the average magnitude of peak discharges in the large basins in response to treatment (broken down by season, size, and type) were examined using linear regression. The peak discharge (dependent) variable was defined as the difference in unit area peak discharge (cubic meter per second per square kilometer) between the two adjacent basins for each paired event. The forest harvest (independent) variable was defined as the difference between basins in the cumulative percent of area harvested. Both variables were continuous and normally distributed. Linear regression models tested how the difference in peak discharge varied as a function of the difference in cumulative percent harvested for each basin pair. A significant positive slope in the regression model indicates that the basin with relatively more area harvested (larger difference in cumulative percent cut) has correspondingly higher peak discharges (larger difference in matched peak discharges). Regression models were tested for sensitivity to outliers, and residuals were plotted against the estimates, event size, and annual rainfall. Models were estimated for all events in each basin pair and for selected subsets of the data: for example, rain, rain on snow, large events, or spring events. When more than one regression model was estimated, probabilities were conservatively adjusted to α/k using a Bonferroni procedure to guarantee an overall significance of 0.05 [*Miller*, 1980, *Neter et al.*, 1990, *SYSTAT, Incorporated*, 1992]. This method was a direct test of cutting effects but only an indirect test of road effects on streamflow, because roads function as linear features and are constructed a few to many years before cutting.

Results

Spatial Patterns of Forest Harvest in the Western Cascades

Forest harvest in large basins produced a dispersed pattern of small clear-cuts whose concentration increased gradually over the six decades of cutting (Figures 2a–2c). Because of wilderness and other restrictions, 86 and 85% of cuts in Blue River/Lookout Creek, 72 and 78% in Salmon Creek/N. Fork Willamette, and 90 and 92% in N. Santiam/Breitenbush River were below 1200 m elevation. Thus almost all forest harvest in large basins was concentrated in the transient snow zone (Figures 1 and 2).

Cutting rates were low (less than 0.1% of basin area per year) in all basins until the 1945–1955 period. Starting in 1945 or 1950, cutting occurred at rates of 0.25% to 1% of basin area per year until 1990 (lower panels of Figures 3a–3c). The Blue River/Lookout Creek basin pair had the most dramatic contrast in harvests over the period of study. In the 1950s and 1960s Lookout Creek was cut at about 1% per year, compared to <0.25% per year for Blue River, but from 1970 to 1990 Blue River was cut at more than 1% per year compared, to <0.25% per year for Lookout Creek (lower panel in Figure 3a). The other two basin pairs had much smaller contrasts in harvest rates. These basins were cut at rates ranging from 0.25 to 0.5% per year, starting in 1945 for Salmon Creek and the N. Fork Willamette and 1955 for Breitenbush River and N. Santiam River (lower panels of Figures 3b and 3c). Roads were constructed to access clear-cuts in all six basins, and road construction rates closely followed harvest rates (lower panel in Figure 3a).

Relationships Among Streamflow Event Types

Part of our analysis examined the influence of event size, season, and event type on peak discharge response to forest harvest. Event size, season, and type are correlated in small basins. About 40% of all storms but only about 10% of all events are rain on snow in Watersheds 1, 2, and 3. Most large events (80%) occur in winter when soils are thoroughly wetted. Over 60% of large winter events are rain on snow. In fall, 84% of events are small or medium in size (less than 0.4-year return periods) and occur when soils are dry. In spring, nearly 90% of events have less than 0.4-year return periods and occur when soils are wetted by rain or snowmelt (R. Perkins, unpublished data, 1995).

Small Basin Peak Discharge Response to Clear-Cutting With No Roads

A significant number of storms had higher peak discharge, higher volume, advanced begin times and delayed peak times in some or all periods after 100% clear-cutting of Watershed 1. Following clear-cutting, a higher-than-expected number of runoff events at Watershed 1 had higher unit area peaks and higher volumes compared to pretreatment counts (Figure 4). Average peak discharges for events of all sizes increased significantly (by more than 50%) in the first 5 years after clear-cutting (Table 2, Figure 5). In the first 5 years after cutting, a higher-than-expected number of storms had later peaks and began to rise earlier (Figure 4). Increases in average peak discharges declined significantly starting in year 6 after treatment but were still significantly (nearly 40%) higher than pretreatment 16 to 22 years after clear-cutting (Table 2).

The magnitude of peak discharge response differed by event size and season. In the first 5 years after clear-cutting the mean peak discharge of small events increased by more than 75% while the mean peak discharge of large events increased by 25%, a statistically insignificant change (Tables 2 and 3, Figure 5). Six to 22 years after treatment, only fall and winter events had peak discharges significantly greater than pretreatment

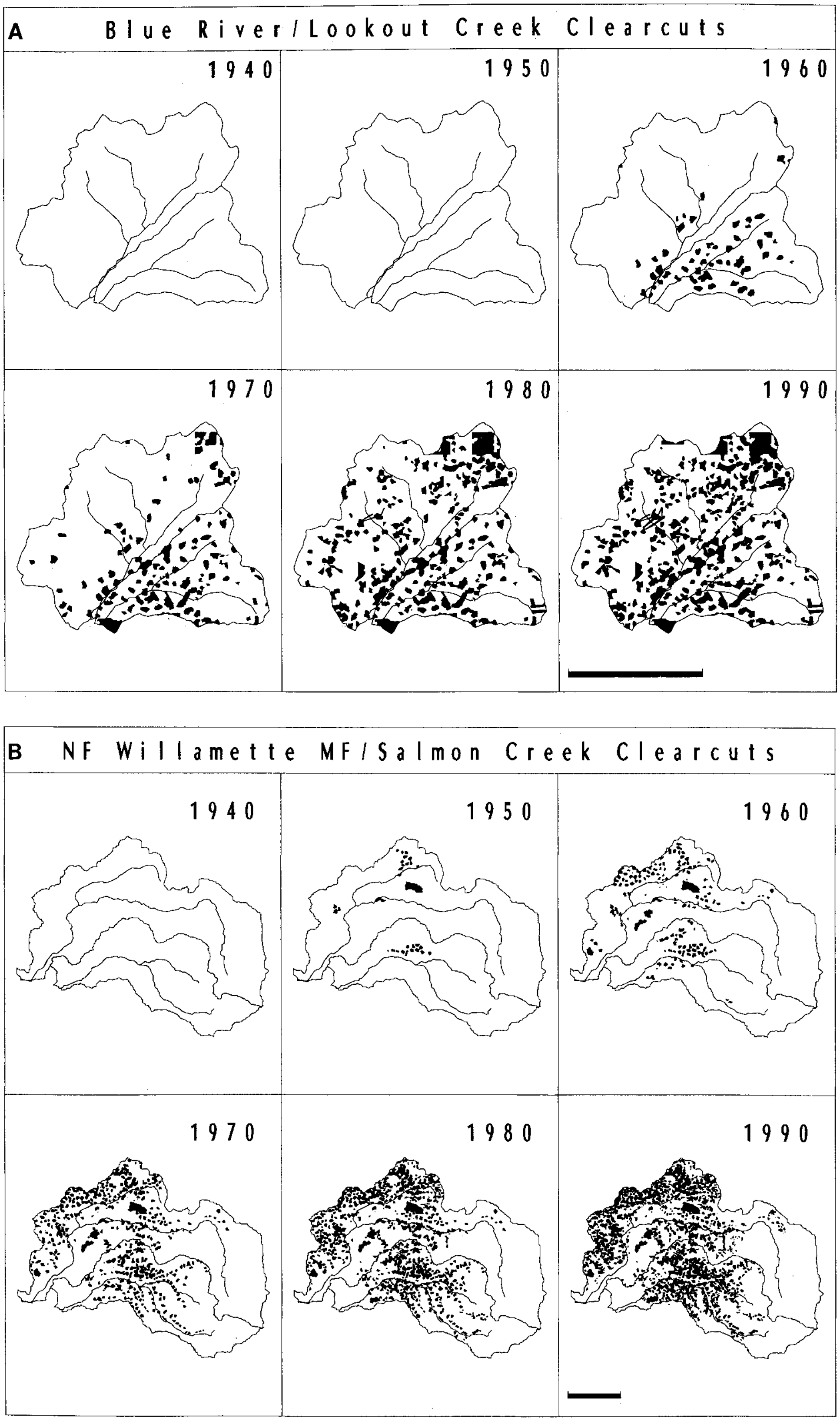

Figure 2. Spatial pattern of cumulative clearcuts and roads by decade in (a) upper Blue River and Lookout Creek basins, (b) Salmon Creek and N. Fork Willamette Middle Fork River basins, and (c) Breitenbush River and N. Santiam River basins. The scale bar is 10 km.

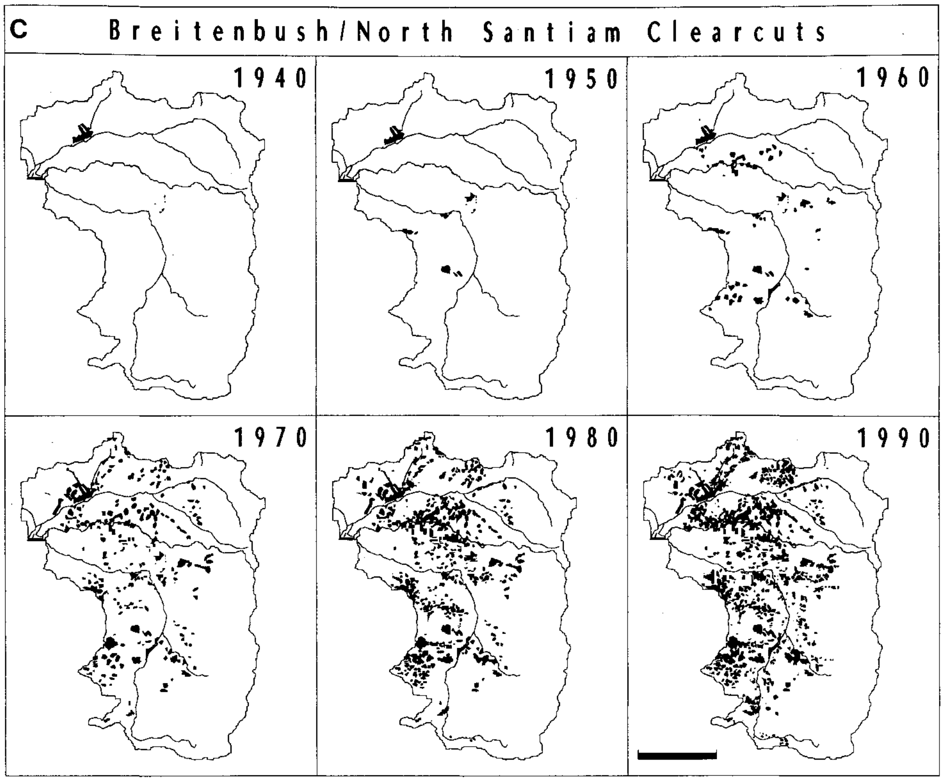

Figure 2. (continued)

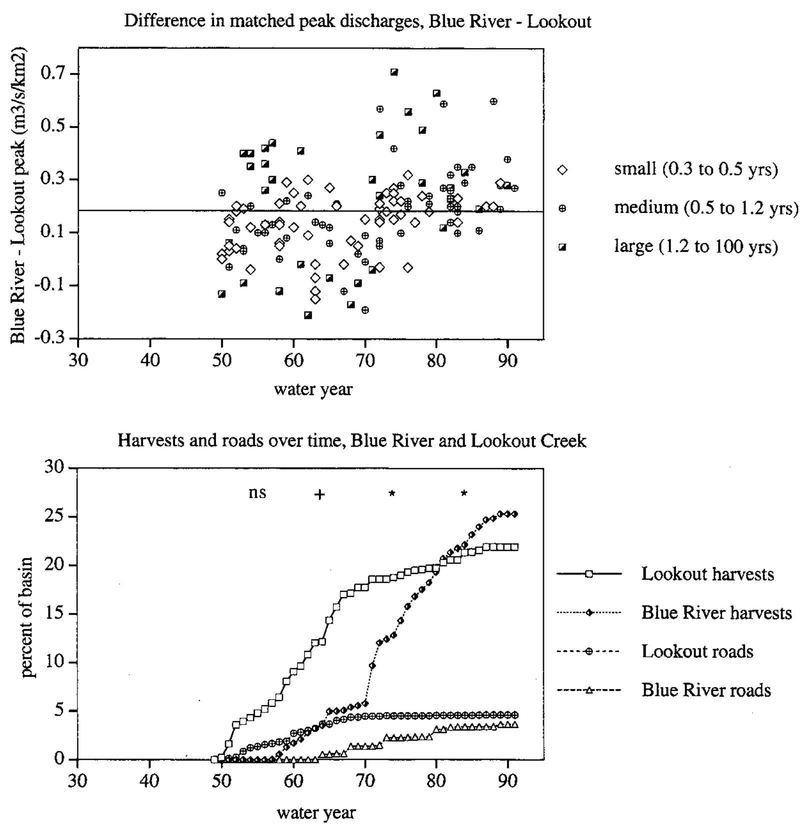

Figure 3a. Cumulative percentages of basin area in patch clear-cuts and roads, and difference in unit area peak storm flows over time for Blue River and Lookout Creek basins, 1930–1991. Horizontal solid lines indicate mean difference in unit area peak storm flows over the period. A plus sign indicates that the number of peaks in Lookout Creek was significantly higher than expected during that decade, while an asterisk indicates that the number of peaks in Blue River was significantly higher than expected during that decade according to a X^2 test with $p < 0.05$.

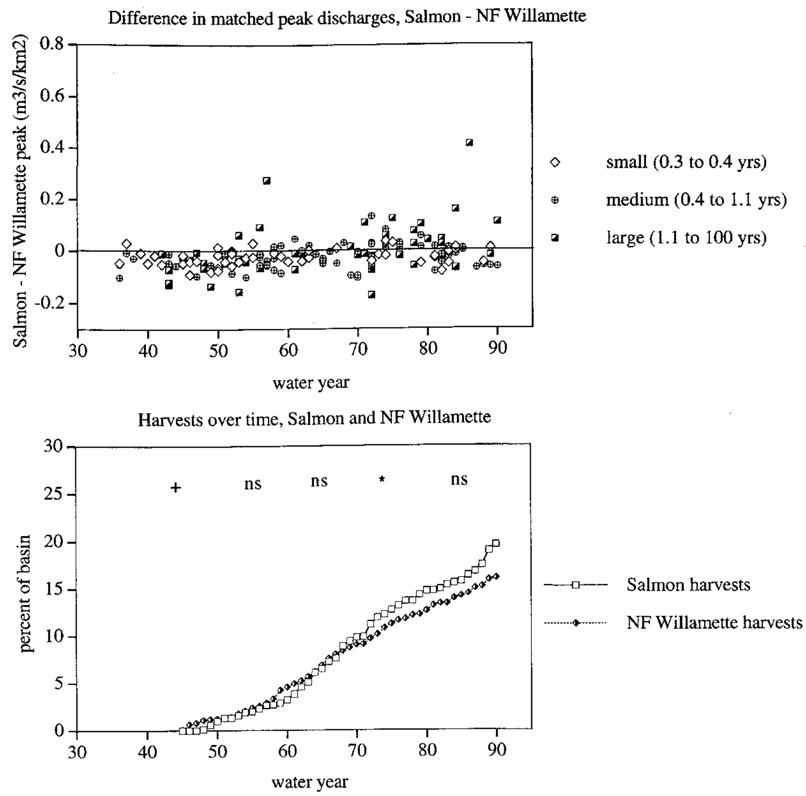

Figure 3b. Cumulative percentages of basin area in patch clear-cuts and roads, and difference in unit area peak storm flows over time for Salmon Creek and North Fork Willamette River basins, 1930–1990. Horizontal solid lines indicate mean difference in unit area peak storm flows over the period. A plus sign indicates that the number of peaks in N. Fork Willamette River was significantly higher than expected during that decade, while an asterisk indicates that the number of peaks in Salmon Creek was significantly higher than expected during that decade according to a X^2 test with $p < 0.05$.

levels (Table 3). Sample sizes below 20 may have contributed to statistically insignificant results for the other event types.

Small Basin Peak Flow Responses to Roads With No Clear-Cutting

Following road construction in 6% of Watershed 3, a higher-than-expected number of events had higher peak discharges and earlier begin times based on pretreatment proportions (Figure 4). In the 4-year period with roads only, the mean begin time of storm hydrographs at Watershed 3 was advanced by 10 hours compared to the before-treatment period. Mean peak discharge at Watershed 3 was 20% higher than pretreatment during the 4-year period after roads were constructed, but this change was not statistically significant (Table 2, Figure 6). These nonsignificant increases were greater for large events than for small events (Table 2) and for winter events than for fall or spring events (Table 3). These results indicate that a significant number of storms had increased peak discharges and earlier begin times after road construction alone, but, due to high variability among the 50 events, these changes did not produce a statistically significant increase in average peak discharge for the 4-year roads-only period.

Small Basin Peak Flow Responses to Clear-Cutting With Roads

A higher-than-expected number of storms had higher peak discharges and increased volumes, began earlier, and lasted longer in some or all time periods, based on pretreatment proportions following 25% clear-cutting and broadcast burning in Watershed 3, which already had 6% of its basin area in roads (Table 2). In the first 5 years after 25% clear-cutting, average peak discharge at Watershed 3 increased by 50% (Table 2, Figure 6), and the mean begin time of hydrographs was advanced by 6 hours, compared to pretreatment levels. More than 25 years later, average peak discharge had declined significantly in Watershed 3 but was still significantly (over 25%) higher than pretreatment levels (Table 2, Figure 6). However, changes in timing were persistent. Mean begin times of hydrographs at Watershed 3 were advanced by 7 to 10 hours compared to pretreatment levels throughout the 25 years after treatment. Peak discharges increased by 50% for all event sizes in response to 25% clear-cutting and roads (Table 2), but the magnitude of response was greater for winter and spring events than for fall events throughout the 25 years after treatment (Table 3). This indicates that hydrographs responded significantly differently to 25% patch cutting with roads than to roads or clear-cutting alone.

Large Basin Peak Flow Responses to Clear-Cutting With Roads

Among large-basin pairs, peak discharge was significantly related to cumulative area harvested and recent rates of cutting according to X^2 tests of expected versus observed counts of events. After the first entry the basin with the higher cumulative area cut tended to have significantly higher than expected numbers of storms with higher peaks (e.g., Lookout

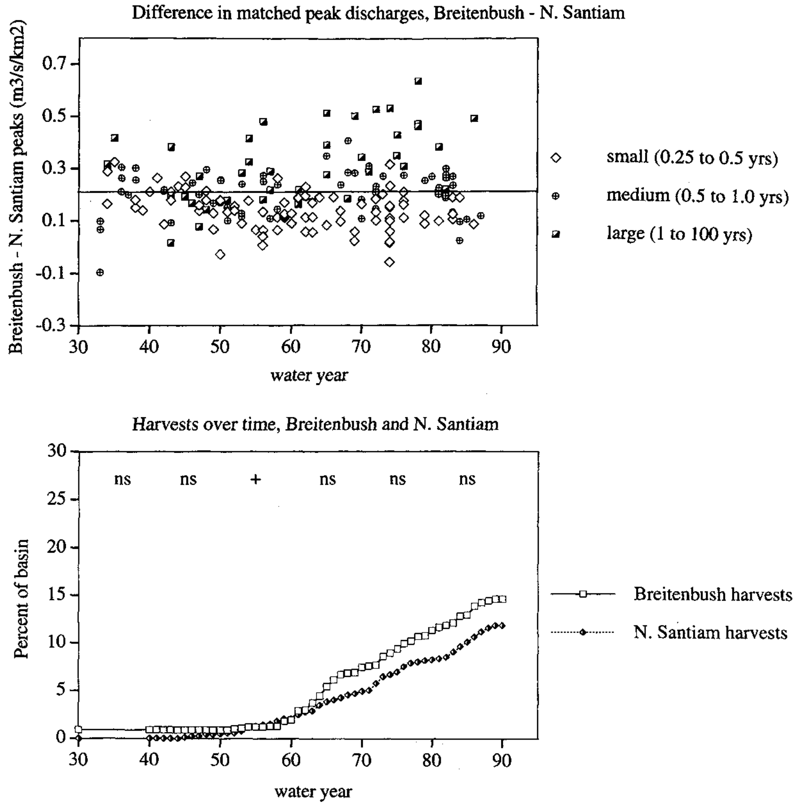

Figure 3c. Cumulative percentages of basin area in patch clear-cuts and roads, and difference in unit area peak storm flows over time for Breitenbush River and North Santiam River basins, 1930–1990. Horizontal solid lines indicate mean difference in unit area peak storm flows over the period. A plus sign indicates that the number of peaks in the N. Santiam River basin was significantly higher than expected during that decade according to a X^2 test with $p < 0.05$.

Creek in the 1960s, N. Fork Willamette in the 1940s; see Figure 3). When there was a transition in cutting rates such that one basin's rate of cutting surpassed the other, this tended to produce significantly higher than expected numbers of storms with higher peaks in the basin with the more rapid cutting rate (e.g., Blue River in the 1970s, Salmon Creek in the 1970s, N. Santiam River in the 1950s). After these transitions the basin with the higher cumulative area cut again tended to have significantly higher than expected numbers of storms with higher peaks (e.g., Blue River and Salmon Creek in the 1980s). In this analysis both cumulative area cut and recent rate of cutting appeared to influence peak discharge proportions.

The magnitude of the difference in unit area peak discharges of matched storms is significantly ($p < 0.05$) and positively related to the difference in cumulative harvest area for all three basin pairs (Figure 7, Table 4). However, the explanatory power (r^2) of the relationships is very low, with large unexplained differences between basins in the behavior of individual storms in each year. Each regression slope term measures the amount by which peak discharges increased in the relatively more cut basin in a pair. The nearly identical slope terms indicate that unit area peak discharges show the same linear response to cumulative harvests in all three basin pairs (Figure 7). These slopes imply that in all three basin pairs, peak discharges in the more heavily cut basin increased on average by 0.014 $m^3 s^{-1} km^{-2}$ for each 1% difference in area cut (Table 4).

In the Blue River/Lookout Creek basin pair, regression analyses of subsets of the data indicated that there was little or no difference in the magnitude of harvest-related increase in peak discharges for events of different sizes, seasons, or types (Table 4). Rain-on-snow events and rain events had nearly identical responses to timber harvest in the Blue River/Lookout Creek basin pair. The regression model for this basin pair indicates that on average, peak discharges in the basin with 15% more area harvested increased by an amount equivalent to 24 to 32% of the 1-year event (Table 4).

The regression model for the Salmon Creek/N. Fork Willamette basin pair indicates that on average, peak discharges in the basin with 5% more area harvested increased by an amount equivalent to 25 to 34% of the 1-year event (Table 4). The model for the Breitenbush/N. Santiam basin pair indicates that on average, peak discharges in the basin with 4% more area harvested increased by an amount equivalent to 10 to 16% of the 1-year event, depending on which basin's 1-year event is used as the reference point (Table 4). Regression models were also run for these two basin pairs using only large events and spring events, which occur when the soil mantle is thoroughly wetted and the channel network is likely to be fully extended. The regression models indicate that in the Salmon Creek/N. Fork Willamette and Breitenbush/N. Santiam basin pairs, on average, peak discharges of large and spring events in the basin with 4 to 5% more area harvested increased by an amount equivalent to 30 to 52% of the 1-year event. The more pronounced response of large events at Breitenbush/N. Santiam is evident in the upper panel of Figure 3c.

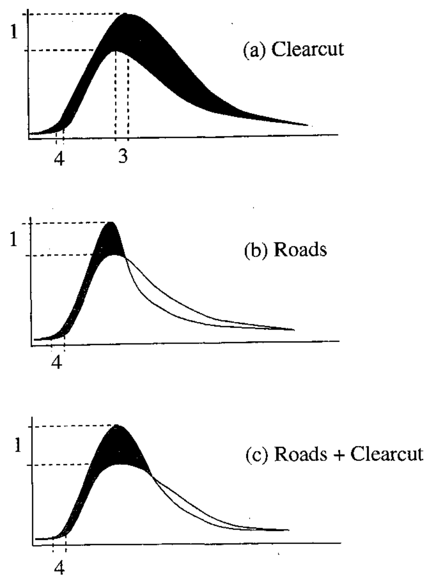

Figure 4. Observed changes in hydrograph shapes from small (<1 km^2) experimental basins at the H. J. Andrews Experimental Forest, based on X^2 tests with $p < .05$. (a) Watershed 1 (100% clear-cut) had significant increases in peak discharges (1) and storm volumes (2) for 0 to 22 years after treatment, significantly later peak times (3) for 0 to 5 years after treatment, and significantly earlier begin times (4) for 0 to 10 years after treatment. (b) Watershed 3 (6% roads), had significantly higher peak discharges (1) and earlier begin times (4), and (c) Watershed 3 (6% roads and 25% clear-cut) had significantly higher peak discharges (1), higher storm volumes (2), and earlier begin times (4) for 0 to 25 years after treatment.

Discussion

This study demonstrated that road construction combined with patch clear-cutting ranging from 10 to 25% of basin area produced significant, long-term increases in peak discharges in small and large basins in the western Cascades. In two pairs of small basins the magnitude and duration of increase in peak discharges after 25% clear-cutting with roads was no different from that after 100% clear-cutting without roads, but the hydrologic mechanisms are different. In the western Cascades, clear-cutting and vegetation removal influence water balances by affecting evapotranspiration and possibly snow accumulation and melt, whereas road construction influences hillslope flow paths by converting subsurface flow to surface flow (Figure 8).

Clear-cutting effects on water balances independent of road effects can only be examined in small basins. Complete clear-cutting produced significant increases in fall events, which are mostly small, and winter events, which range from small to large, but not for large events as a group. These results support the hypothesis that suppression of evapotranspiration after removal of deep-rooted conifers led to increased deep subsurface moisture storage, even though shallow soil moisture returned to pretreatment levels 1 year after harvest was completed [*Adams et al.*, 1991]. The rapid recovery of shallow soil moisture is attributable to the rapid recovery of low shrubs and herbs in Watershed 1 [*Rothacher*, 1970; *Halpern*, 1989]. However, cover of tall, deep-rooted shrubs had reached only 76%, and conifer cover was only 44% by 17 years after 100% clear-cutting in Watershed 1 [*Halpern*, 1989]. Evapotranspiration in Douglas fir increases with leaf area up to maturity (at perhaps 100-plus years) [*Running et al.*, 1975]. The pretreatment 120- to 450-year-old Douglas fir stands had an estimated leaf area index (LAI) of 8 to 12, [*Marshall and Waring*, 1985; *Waring and*

Table 2. Magnitude and Duration of Peak Flow Response, by Size of Storm Flow Event From 1955 to 1988 in 1-km^2 Basins in the Western Cascades of Oregon

		All Events*			Small Events*			Large Events*		
Years	Treatment	*n*	Mean†	Index‡	*n*	Mean†	Index‡	*n*	Mean†	Index‡
				100% Clear-Cutting Without Roads (Watershed 1)						
1955–1961	None	74	0.70a	100	29	0.67a	100	16	0.73a	100
1962–1966	100% cut	49	0.94b	134	15	0.85a	127	8	0.97a	133
1967–1971	0–5 years postcut	50	1.08c	154	18	1.18b	176	9	0.91a	125
1972–1976	6–10 years postcut	58	0.95b	136	10	0.99ab	148	16	0.95a	130
1977–1981	11–15 years postcut	54	0.97bc	139	21	1.02ab	152	12	0.88a	121
1982–1988	16–22 years postcut	67	0.96b	137	19	1.03ab	154	14	0.88a	121
				25% Patch Cutting With Roads (Watershed 3)						
1955–1958	None	43	0.50a	100	10	0.62a	100	15	0.44a	100
1959–1962	6% roads	50	0.60a	120	16	0.66a	107	5	0.50a	114
1963–1968	25% cut	69	0.75b	150	20	0.93b	150	14	0.65b	148
1969–1973	6–10 years postcut	53	0.70bc	140	17	0.86bc	139	13	0.64b	146
1974–1978	11–15 years postcut	56	0.66bc	132	8	0.77ab	124	14	0.56a	127
1979–1983	16–20 years postcut	60	0.63c	126	16	0.76ac	123	18	0.56a	127
1984–1988	21–25 years postcut	46	0.63c	126	15	0.73ac	118	6	0.58a	132

Group means in the same column followed by the same letter are not significantly different from each other according to Tukey's highest significant difference multiple comparisons procedure with an overall protection level of $p < 0.05$.

*The size classes are as follows: small events are those with <0.125-year return periods and unit area peak discharges <0.11 m^3 s^{-1} km^{-2}; small to medium events are those with return periods from 0.125 to 0.2 years (0.11 to 0.21 m^3 s^{-1} km^{-2}); medium to large events are those with return periods from 0.2 to 0.4 years (0.21 to 0.35 m^3 s^{-1} km^{-2}); and large events are those with return periods from 0.4 to 100 years (>0.35 m^3 s^{-1} km^{-2}).

†Mean value for this group of the response variable, defined as the difference in log-transformed matched peak discharges, Watershed 1 minus Watershed 2.

‡The post-treatment mean as a percent of the pretreatment mean in the treated watershed, controlling for changes over time in means in the untreated watershed.

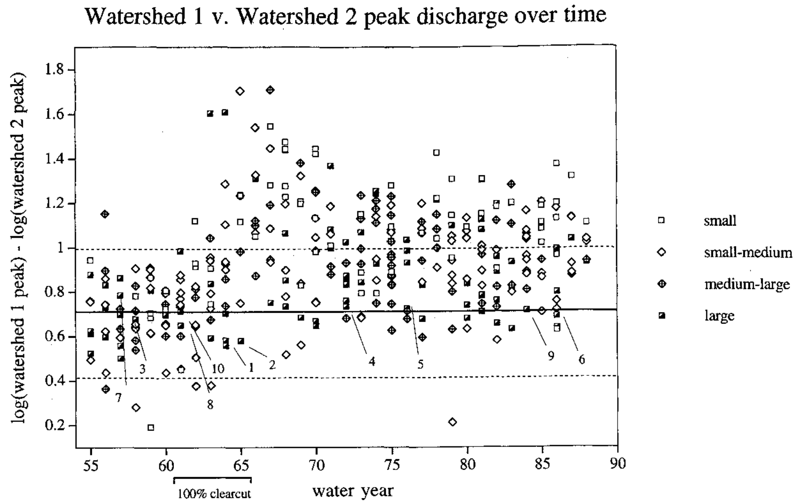

Figure 5. Magnitude of peak flow response to 100% clear-cutting without roads from 1955 to 1988, based on difference in log-transformed peak discharges, Watershed 1 minus Watershed 2. Solid and dashed lines indicate pretreatment mean difference plus or minus standard deviation. Numbers refer to the 10 largest matched events for the period of record.

Schlesinger, 1985], while the regenerating Douglas fir in Watershed 1 may have had an LAI of 2 or 3 by 25 years after treatment, taking into account canopy cover (R. Waring, personal communication, 1995). Therefore the gradual recovery of peak discharges over time after clear-cutting is attributable to changes in evapotranspiration.

Harr [1977] determined that unsaturated drainage of soils in these small basins leads to the production of discontinuous, ephemeral saturated zones below 1 m depth. These zones route saturated flow downslope, where it emerges as seeps in stream banks and contributes to peak discharges via "translatory flow," a quick flow response to precipitation without overland flow [*Harr*, 1976b]. The flux rates measured in upslope, unsaturated zones are so slow that only saturated zones in lower slopes near channels can contribute to quickflow storm response [*Harr*, 1977]. Clearcutting apparently suppressed transpiration losses from soil depths >1 m and increased the volume of water stored in discontinuous saturated or near-saturated zones in the lower hillslopes of Watershed 1. This produced an especially pronounced response of peak discharges to small fall storm events following periods of evapotranspiration and hillslope drainage, and a lesser response to large events which are less likely to be affected by prior drainage. However, this greater response of fall events is not seen in

Table 3. Magnitude and Duration of Peak Flow Response, by Season of Storm Flow Event From 1955 to 1988 in 1-km^2 Basins in the Western Cascades of Oregon

		All Events			Fall Events*			Winter Events*			Spring Events*		
Years	Treatment	*n*	Mean†	Index‡	*n*	Mean†	Index‡	*n*	Mean†	Index‡	*n*	Mean†	Index‡
	100% Clear-Cutting Without Roads (Watershed 1)												
1955–1961	None	74	0.70a	100	27	0.73a	100	33	0.68a	100	14	0.68a	100
1962–1966	100% cut	49	0.94b	134	18	1.06b	145	19	0.88b	129	12	0.87a	128
1967–1971	0–5 years postcut	50	1.08c	154	16	1.25c	171	28	0.95b	140	6	1.21b	178
1972–1976	6–10 years postcut	58	0.95b	136	13	0.99b	136	39	0.93b	137	6	0.96a	141
1977–1981	11–15 years postcut	54	0.97b	139	17	0.94ab	129	28	0.99b	146	9	0.93a	137
1982–1988	16–22 years postcut	67	0.96b	137	20	0.97b	133	35	0.92b	135	12	1.06ab	156
	25% Patch Cutting With Roads (Watershed 3)												
1955–1958	None	43	0.50a	100	16	0.61a	100	20	0.43a	100	7	0.46a	100
1959–1962	6% roads	50	0.60a	120	26	0.68a	111	13	0.51ab	119	11	0.51a	110
1963–1968	25% cut	69	0.75b	150	24	0.87b	143	35	0.64b	149	10	0.81b	176
1969–1973	6–10 years postcut	53	0.70bc	140	19	0.82bc	134	26	0.63b	147	8	0.68ab	148
1974–1978	11–15 years postcut	56	0.66bc	132	16	0.72ac	118	32	0.62b	144	8	0.67ab	146
1979–1983	16–20 years postcut	60	0.63c	126	19	0.75abc	123	33	0.58b	135	8	0.53ab	115
1984–1988	21–25 years postcut	46	0.63c	126	15	0.66a	108	19	0.64b	149	12	0.60ab	130

Group means in the same column followed by the same letter are not significantly different from each other according to Tukey's highest significant difference multiple comparisons procedure with an overall protection level of $p < 0.05$.

*The seasons are as follows: fall, August through November; winter, December through February; spring, March through June.

†Mean value for this group of the response variable, defined as the difference in log-transformed matched peak discharges, Watershed 1 minus Watershed 2.

‡The post-treatment mean as a percent of the pretreatment mean in the treated watershed, controlling for changes over time in means in the untreated watershed.

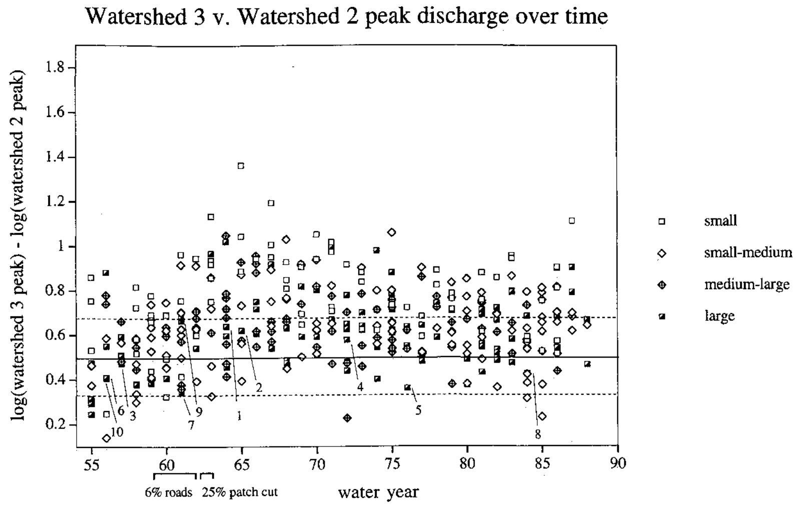

Figure 6. Magnitude of peak flow response to 25% clear-cutting with roads from 1955 to 1988, based on difference in natural logs of storm peak flows, Watershed 3 minus Watershed 2. Solid and dashed lines indicate pretreatment mean difference plus or minus standard deviation. Numbers refer to the 10 largest matched events for the period of record.

either small or large basins where clear-cutting and roads were combined. Thus water balance mechanisms associated with vegetation removal are inadequate to explain the response of peak discharges to clear-cutting with roads.

The addition of roads to clear-cutting in small basins produced a quite different hydrologic response than clear-cutting alone, leading to significant increases in all sizes of peak discharges in all seasons, and especially prolonged increases in peak discharges of winter events. These results support the hypothesis that roads interact positively with clear-cutting to modify water flow paths and speed the delivery of water to channels during storm events (Figure 8), producing much greater changes in peak discharges than either clear-cutting or roads alone. Roads alone appear to advance the time of peak discharges and increase them slightly. Road surfaces, cutbanks, ditches, and culverts all can convert subsurface flow paths to surface flow paths [*Harr et al.*, 1975; *King and Tennyson*, 1984; *Wemple*, 1994; *Wright et al.*, 1990]. *Reid* [1981] and *Reid and Dunne* [1984] estimated discharges from culvert outfalls in western Washington and associated them with runoff from road surfaces.

Roadside ditches in Watershed 3, which are normal to hillslope flow paths, appear to capture the increased subsurface moisture stored in clear-cuts above road cutbanks. This water can be routed directly to stream channels by ditches connected to streams and by new channels etched below culvert outfalls [*Wemple*, 1994]. In Watershed 3, 50% of the road network is connected to the stream by these surface flow paths, and in Lookout Creek and Blue River, 60% of the road network is connected, producing up to 40% increases in stream drainage density [*Wemple*, 1994]. Cutbank interception of subsurface flow paths is most likely to be significant during wet soil mantle

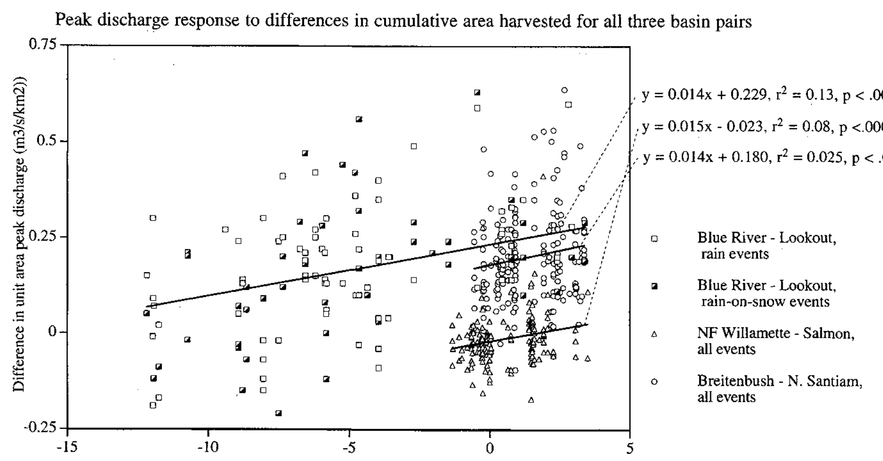

Figure 7. Magnitude of peak flow response to cumulative patch clearcutting with roads in 60- to 600-km^2 basins, based on relationship between difference in cumulative percent of basin harvested (independent variable) and difference in unit area peak discharge (dependent variable) for three pairs of large basins: upper Blue River/Lookout Creek, Salmon Creek/N. Fork Willamette Middle Fork River, and Breitenbush River/North Santiam River. Lines show regression models for all events in each basin pair.

Table 4. Magnitude of Peak Flow Response to Cumulative Patch Clear-Cutting and Roads in 60- to 600-km² Basins in the Western Cascades of Oregon, Based on Estimated Linear Regression Models

	n	Intercept Coefficient	Intercept Error	Slope Coefficient	Slope Error	Adjusted r^2	1-Year Return Event, m^3/s^{-1} km^{-2} Basin 1	1-Year Return Event, m^3/s^{-1} km^{-2} Basin 2	Change as % of 1-Year Event* Basin 1	Change as % of 1-Year Event* Basin 2
				Blue River (1)/Lookout Creek (2)						
All events	146	0.229†	0.018	0.014†	0.003	0.13	0.88	0.66	32	24
Rain	76	0.268†	0.028	0.017†	0.004	0.16	···	···	39	29
Rain on Snow	55	0.253†	0.031	0.018‡	0.005	0.18	···	···	41	31
				Salmon Creek (1)/N. Fork Willamette River (2)						
All events	169	−0.023†	0.005	0.015‡	0.004	0.08	0.22	0.30	34	25
Large plus Spring	69	−0.019§	0.008	0.022‡	0.006	0.13	···	···	50	37
				Breitenbush River (1)/N. Santiam River (2)						
All Events	189	0.180†	0.012	0.014§	0.007	0.02	0.57	0.33	10	16
Large plus Spring	67	0.180†	0.031	0.043‡	0.019	0.09	···	···	30	52

The dependent variable was difference in unit area peak discharge, the independent variable was difference in cumulative percent of basin harvested. The slope indicates the average increase in peak discharge (m^3 s^{-1} km^{-2}) for each 1% difference in cumulative harvest area. A significant positive slope term indicates an increase in peak discharge in the basin with greater cumulative area harvested at a Bonferroni-corrected significance level of p (see following footnotes).

*Implied percentage increase in median peak discharge for that category of events associated with the maximum difference in cumulative harvests between basins. Calculated from the regression slope multiplied by the range of the independent variable (15% for Blue River/Lookout Creek, 5% for Salmon Creek/N. Fork Willamette, and 4% for Breitenbush River/N. Santiam River; see Figure 7), divided by the median peak discharge.

†Value of $p < 0.0001$.

‡Value of $p < 0.001$.

§Value of $p < 0.05$.

conditions, thus explaining the 50 to 75% increases in winter and spring events. The somewhat more rapid recovery of peak discharges over time after treatment in Watershed 3 compared to Watershed 1 (Table 2) is attributable to the fact that conifers had reached 63% by 17 years after cutting in Watershed 3, compared to only 44% in Watershed 1 [*Halpern*, 1989].

The removal and salvage of wood from stream channels could have contributed to changes in storm hydrograph shape by reducing channel roughness and flow resistance, thereby increasing flow velocity. However, wood-related channel changes in Watersheds 1 and 3 had inconsistent effects. That is, peak arrival time should have been advanced after wood removal in 1967 in Watershed 1, but peak arrival times in fact were delayed. Wood additions by a landslide into the channel in 1960 in Watershed 3 should have reduced channel efficiency, delaying peak arrival, but peaks in fact were advanced after 1960, probably due to road construction in 1959. Peaks continued to be advanced in Watershed 3 after a series of massive debris flows (mostly road-related) in 1964. Complete scouring of the channel down to bedrock may have exacerbated cutting and road effects, all three factors contributing to increased peak discharges in Watershed 3.

Road interactions with clear-cuts also appeared to increase peak discharges in large basins. Despite differences in basin size, geology, and elevation, all six basins had the same rate of response to cumulative cutting (Figure 7). Differences in peak discharges were detectable when basins differed by only 5% in cumulative area cut. These results support the hypothesis that water balance effects diminish and flow routing changes are increasingly important as basin size increases. These findings are consistent with model results of *Garbrecht* [1991] which indicated that upstream spatial variability should decrease in importance in determining the downstream hydrologic response as basin size increases. The low r^2 of the regressions are

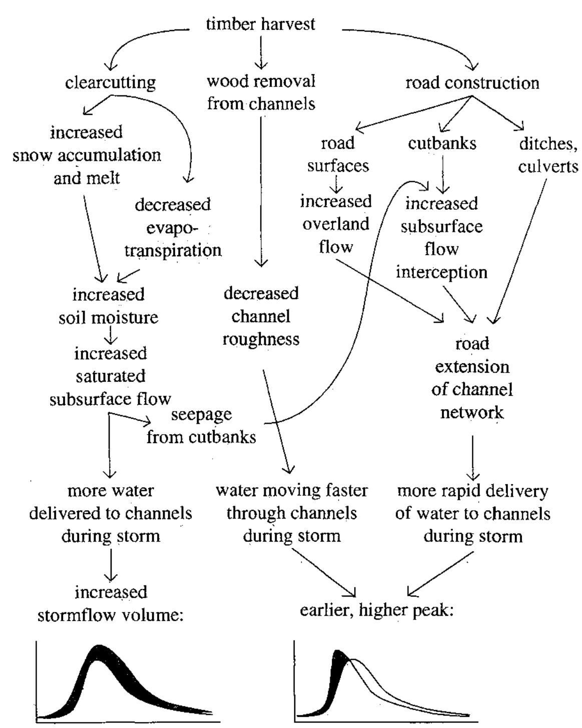

Figure 8. Hypothesized mechanisms for hydrograph changes resulting from timber harvest activities. The four major mechanisms are (1) increased snow accumulation and melt, (2) decreased evapotranspiration, (3) decreased channel roughness, and (4) road extension of channel network. Mechanisms (1) and (2) affect the hillslope water balance and would be expected to increase peak discharge and storm flow volume, whereas mechanisms (3) and (4) affect flow routing and would be expected to speed storm flow, advancing the peak without changing the volume.

in part attributable to between-basin differences in actual precipitation received and antecedent moisture conditions for paired events. The r^2 also may be low because cumulative area cut is an imperfect index of the mechanism contributing to increased peak discharges. That is, road effects may not be precisely indexed by cutting history in extent or timing since cutting lags behind road construction. In Lookout Creek, 1.8 km km^{-2} of roads (80% of final road network) had been constructed by 1970 when only 17% of basin area had been harvested; in Blue River 1.2 km km^{-2} of roads had been constructed by 1980 when only 18% of basin area had been harvested. Rapid road network expansion during those early periods of basin entry also may account for the higher than expected numbers of high peak discharges in periods of rapid acceleration of cutting (e.g., Blue River and Salmon Creek in the 1970s, N. Santiam in the 1950s; see Figure 3).

Much debate has focused on whether the largest (>10 years) peak discharges have been significantly affected by land use. This inevitably is an inconclusive debate, despite the overwhelming importance of large peak discharges for channel morphology. Because of the rate of vegetation recovery (i.e., 60% recovery of canopy cover and LAI within 30 years), ongoing land transformations such as road obliteration and abandonment, and limited record lengths (50 to 60 years at most), sample sizes will always be inadequate to statistically test changes in peak discharges with >10-year return periods. Even subdividing events by size or season in this study produced notable losses of significance when sample sizes fell below 20 (Tables 2 and 3). The statistical analysis strongly suggests that the entire population of peak discharges is shifted upward by clear-cutting and roads; we see no reason to expect the biggest storms to behave differently from the rest of the population.

Collectively, the statistical analyses reported here strongly suggest that there has been a large increase in peak discharges attributable to forest harvest in both small and large basins in the western Cascades. The major mechanism responsible for these changes is the increased drainage efficiency of basins attributable to the integration of the road/patch clear-cut network with the preexisting stream channel network. In small basins discharges increased by 50% in the first 5 years after treatment and were 25 to 40% higher than pretreatment up to 25 years later. Peak discharges have increased even more in large basins, by 10 to 15% or 30 to 55% of the 1-year flow, depending on the basin, for a 5% difference in area cut. When extrapolated to the cumulative area cut (which ranged from 10 to 25%) this implies that peak discharges have increased by at least 50% and perhaps by as much as 250% of the 1-year flow over the 50-year period. For large basins our analysis must have underestimated the magnitude of peak discharge increase because it was based on comparisons between more- versus less-harvested basins, not harvested versus control basins. Extrapolations of these rates into the future should be tempered by the fact that future management of public land may involve lower rates of cutting and road construction than those that have occurred over the past 50 years.

Increases of this magnitude over the past 50 years are consistent with USGS modifications over time of the size of the 1.1-year peak discharge. This base was increased by 47% in 1959 after 10% of Lookout Creek had been harvested, by 25% in 1964 after 6% of Blue River had been harvested, by 11% in 1959 after 3% of Salmon Creek had been harvested, by 25% in 1949 after 2% of Breitenbush River had been harvested, and by 16% in 1959 after 3% of N. Santiam River had been harvested (J. Miller, USGS, unpublished data, 1991). Increases of this magnitude also are consistent with our finding that three to five storms per year over the past 50 years exceeded the original USGS base flow, so that by 1990 the USGS 1.1-year return event had a return period as frequent as 0.3 years in these basins.

Peak discharges of statistically tractable events (i.e., up to 5-year events) may have doubled over the past 50 years in large basins of the Cascades. Such changes have implications for stream geomorphology and ecology. If all peak discharges have been increased systematically, there may be more frequent inundation of the riparian zone, more rapid turnover of riparian zone vegetation, and perhaps increased transport of woody debris and sediment. However, these changes will be difficult to discriminate since stream channels are annually subjected to fluctuations of 2 orders of magnitude in peak discharges.

Conclusions and Further Work

The main conclusion of this study is that landscape-scale forest harvesting has produced detectable changes in peak discharges in basins ranging up to 600 km^2 in the western Cascades. These increases are attributable to changes in flow routing (due to roads) rather than to mere changes in water storage due to vegetation removal (i.e., evapotranspiration, rain on snow, fog drip) invoked in early analyses of small-basin hydrology. Three important implications arise from this study. First, there is much to be learned from more analyses of large-scale, long-term hydrologic data sets especially if they contain nested, paired basin experiments. Second, we need to improve our understanding of subsurface/surface flow path interactions and how they may be affected by roads, which at 2 to 3 km km^{-2} [*Freid*, 1994] have densities at least equal to stream drainage densities in forest landscapes of the Pacific Northwest. Third, we need to reexamine channels of unregulated fifth- to seventh-order streams for evidence of possible changes in channel morphology and stream ecology that might be attributable to these long-term increases in peak discharges.

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