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Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon

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Abstract. The magnitude, seasonality, and duration of peak discharge responses to forest removal and regrowth and roads in 10 pairs of experimental basins in the western Cascade Range of Oregon are consistent with fundamental water balance and routing concepts in hydrology. Hypothesized effects of forestry treatments on evapotranspiration, cloud water interception, snowpack dynamics, and subsurface flow interception vary predictably by season, geographic setting, amount of forest canopy removal, stage of canopy regrowth, and arrangement of roads in the basin. Posttreatment responses of selected subpopulations of matched peak discharge events were examined over 10- to 34-year posttreatment periods in treated-control basin pairs in a range of geographic settings. Changes in evapotranspiration associated with forest canopy removal and regrowth apparently accounted for significant increases (31–116%) in peak discharges during the first postharvest decade in 8 of 10 treated basins, but the events that were affected were small (<0.22- or 0.28-year return periods) and occurred in the fall (September–November), when soils are in moisture deficit, rather than in spring (March–May), when soils are in moisture surplus. For a given amount of forest canopy removal, initial increases in small, fall events were greater in drier basins than wetter basins, and increases tended to disappear as forest canopies regrew. Changes in cloud water interception apparently offset changes in evapotranspiration in two partially cut basins. Changes in snowpack dynamics apparently accounted for significant increases (25–31%) in winter rain-on-snow events, but other types of winter events did not change, in four of five basins at the H. J. Andrews Experimental Forest. Changes in subsurface flow interception apparently accounted for significant increases (13–36%) in large (>1-year return period) events in seven of eight basins with roads, and, controlling for geographic location, the magnitude of increases was related to the density of midslope roads.

1. Introduction

This study examined the interactions among hydrologic processes, geographic setting, and forestry treatments in 10 pairs of experimental basins in the western Cascade Range of Oregon, demonstrating that small-basin responses are consistent with fundamental water balance concepts. Such interactions have long been recognized as a challenging problem in hydrology. For example, although they provide a quantitative, process-based approach for predicting runoff response, hydrologic models may be difficult to apply regionally because they typically are "overdetermined"; that is, many alternative mechanisms can explain observed changes in runoff. Also, while paired-basin experiments indicate that forest removal and forest roads often modify runoff, it is difficult to derive general predictions of forestry treatment effects because runoff responses vary by geographic setting, type of runoff event, road configuration, and time since treatment. For these reasons, the relation between forest harvest and peak discharges has been an important and controversial issue in many regions, including the Pacific Northwest. [*Rothacher*, 1973; *Harr et al.*, 1975; *Harr and McCorison*, 1979; *Harr*, 1986; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998; J. A. Jones and G. E. Grant, Comment on "Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion," submitted to *Water Resources Research*, 1999 (hereinafter referred to as Jones and Grant, submitted manuscript, 1999); R. B. Thomas and W. F. Megahan, Reply, submitted to *Water Resources Research*, 2000].

The central premise of this paper is that examination of the collective behavior of multiple pairs of experimental basins can reveal hydrologic mechanisms that respond to forest canopy removal, canopy regrowth, and the presence of roads in a range of geographic settings in the Pacific Northwest. Streamflow records from the paired-basin experiments in the western Cascades of Oregon are well suited for such an analysis in three respects. First, the records span up to several decades after forest removal treatment. In the western Cascades of Oregon there exist 449 station years of high-quality streamflow records from small paired experimental basins, but despite numerous publications only a fraction of this record has been analyzed [e.g., *Harr*, 1982; *Harr et al.*, 1975, 1979, 1982; *Rothacher*, 1965; *Jones and Grant*, 1996; *Thomas and Megahan*, 1998]. Long-term records have large sample sizes and display trends over time; hence they facilitate distinguishing transient from persistent phenomena.

A second beneficial aspect of these streamflow data sets is that multiple paired-basin experiments were conducted in dif-

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ferent parts of the western Cascade Range of Oregon using similar forestry treatments over roughly the same few decades. *Hewlett and Hibbert* [1961, p. 16] noted that "treatment as presently conceived can [n]ever be considered independently of the piece of land on which it is carried out, particularly in mountainous terrain." Comparisons among experiments with similar treatments in different geographic settings facilitate quantifying the effect of geographic variation upon streamflow response to forest removal and roads.

Third, *Leopold* [1970] noted that it has been notoriously difficult to make inferences about hydrologic processes from paired-basin experiments. Studies of paired-basin hydrology in the western Cascades of Oregon [e.g., *Harr et al.*, 1975, 1979, 1982; *Harr*, 1976a, b, 1981, 1982, 1986; *Jones and Grant*, 1996] have invoked a range of hydrologic processes, including evapotranspiration, cloud water interception, snowpack dynamics, and subsurface flow interception by roads to explain observed responses of peak discharges to forestry treatments. However, multiple mechanisms operate simultaneously in a single basin and may reinforce, overwhelm, or offset each other. Moreover, the relative importance of any hydrologic mechanism to runoff depends upon basin geography, seasonal variation, and individual storm characteristics. Comparisons among selected subpopulations of runoff events facilitate disentangling the variety of hydrologic mechanisms comprising a single basin's hydrologic response.

This study attempted to disentangle the roles of certain hydrologic processes as they influence peak discharge responses to forest removal, regrowth, and roads in small basins in the Douglas fir–western hemlock zone of the western Cascades of Oregon. This analysis builds on previous work on long-term streamflow records [*Jones and Grant*, 1996], but whereas most previous work focused on effects of forest practices, this paper emphasizes examination of hydrologic processes. It expands the earlier analysis to 10 treated-control basin pairs, spanning a wider range of treatments and geographic settings; identifies selected populations of peak discharge events that appear to be controlled by distinct hydrologic processes; and infers the timing, magnitude, and duration of effects by statistical comparisons among relevant event populations before and after treatment.

2. Approach and Hypotheses

The pooled population of peak discharge events from a basin violates the homogeneity assumption for statistical analysis [*Holland*, 1986], since different types of peak discharges occur under differing water balance conditions. The approach of this study was to identify relatively homogeneous subpopulations of peak discharge event types, controlled by various components of the hydrologic cycle, that might display contrasting effects of forestry treatments. This approach involves identifying (1) the components of a water balance that would be affected by forest canopy removal, forest canopy regrowth, and forest roads, and (2) runoff event subpopulations that would be expected to be influenced by these processes, given observed water balances of forested basins in the western Cascade Range of Oregon.

In this conceptual model the net change in runoff from a basin is the sum of changes in three major storage components of the water balance: the forest canopy F, the snowpack N, and the soil and regolith S (Figure 1):

$$\Delta R = \Delta F + \Delta N + \Delta S. \quad (1)$$

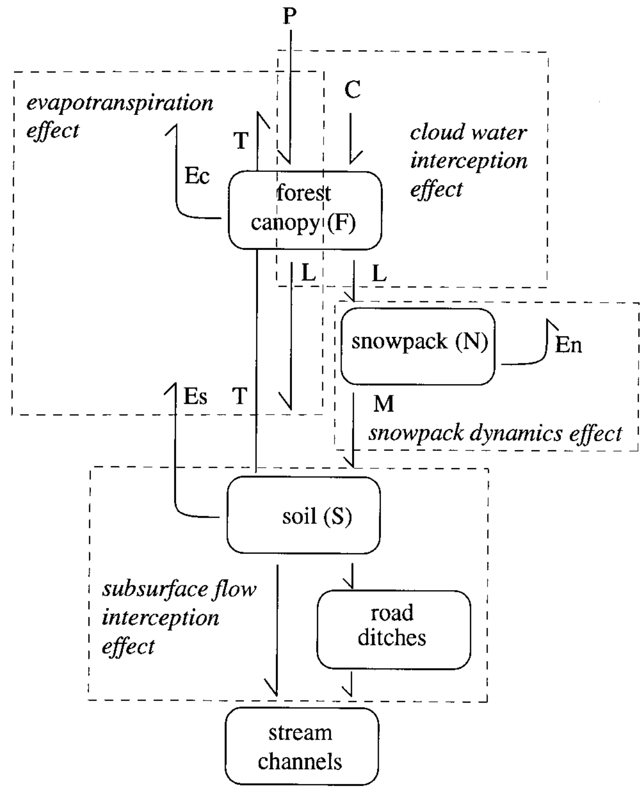


Figure 1. Conceptual model of water balance components and hydrologic mechanisms modified by forest canopy removal, canopy regrowth, and road construction.

Change in water storage in forest canopies is a function of changes in inputs from precipitation P and cloud water interception C and changes in outputs to evaporation E_c and throughfall L:

$$\Delta F = \Delta P + \Delta C - \Delta E_c - \Delta L. \quad (2)$$

Change in water storage in the snowpack is a function of changes in inputs from throughfall and changes in outputs to evaporation E_n and snowmelt M:

$$\Delta N = \Delta L - \Delta E_n - \Delta M. \quad (3)$$

Change in water storage in the soil is a function of changes in inputs from throughfall and snowmelt and changes in outputs to evaporation E_s and transpiration T:

$$\Delta S = \Delta L + \Delta M - \Delta E_s - \Delta T. \quad (4)$$

A number of different hydrologic processes, represented by terms in these equations, respond to forest canopy removal, forest canopy regrowth, and roads. Forest canopy removal greatly reduces transpiration T, evaporation from the canopy E_c, and cloud water interception C, as well as the capacity of the canopy to store water ΔF. Reductions in canopy evaporation and canopy storage increase throughfall L and hence increase water delivery to the soil, while reductions in transpiration also increase soil moisture storage ΔS, thus increasing runoff (equations (1), (2) and (4)). This is called the evapotranspiration effect (Figure 1). On the other hand, reductions in cloud water interception decrease throughfall and hence decrease soil moisture storage and runoff (equations (1), (2), and (4)). This is called the cloud water interception effect

(Figure 1). Note that the evapotranspiration effect, which increases runoff, and the cloud water interception effect, which decreases runoff, have counteracting effects upon runoff in response to the same treatment, forest canopy removal. In winter after forest canopy removal, decreased canopy evaporation and increased throughfall increase snowpack accumulation ΔN, while specific energy exchanges during rain-on-snow events may enhance snowpack melting M [*Harr*, 1981], thus increasing soil moisture and runoff (equations (1), (3), and (4)). This is called the snowpack dynamics effect (Figure 1).

Road construction creates relatively permanent forest canopy gaps, which also influence storage of water in the canopy, snowpack, and soil. In addition, roads may interact with these changes and alter water routing to streams, influencing the height but not the volume of peak discharges. This is called the subsurface flow interception effect (Figure 1).

In forests of the Pacific Northwest the evapotranspiration effect would be expected to be large, but to vary with season and forest canopy regrowth. On an annual basis, evapotranspiration may account for 40% of annual precipitation in conifer forests of the Pacific Northwest [*Post et al*., 1998]; much of this water may have been intercepted and temporarily stored in forest canopies [*Law*, 1958; *Rothacher*, 1963; *Patric*, 1966]. Transpiration rates in forest vegetation vary by species and age, as well as by atmospheric vapor pressure and soil moisture [*Lee*, 1967; *Waring and Schlesinger*, 1985]; hence evapotranspiration may be an important control on soil moisture during fall and spring in Pacific Northwest forests when moisture and temperature are optimal for transpiration by conifer canopies [*Rothacher*, 1965; *Harr*, 1976b]. Decreased evapotranspiration has been invoked to explain observed increases in runoff after forest canopy removal [*Rothacher*, 1970, 1973; *Harr et al*., 1975, 1982, 1979; *Harr*, 1976a]. This effect would be expected to diminish as vegetation regrows and evapotranspiration increases [*Marshall and Waring*, 1986; *Adams et al*., 1991].

The cloud water interception effect would be expected to be large in coastal, fog-affected forests in the Pacific Northwest, where it could offset the evapotranspiration effect. When clouds enter the canopy (often called fog), droplets may nucleate on the high leaf area of needle leaf foliage. Cloud water interception is difficult to measure but may be quite large in some forests of the Pacific Northwest [*Oberlander*, 1956; *Rothacher*, 1963; *Harr*, 1982].

A snowpack dynamics effect may be large in forests of the Pacific Northwest, but it would vary by season, elevation, and forest canopy structure. Canopy gaps have more snow accumulation than forests, and their snowpacks melt more rapidly during rain-on-snow events [*Harr*, 1981; *Marks et al*., 1998]. Snowpack thickness and temperature also affect the rate of melting [*Harr and McCorison*, 1979; *Perkins*, 1997]. Increased snow accumulation and faster snowmelt have been invoked to explain increased peak discharges after forest canopy removal [*Harr*, 1986], but this effect would be expected to diminish as vegetation regrows.

A road effect upon water routing might be large in Pacific Northwest forests; it would vary seasonally, would depend upon road configurations relative to water flow paths [*Jones et al*., 2000], and could persist as long as roads remain in the forest landscape. In undisturbed forests of the Pacific Northwest, soil infiltration capacities typically exceed precipitation intensities, and subsurface flow dominates [*Harr*, 1976b]. Modifications of the soil and subsoil, such as by roads, alter surface and subsurface flow paths [*Megahan and Clayton*, 1983; *King and Tennyson*, 1984; *Montgomery*, 1994; *Wemple et al*., 1996; *Bowling and Lettenmaier*, 1997; *Wemple*, 1998]. Roads intercept subsurface flow and convert it to surface flow (which travels orders of magnitude faster), and although some road configurations may locally route water away from streams, in most cases these new flow paths are connected to the stream network [*Wemple et al*., 1996; *Wemple*, 1998]. Thus except at small scales where they divert water away from streams, roads would be expected to speed the delivery of water into the stream network, thus potentially synchronizing flows and increasing the magnitudes of peak discharges without affecting streamflow volume [*Jones and Grant*, 1996].

In the western Cascades of Oregon, precipitation, soil moisture, air temperature, and transpiration vary seasonally, and hence different hydrologic processes dominate runoff in each season. Evapotranspiration is most likely to affect runoff in the fall, when air temperatures are moderate, conifer forests are transpiring and taking up soil moisture, soil moisture is low after the long dry summer (Figure 2), and runoff events are small (Figure 3) compared to soil moisture storage capacity. In the spring, air temperatures are moderate, conifer forests are taking up moisture (Figure 2), and runoff events occur (Figure 3), but these effects are small relative to soil moisture. Hence evapotranspiration would be expected to influence soil moisture and runoff during small, fall events (A, Figure 3) but not small, spring events (E, Figure 3).

Cloud water interception is most likely to affect summer runoff events at sites where clouds enter the forest. In the summer and, to a lesser extent, in fall, air temperatures are high, soil moisture is low (Figure 2), and runoff events are small (Figure 3). During summer and fall, in sites where fog is prevalent, cloud water interception by forest canopies may add relatively large amounts of water compared to precipitation or moisture stored in soil. Hence cloud water interception would be expected to influence runoff in summer and fall (A and F, Figure 3), but only in sites prone to fog.

The snowpack dynamics effect is likely to affect runoff in winter rain-on-snow events, but not rain events, while the subsurface flow effect is most likely to affect runoff in large events. In the winter, air temperatures are low, transpiration by conifer forests is small compared to soil moisture storage and precipitation (Figure 2), and runoff events are large (Figure 3). Evapotranspiration would be expected to have a relatively small effect upon soil moisture and runoff, especially for the subset of winter runoff events that are large (B, Figure 3). However, snowpack moisture storages and snowpack melting rates would be expected to influence runoff events in winter (B, C, and D, Figure 3). Moreover, the rate of delivery of water by subsurface flow to channels (streams or roadside ditches) would be expected to have a detectable effect upon runoff events that occur under conditions of very high soil moisture (B, Figure 3).

In summary, subpopulations of peak discharge events from experimental basins in the western Cascades were expected to display the following responses to forestry treatments: (1) temporary increases in small, fall events, but lesser or no increases in small, spring events after forest removal, as a result of decreases in evapotranspiration; (2) offsetting of these increases in small, fall events after forest canopy removal, as a result of decreases in cloud water interception in sites prone to low clouds; (3) increases in winter rain-on-snow events but not in winter rain events after forest canopy removal, as a result of

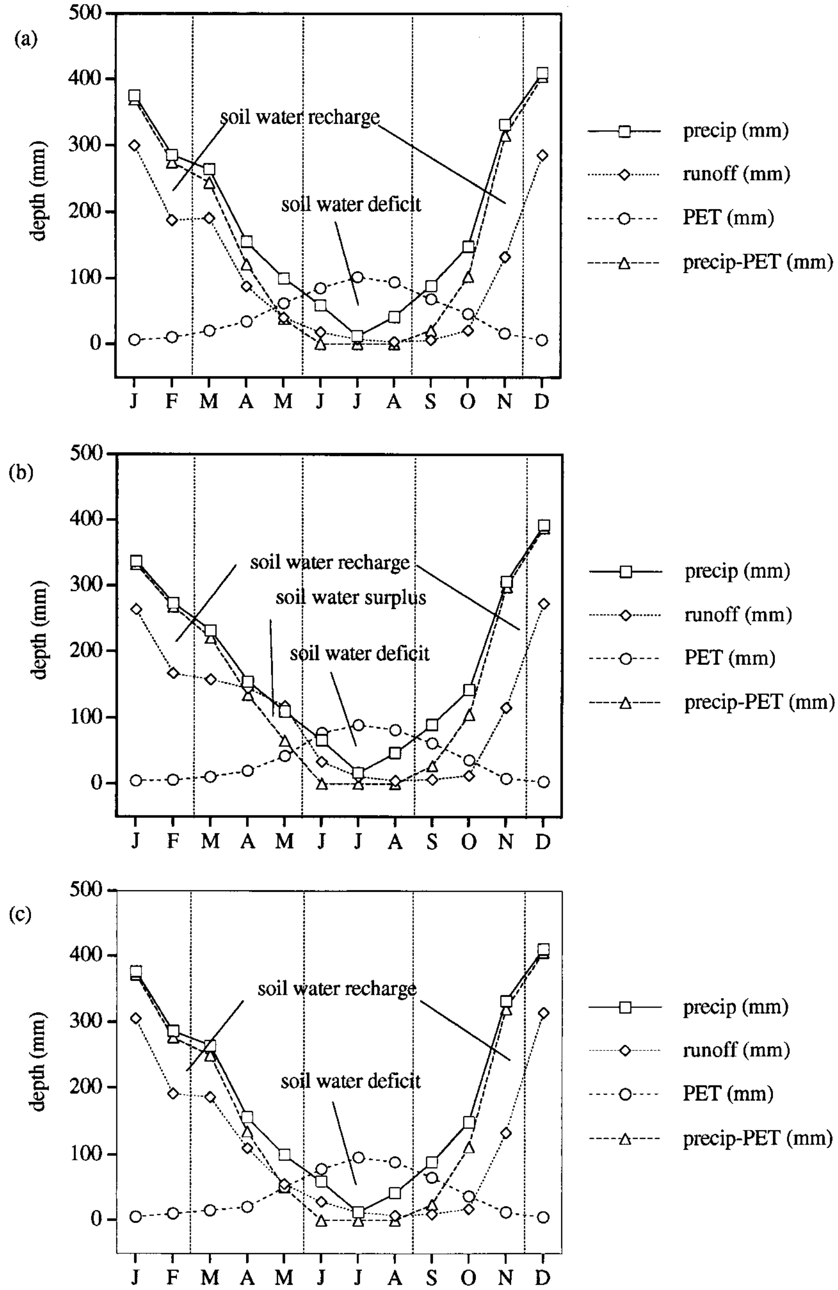


Figure 2. Water balances for each control basin in five paired-basin experiments, western Cascades, Oregon: (a) Andrews 9, (b) Andrews 8, (c) Andrews 2, (d) Fox 2, and (e) Coyote 4. Water balances were calculated from long-term precipitation, runoff, and air temperature (for Thornthwaite potential evapotranspiration) data collected over periods of streamflow records (Table 1) at each site.

decreased interception, increased snowpack accumulation, and more rapid melting; and (4) persistent increases in large events after road construction, as a result of interception of subsurface flow by new surface flow pathways.

3. Methods

3.1. Study Site Description

Fourteen basins, comprising 10 treated-control basin pairs from five paired-basin experiments, were included in the study (Figure 4 and Table 1). A fifteenth basin, Andrews 9, a control, was not included for reasons explained below. Basin size ranged from 10 to 253 ha, and streamflow record length varied from 17 to 43 years. The basins are described in many publications: Andrews 1, 2, and 3 [*Adams et al.*, 1991; *Dyrness*, 1965, 1969, 1973; *Grant and Wolff*, 1990; *Halpern*, 1989; *Halpern and Spies*, 1995; *Hicks et al.*, 1991; *Jones and Grant*, 1996; *Rothacher*, 1965, 1970, 1973; *Thomas and Megahan*, 1998]; Andrews 6, 7, and 8 [*Harr et al.*, 1982]; Andrews 9 and 10 [*Harr and McCorison*, 1979]; Coyote Creek (Coyote 1, 2, 3, and 4) [*Harr et al.*, 1975, 1979]; and Fox Creek (Fox 1, 2, and 3) [*Harr*, 1982; *Sinton et al.*, 2000].

The study basins span a range of climate and vegetation influenced by elevation and latitude. Precipitation and runoff

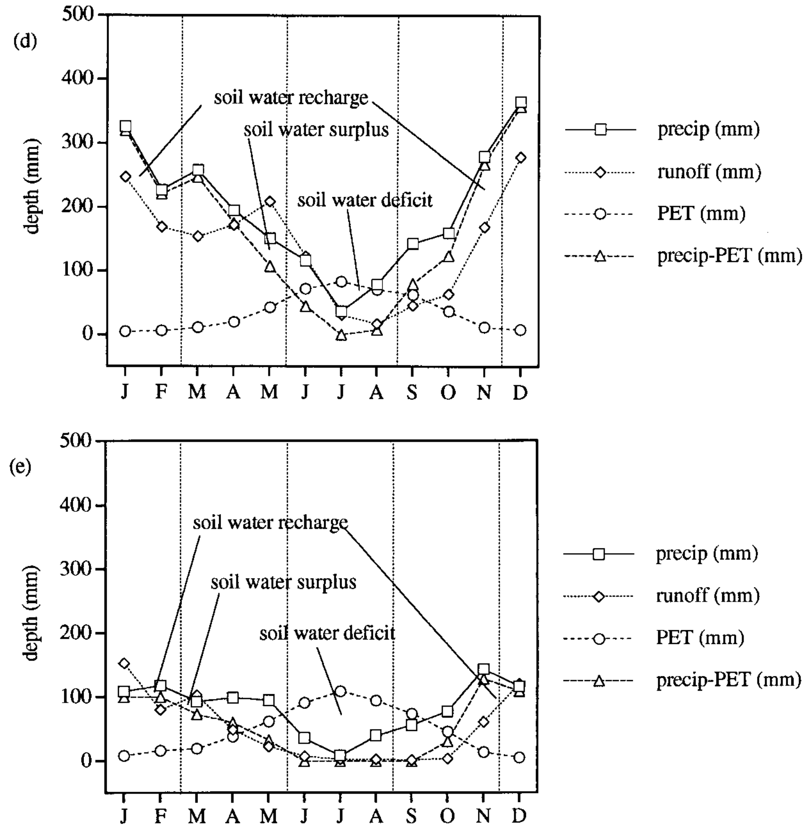


Figure 2. (continued)

increase, and air and soil temperature decrease, from south to north and from low to high elevations. Summers are hot and dry, and winters are cool and wet; over 80% of precipitation occurs from November to April. Summer, early fall, and total precipitation are highest at Fox Creek and lowest at Coyote Creek; air temperatures show the reverse trend (Figure 2). Soil temperatures fall below freezing for fewer than 1–2 days per year, on average, at all sites.

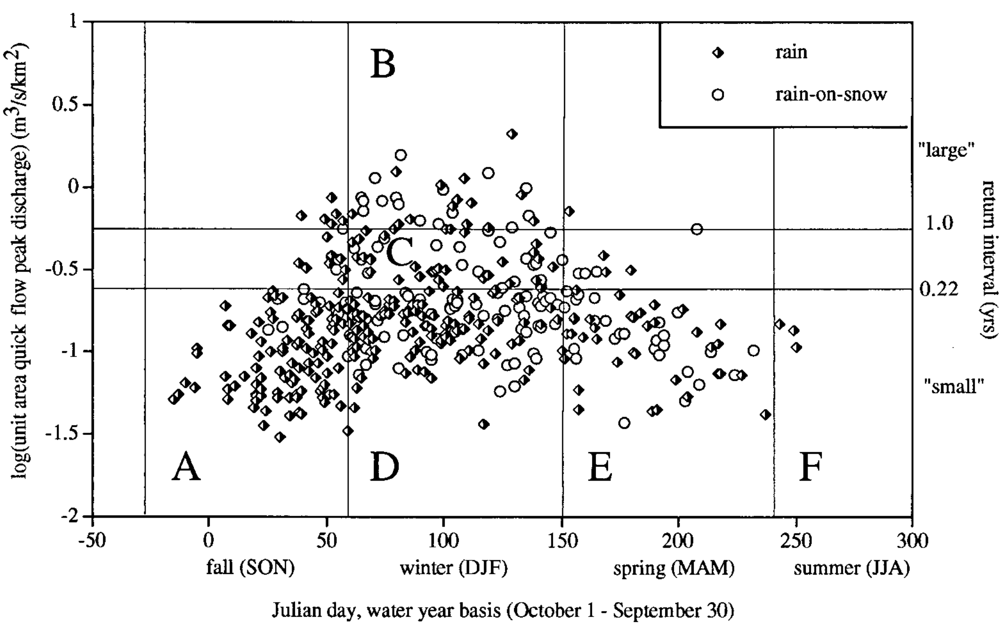


Figure 3. Populations of peak discharge events used in analysis, illustrated for Andrews 2 record (n = 442), by Julian day on water year basis (Julian day 1 = October 1). Six populations of peak discharge events were defined: all; small, fall (B); all winter (B, C, and D); large, winter (B); small, spring (E); and small, summer events (F) (see text).

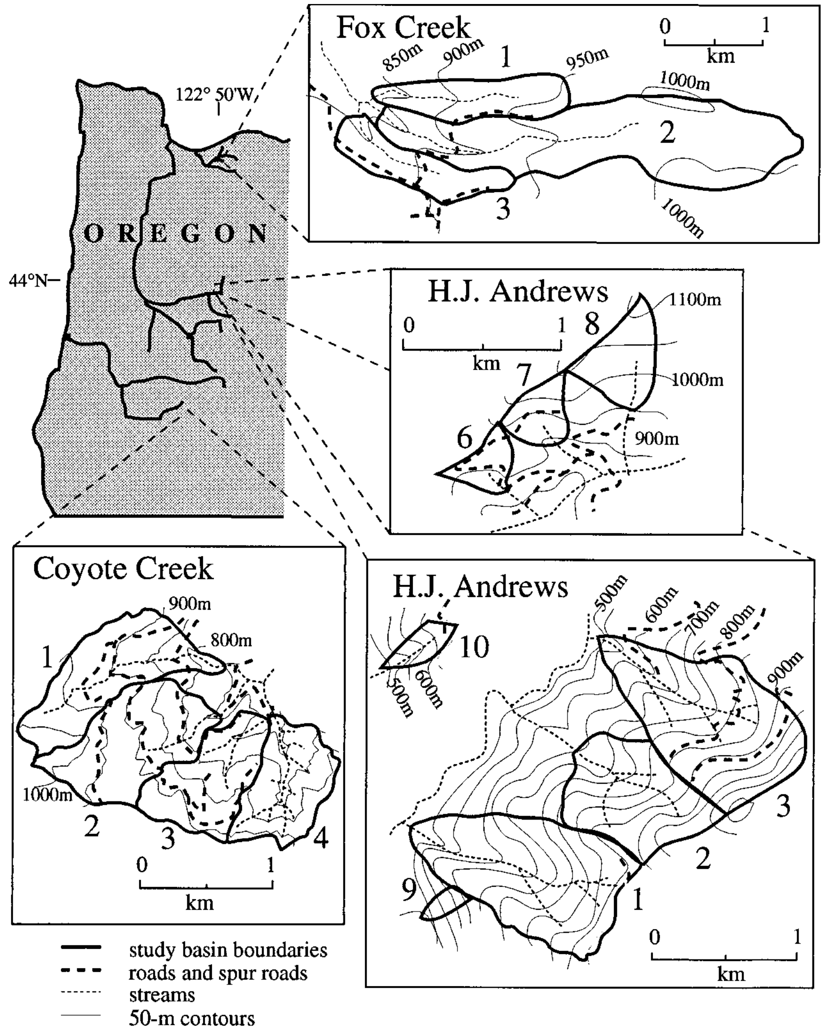


Figure 4. Fourteen experimental basins examined in this study (Andrews 9 was not used); see Table 1 for basin areas and treatments. The 10 treated-control basin pairs are from five paired-basin experiments (shown in separate boxes, except for Andrews 1, 2, and 3 and Andrews 9 and 10, which are combined in one box) designed and implemented by USDA Forest Service personnel in the 1950s and 1960s. The Fox Creek basins are in the Mount Hood National Forest; the Andrews basins are in the H. J. Andrews Experimental Forest in the Willamette National Forest; and the Coyote Creek basins are in the Umpqua National Forest.

The basins lie along gradients of snow cover amounts and durations [*Harr*, 1981, 1986]. Snowpacks are deepest and persist longest at northern sites and high elevations. Snow depth may exceed 1.5 m, and snow may persist for six months, at Andrews 6, 7, and 8 and the Fox Creek basins, while snowpacks at the Coyote Creek basins occasionally persist 1–3 months but usually melt within 1–2 weeks. At Andrews 9 and 10, snow rarely persists longer than 1–2 weeks and usually melts within 1–2 days [*Harr et al.*, 1979; *Harr and McCorison*, 1979; *Harr*, 1982; *Perkins*, 1997].

Soil infiltration rates exceed 20 cm h^{-1} as a result of strongly developed granular structure and large pore spaces; these rates exceed most precipitation rates, and overland flow rarely occurs [*U.S. Forest Service*, 1973; *Dyrness*, 1969]. Soil permeability declines with depth as a result of decreasing densities of root channels, fewer water-stable aggregates, and more common rock fragments. Soil parent materials are weathered Tertiary or Quaternary volcanic rocks with some glacial deposits [*Sherrod and Smith*, 1989]. Basin-wide average hillslope gradients vary from <10% (Fox Creek) to 30% (Coyote Creek, Andrews 6, 7, and 8) to >60% (Andrews 1, 2, 3, 9, and 10) (Figure 4), and soil depth ranges from <1 m (Andrews 10) to several meters (Andrews 6, 7, and 8).

Before forest removal the vegetation of these basins consisted of mature to old-growth conifer forest with leaf area indices exceeding 8.0 [*Marshall and Waring*, 1986]. Forests are dominated by Douglas fir (*Pseudotsuga menziesii*), other conifers, and evergreen hardwoods at Coyote Creek; by Douglas fir, western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) at the Andrews; and by mountain hemlock (*Tsuga mertsiana*) and Pacific silver fir (*Abies amabilis*) at Fox Creek. Posttreatment vegetation consists of shrub and deciduous tree species (e.g., *Ceanothus* spp., *Acer* spp., and *Alnus rubra*) and planted Douglas fir [*Dyrness*, 1965, 1973; *Halpern*, 1989; *Halpern and Spies*, 1995]. Forestry treatments were imposed from 1959 to 1984 and ranged from 25% patch cutting to 100% clear-cutting, with various amounts of road construction (Table 1). All treated basins had some roads, but densities varied; one control basin (Fox 2) also had short lengths of road (Figure 4).

Table 1. Descriptions of 10 Treated-Control Pairs of Small Experimental Basins in the Western Cascades of Oregon

Treated Basin					Control Basin			Paired-Basin Record			
Basin	Size, ha	Elevation, m	Roads, km km^{-2}	Treated, years	Basin	Size, ha	Elevation, m	Total, years	Pretreatment, years	Posttreatment, years	Number of Events
					100% Clear-Cut						
Andrews 1	96	460–990	0.0	1962–1966	Andrews 2	60	530–1070	1952–1996	9	30	442
Andrews 10	10	425–700	0.0	1975	Andrews 2	60	530–1070	1968–1996	6	21	301
Andrews 6	13	880–1010	4.6	1974	Andrews 8	21	960–1130	1963–1996	11	23	306
Coyote 3	50	730–1065	3.2	1971	Coyote 4	49	730–1065	1963–1981	7	10	201
					50% Selection Cut						
Andrews 7	15	910–1020	1.5*	1974, 1984*	Andrews 8	21	960–1130	1963–1996†	11	13, 15*	301
Coyote 1	69	730–1065	2.2	1971	Coyote 4	49	730–1065	1963–1981	7	10	181
					25–30% Patch Cut						
Andrews 3	101	490–1070	3.0	1959, 1963‡	Andrews 2	60	530–1070	1952–1996	9	34	479
Coyote 2	68	730–1065	4.1	1971	Coyote 4	49	730–1065	1963–1981	7	10	184
Fox 1	59	840–925	2.1	1965, 1969‡	Fox 2	253	840–1040	1958–1988	6	19	328
Fox 3	71	840–950	1.3	1965, 1969‡	Fox 2	253	840–1040	1958–1988	11	19	338

*The canopy at Andrews 7 was removed in two cuts, 50% in 1974 and the remaining 50% in 1984, when some spur roads were constructed.
†The streamflow gage at Andrews 7 was inoperative from September 1987 through August 1994.
‡Roads in Andrews 3 were constructed in 1959, and cutting occurred in 1963; roads in Fox 1 and Fox 3 were constructed in 1965, and cutting occurred in 1969.

3.2. Climate and Streamflow Data

Mean monthly values of air temperature, precipitation, and runoff (from the Forest Science Data Bank, available from the World Wide Web server for the Forestry Sciences Laboratory of the USDA Forest Service Pacific Northwest Research Station node at http://www.fsl.orst.edu/lter) were used to create water balances for all five control basins. Potential evapotranspiration was calculated from air temperature data using only average monthly temperature and precipitation [*Thornthwaite and Mather*, 1955; *Dunne and Leopold*, 1978]; this underestimates annual evaporative demand by up to one third [*Waring and Franklin*, 1979].

Streamflow records began between 1952 and 1970, but only the Andrews basins were monitored after the mid-1980s (Table 1). Treated-control basin pairs have pretreatment records of 6–11 years and posttreatment records of 10–34 years in length. Continuous stage flow records from A-35 Stevens recorders at each gaging station were hand-digitized. Stage records were converted to discharge using a single rating curve based on a calibration made early in the pretreatment period for each basin, with the exception of three basins whose rating curves were revised when flumes were replaced. The flume was replaced at Andrews 1 in 1957, 5 years prior to treatment, but this did not appear to confound the interpretation of postharvest streamflow responses. However, after flumes were replaced at Andrews 9 (control) and 10 (treated) in August 1973 (1.5 years prior to treatment), peak discharges at both Andrews 9 and Andrews 10 increased statistically significantly relative to Andrews 2 (control). Therefore increases in peak discharges for Andrews 10 were determined by comparison to Andrews 2, but the measured effect inevitably incorporates both the effect of the flume change and the treatment.

Several steps were involved in creating the data sets of matched peak discharges. First, the digital record of continuous streamflow was screened, using a computer algorithm to select an initial set of peak events based on gage height criteria specified for each basin (see criteria available at http://www.fsl.orst.edu/lter). Gage height criteria were chosen for each basin to produce a statistically tractable sample, i.e., 10–15 events per year on average, producing initial data sets with 208–591 events, depending on the basin. Second, the peak magnitudes (the difference in discharge between event beginning and peak times) were selected for each event. Third, the initial sets of peaks for each treated-control basin pair were merged by date and time of the peak. Fourth, peak discharges were matched by hand for each treated-control pair. Peak discharges were retained as matched only if instantaneous peaks at the treated and control basins occurred within 12 hours of each other, but in most cases, matched peaks occurred within a few hours of each other. When more than one candidate peak at the treated basin occurred within 12 hours of a peak at the control basin, the peak at the treated basin occurring closest in time to that at the control was selected. All other, unmatched peaks (from 3 to 40% of the initial set selected by the algorithm, depending upon the basin pair) were discarded. The resulting matched peak discharge data sets contained 181–479 matched events, depending on the basin, or 9–12 matched events per year (Table 1).

3.3. Peak Discharge Event Classification

Subpopulations of peak discharge events were defined according to event size, season, and type (Figures 2 and 3), and analyses were conducted on six of these populations: all; small, fall; small, spring; small, summer; winter rain-on-snow versus rain or mixed; and large, winter events. Seasons were fall (September–November), winter (December–February), spring (March–May), and summer (June–August). Event size categories were defined by a nonparametric ranking procedure [*Haan*, 1977] using the events at the control basin. The nonparametric ranking procedure is preferable to the commonly used log-Pearson method in this instance because it is less sensitive to the nearly threefold differences in record length among the basins and to the uneven representation of extreme events (for example, the extreme flood of February 1996 was recorded only at the Andrews basins). "Small" events were the smallest two thirds of the ranked events and had recurrence intervals of 0.22–0.28 years, depending upon the control basin (0.22 years for Andrews 2, 0.24 years for Coyote 4, and 0.28 years for Andrews 8 and Fox 2). "Large" events were the top n events in a record of n years and had recurrence intervals of >1 year. Small events, which occurred at least 3 and as many as 12 times per year, do not discernibly affect the geomorphology of these high-gradient mountain streams, and volumes of water discharged are equivalent to only a few percent of the soil moisture storage capacity. Large events, which occurred as often as once (or twice) per year and as rarely as once every 50 years, come close to filling up the channel and include some events which produce detectable changes in channel geomorphology [*Faustini*, 2000] and volumes of water discharged are equivalent to tens of percent of the soil moisture storage capacity.

For the Andrews basins only, peak discharges were classified into three event types following *Perkins* [1997]: rain, rain-on-snow, and mixed and mixed-on-snow, based on the basin-wide air temperature and snowpack conditions determined by a distributed-parameter hydrologic model [*Leavesley et al.*, 1983]. Events were designated as "rain" if the modeled basin-wide, area-weighted, average daily air temperature ranges of hydrologic response units were at or above 0°C, and designated "mixed" otherwise [*Perkins*, 1997]. Events were designated as "on snow" if the modeled snowpack water content (a daily mass and heat balance with inputs from snow accumulation and rain and outputs from snowmelt in excess of the snowpack water storage capacity) exceeded 0.25 cm [*Perkins*, 1997]. Daily modeled snowpack presence/absence agreed well with snowpack field measurements from 1989 to 1994, although the snowpack water content estimated by the model (parameterized for forest conditions) was less than snowpack water content measured in a canopy gap [*Perkins*, 1997]. The classification system explained variation in observed snow lysimeter output for events from October 1, 1992, to September 30, 1994: The average ratio of lysimeter output to precipitation inputs was 1.3 during events classified as rain-on-snow compared to only 0.8 during events classified as rain [*Perkins*, 1997].

3.4. Statistical Analysis

Changes in the average magnitude of peak discharge events over time in each treated-control basin pair were examined using analysis of variance (ANOVA) with post hoc tests of effects using multiple-comparisons procedures [*Miller*, 1980; *Neter et al.*, 1990; *Wilkinson et al.*, 1996]. For each of the six populations of peak discharge events a one-way ANOVA related the difference in log-transformed peak discharges between the treated and the control basin for each event (dependent variable) to time after treatment (independent variable). (The dependent variable is shown in the column labeled "Mean" in Tables 2–6.) When multiple posttreatment 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; *Wilkinson et al.*, 1996]. Data were tested for independence, equality of variance, and normality before analysis. Because peak discharges were lognormally distributed, the difference in log-transformed peak discharges between the treated and control basins for each matched event was used as the dependent variable, following *Eberhardt and Thomas* [1991].

It has been debated whether it is appropriate to use ANOVA (as in this study and that by *Jones and Grant* [1996]) or analysis of covariance (ANCOVA) (i.e., regression, used by *Thomas and Megahan* [1998]) for analysis of peak discharge response to forest harvest. Jones and Grant (submitted manuscript, 1999) showed that after accounting for differences in sample sizes, data pretreatment, and critical significance levels, these two approaches produced almost identical results from the same data set. ANOVA was used here because it facilitated examination of hydrologic processes (Jones and Grant, submitted manuscript, 1999). Probabilities of all tests are reported to aid interpretation of significance.

Percent changes in peak discharges (Figure 6 and column labeled "Change, %" in Tables 2–6) were calculated as $[\exp(A - B) - 1] \times 100$, where posttreatment mean difference $A = 1/(n - m)\ \Sigma_{i=n+1 \text{ to } m}\ [\log_e(t_n) - \log_e(c_n)]$, pretreatment mean difference $B = 1/m\ \Sigma_{i=1 \text{ to } m}\ [\log_e(t_n) - \log_e(c_n)]$, t_n is the peak discharge in the treated basin, c_n is the matched peak discharge in the control basin, and peak discharge events are indexed $i = 1, 2, \ldots, m, \ldots, n$, where m is the number of events in the pretreatment period and $n - m$ is the number of events in the posttreatment period. Values of A and B are shown in columns labeled "Mean" in Tables 2–6; means >0 indicate that on average, peak discharges in the treated basin exceeded those in the control, and means <0 indicate the reverse. Relative sizes of peak discharges for single events (Figure 5) were expressed as percents of the pretreatment mean difference (see legend to Figure 5).

4. Results

Populations of peak discharge events display distinct responses over time that vary by treatment type, basin, and event type (Figure 5). During the pretreatment period the treated-control basin relationship (the variation around the mean of zero in Figure 5) was tighter (less variation) for treated-control basin pairs which were adjacent and of the same size and elevation range (e.g., Andrews 1-2, Andrews 3-2, and Coyote 3-4) and looser (more variation) for basin pairs which differed in size or elevation range (Fox 1-2 and Fox 3-2) or were separated by more than 1 km (Andrews 6-8, Andrews 10-2, and Coyote 1-4) (Figures 4 and 5). Also, certain event subpopulations were distinct, even in the pretreatment period; for example, treated-control differences for large events were less than for small events in Andrews 1-2 and Andrews 3-2 but greater in Andrews 6-8 and Andrews 7-8 (Figure 5). After treatment, populations of peak discharge events displayed several distinct behaviors among basins: qualitative increases in the mean but not the variance (Andrews 6-8, Andrews 7-8, and Andrews 10-2), increases in both the mean and the variance (Andrews 1-2, Andrews 3-2, and all Coyote basin pairs), or neither (Fox 1-2 and Fox 3-2).

Different subpopulations of peak discharge event types, basins, and treatments display distinct trends over time (Figure 6). For example, when the entire forest canopy was removed (100% clear-cutting), small, fall events increased dramatically in percent terms, but only for the first decade (Figure 6a). Less canopy removal (e.g., 25% patch cutting) produced smaller percent increases in small, fall events, and these increases also were transitory (Figure 6b). Large events also increased after canopy removal in basins with roads, but increases were persistent and not apparently related to the amount of forest canopy removed (Figures 6c and 6d).

Posttreatment peak discharges were significantly different from pretreatment peak discharges, and the magnitude, timing, and duration of significant responses varied among basins, treatments, and event types. Overall, peak discharges in small experimental basins increased significantly in response to for-

Table 2. Peak Discharge Response to Forestry Treatments, for All Events Pooled, in 10 Pairs of Small Experimental Basins in the Western Cascades of Oregon

Years	Treatment	*n*	Mean	Change, %
	Andrews 1 (100% Clear-Cut, No Roads) Versus 2 (Control)			
1952–1961	none	98	0.83a	0
1962–1966	100% clearcut*	48	1.03b	22
1967–1976	0–10 years postcut	104	1.09b	31
1977–1986	11–20 years postcut	104	1.06b	26
1987–1996	21–30 years postcut	88	1.02b	21
	Andrews 10 (100% Clear-Cut, No Roads) Versus 2 (Control)			
1968–1974	none	74	−1.25a	0
1975–1984	0–10 years postcut	92	−1.03b	25
1985–1996	11–22 years postcut	85	−1.02b	26
	Andrews 6 (100% Clear-Cut, Roads) Versus 8 (Control)			
1963–1973	none	122	−0.79a	0
1974–1983	0–10 years postcut	90	−0.48b	37
1984–1996	11–23 years postcut	94	−0.62b	20
	Coyote 3 (100% Clear-Cut, Roads) Versus 4 (Control)			
1963–1969	none	55	−0.06a	0
1970–1974	0–5 years postcut	73	0.30b	45
1975–1981	5–12 years postcut	73	0.49b	73
	Andrews 7 (50% Selection Cut, No Roads) Versus 8 (Control)			
1963–1973	none	131	−0.79a	0
1974–1983	0–10 years postcut	119	−0.56b	25
1984–1996	0–12 years postcut†	51	−0.48b	36
	Coyote 1 (50% Selection Cut, Roads) Versus 4 (Control)			
1963–1969	none	48	−0.14a	0
1970–1974	0–5 years postcut	67	0.16b	36
1975–1981	5–12 years postcut	66	0.20b	42
	Andrews 3 (25% Patch Cut With Roads) Versus 2 (Control)			
1952–1958	none	75	0.55a	0
1959–1962	roads	47	0.63ab	8
1963–1972	0–10 years postcut	110	0.72b	19
1973–1982	11–20 years postcut	113	0.68b	14
1983–1996	21–33 years postcut	134	0.65b	10
	Coyote 2 (30% Patch Cut With Roads) Versus 4 (Control)			
1963–1969	none	47	0.12a	0
1970–1974	0–5 years postcut	68	0.39b	32
1975–1981	5–12 years postcut	68	0.46b	40
	Fox 1 (25% Patch Cut With Roads) Versus 2 (Control)			
1958–1964	none	88	−1.23a	0
1965–1968	roads	23	−1.13a	10
1969–1978	0–10 years postcut	135	−1.10b	12
1979–1988	11–20 years postcut	82	−1.17ab	5
	Fox 3 (25% Patch Cut With Roads) Versus 2 (Control)			
1958–1964	none	94	−1.06a	0
1965–1968	roads	20	−1.00a	4
1969–1978	0–10 years postcut	133	−1.06a	1
1979–1988	11–20 years postcut	91	−1.04a	2

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 $p < 0.05$. Calculations for "Mean" and "Change, %" are explained in the text.

*Clear-cutting in Andrews 1 occurred over a 4-year period.

†The canopy at Andrews 7 was removed in two cuts, 50% in 1974 and the remaining 50% in 1984.

estry treatments (Figure 5 and Table 2). In 8 of 10 basin pairs, forestry treatments were associated with significant increases in peak discharges for all 5- to 10-year posttreatment periods, up to 30 years after treatment (Table 2). For the pooled sample of all event sizes, significant increases in peak discharges ranged from +21 to +73% in 100%-cut basins, +25 to +42% in 50%-cut basins, and +10 to +40% in 25%-cut basins with roads (Table 2). Changes were significantly positive for 10 of 10 posttreatment periods in four 100%-cut basin pairs, 4 of 4 posttreatment periods in two 50%-cut basin pairs, and 6 of 12 posttreatment periods in four 25%-cut basin pairs with roads (Table 2). The magnitude of the increase remained constant or increased at Andrews 7 and the Coyote basins (posttreatment records of 12 years) and at Andrews 10 (posttreatment record of 22 years) but declined over time at Andrews 1, Andrews 6, and Andrews 3 (posttreatment records of 23–33 years) (Table 2).

Small, fall (<0.28 years, September–November) events in-

Table 3. Peak Discharge Response to Forestry Treatments, for Small, Fall (<0.28 years, September–November) Events, in 10 Pairs of Small Experimental Basins in the Western Cascades of Oregon

Years	Treatment	*n*	Mean	Change, %
	Andrews 1 (100% Clear-Cut, No Roads) Versus 2 (Control)			
1952–1961	none	18	0.77a	0
1962–1966	100% clearcut*	12	1.09b	38
1967–1976	0–10 years postcut	21	1.19b	53
1977–1986	11–20 years postcut	30	1.05b	33
1987–1996	21–30 years postcut	19	0.95ab	20
	Andrews 10 (100% Clear-Cut, No Roads) Versus 2 (Control)			
1968–1974	none	20	−1.32a	0
1975–1984	0–10 years postcut	21	−0.83b	65
1985–1996	11–22 years postcut	14	−0.99b	40
	Andrews 6 (100% Clear-Cut, Roads) Versus 8 (Control)			
1963–1973	none	40	−1.19a	0
1974–1983	0–10 years postcut	24	−0.73b	59
1984–1996	11–23 years postcut	19	−1.27a	−8
	Coyote 3 (100% Clear-Cut, Roads) Versus 4 (Control)			
1963–1969	none	12	0.01a	0
1970–1974	0–5 years postcut	12	0.78b	116
1975–1981	5–12 years postcut	18	0.57b	75
	Andrews 7 (50% Selection Cut, No Roads) Versus 8 (Control)			
1963–1973	none	41	−0.99a	0
1974–1983	0–10 years postcut	32	−0.59b	49
1984–1996	0–12 years postcut†	12	−0.64b	42
	Coyote 1 (50% Selection Cut, Roads) Versus 4 (Control)			
1963–1969	none	12	−0.17a	0
1970–1974	0–5 years postcut	11	0.38b	73
1975–1981	5–12 years postcut	17	0.32b	63
	Andrews 3 (25% Patch Cut With Roads) Versus 2 (Control)			
1952–1958	none	13	0.59a	0
1959–1962	roads	20	0.73ac	15
1963–1972	0–10 years postcut	29	0.86b	31
1973–1982	11–20 years postcut	32	0.78bc	21
1983–1996	21–33 years postcut	37	0.71ac	12
	Coyote 2 (25% Patch Cut With Roads) Versus 4 (Control)			
1963–1969	none	8	−0.05a	0
1970–1974	0–5 years postcut	10	0.48b	71
1975–1981	5–12 years postcut	15	0.42b	61
	Fox 1 (25% Patch Cut With Roads) Versus 2 (Control)			
1958–1964	none	18	−1.20a	0
1965–1968	roads	5	−1.26a	−5
1969–1978	0–10 years postcut	28	−1.14a	7
1979–1988	11–20 years postcut	19	−1.09a	12
	Fox 3 (25% Patch Cut With Roads) Versus 2 (Control)			
1958–1964	none	19	−1.11a	0
1965–1968	roads	3	−1.09a	2
1969–1978	0–10 years postcut	25	−1.09a	2
1979–1988	11–20 years postcut	24	−1.03a	8

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 $p < 0.05$. Calculations for "Mean" and "Change, %" are explained in the text.

*Clear-cutting in Andrews 1 occurred over a 4-year period.

†The canopy at Andrews 7 was removed in two cuts, 50% in 1974 and the remaining 50% in 1984.

creased in all basin pairs except at the Fox Creek basins (Table 3). In the first 10 years after forest canopy removal, small, fall events increased by 53% at Andrews 1 ($p < 0.0005$), 65% at Andrews 10 ($p < 0.0001$), 59% at Andrews 6 ($p < 0.0001$), 75–116% at Coyote 3 ($p < 0.003$, $p < 0.02$), 49% at Andrews 7 ($p < 0.0001$), 63–73% at Coyote 1 ($p < 0.0002$), 31% at Andrews 3 ($p < 0.0001$), and 61–71% at Coyote 2 ($p < 0.01$). At Andrews 7 and the Coyote basins (12 years of posttreatment record) and Andrews 10 (22 years of posttreatment record), small, fall peak discharges remained significantly higher than pretreatment for the period of record. However, in the second posttreatment decade, small, fall peaks in Andrews 6 had declined significantly compared to the first posttreatment decade ($p < 0.0001$) and were no longer significantly different than during the pretreatment period. In the third posttreatment decade, small, fall peak discharges had declined significantly compared to the first posttreatment decade in Andrews 1 ($p < 0.10$) and Andrews 3 ($p < 0.008$)

Table 4. Peak Discharge Response to Forestry Treatments, for Small, Spring (<0.28 years, March–May) Events, in 10 Pairs of Small Experimental Basins in the Western Cascades of Oregon

Years	Treatment	*n*	Mean	Change, %
	Andrews 1 (100% Clear-Cut, No Roads) Versus 2 (Control)			
1952–1961	none	13	0.89a	0
1962–1966	100% clearcut*	11	0.97a	9
1967–1976	0–10 years postcut	5	1.23a	41
1977–1986	11–20 years postcut	15	1.14a	28
1987–1996	21–30 years postcut	9	1.09a	22
	Andrews 10 (100% Clear-Cut, No Roads) Versus 2 (Control)			
1968–1974	none	7	−1.25a	0
1975–1984	0–10 years postcut	10	−0.95b	36
1985–1996	11–22 years postcut	7	−0.91b	41
	Andrews 6 (100% Clear-Cut, Roads) Versus 8 (Control)			
1963–1973	none	16	−0.62a	0
1974–1983	0–10 years postcut	8	−0.04b	77
1984–1996	11–23 years postcut	15	−0.42ab	21
	Coyote 3 (100% Clear-Cut, Roads) Versus 4 (Control)			
1963–1969	none	6	0.07a	0
1970–1974	0–5 years postcut	8	0.28ab	24
1975–1981	5–12 years postcut	9	0.61b	71
	Andrews 7 (50% Selection Cut, No Roads) Versus 8 (Control)			
1963–1973	none	19	−0.68a	0
1974–1983	0–10 years postcut	14	−0.47a	23
1984–1996	0–12 years postcut†	9	−0.61a	8
	Coyote 1 (50% Selection Cut, Roads) Versus 4 (Control)			
1963–1969	none	5	−0.01a	0
1970–1974	0–5 years postcut	5	0.14a	17
1975–1981	5–12 years postcut	8	0.13a	15
	Andrews 3 (25% Patch Cut With Roads) Versus 2 (Control)			
1952–1958	none	10	0.54a	0
1959–1962	roads	9	0.62a	9
1963–1972	0–10 years postcut	11	0.74a	22
1973–1982	11–20 years postcut	7	0.62a	8
1983–1996	21–33 years postcut	15	0.64a	10
	Coyote 2 (25% Patch Cut With Roads) Versus 4 (Control)			
1963–1969	none	6	0.29a	0
1970–1974	0–5 years postcut	6	0.53a	26
1975–1981	5–12 years postcut	9	0.60a	36
	Fox 1 (25% Patch Cut With Roads) Versus 2 (Control)			
1958–1964	none	20	−1.18a	0
1965–1968	roads	2	−1.45a	−27
1969–1978	0–10 years postcut	21	−0.97a	22
1979–1988	11–20 years postcut	13	−1.23a	−5
	Fox 3 (25% Patch Cut With Roads) Versus 2 (Control)			
1958–1964	none	23	−1.00a	0
1965–1968	roads	3	−0.91a	9
1969–1978	0–10 years postcut	22	−0.96a	4
1979–1988	11–20 years postcut	14	−1.08a	−8

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 $p < 0.05$. Calculations for "Mean" and "Change, %" are explained in the text.

*Clear-cutting in Andrews 1 occurred over a 4-year period.

†The canopy at Andrews 7 was removed in two cuts, 50% in 1974 and the remaining 50% in 1984.

and were no longer significantly higher than during the pretreatment period (Table 3 and Figures 5 and 6).

Small, spring (<0.2 years, March–May) peak discharges increased in only 3 of the 10 basin pairs, and all of these were 100%–clear-cut basins (Table 4). In the first 10 years after treatment, small spring events increased by 36% at Andrews 10 ($p < 0.04$), 77% at Andrews 6 ($p < 0.01$), and 71% at Coyote 3 ($p < 0.02$). By the second posttreatment decade, small, spring peak discharges were no longer significantly higher than during the pretreatment period in Andrews 6, but they remained significantly higher than pretreatment discharges in Andrews 10 and Coyote 3 (Table 4 and Figure 5).

Summer peak discharges declined significantly following forest canopy removal, but only for 2 or 3 years, and only in the Fox Creek basins. Twenty (Fox 1) and 21 (Fox 3) matched events occurred in summer (June–August) over the entire period of record; the two summer events that occurred during the first 2 years after treatment were lower than all other summer

Table 5. Peak Discharge Response to Forestry Treatments, for Winter (December–February) Rain, Rain-on-Snow, and Mixed Events, in Five Pairs of Small Experimental Basins in the H. J. Andrews Forest, Western Cascades of Oregon

		Rain			Mixed, Mixed-on-Snow			Rain-on-Snow		
Years	Period	*n*	Mean	Change, %	*n*	Mean	Change, %	*n*	Mean	Change, %
				Andrews 1 (100% Clear-Cut, No Roads) Versus 2 (Control)						
1952–1961	P	15	0.84a	0	7	0.89a	0	21	0.75a	0
1962–1996	R	32	1.03a	22	48	1.08a	22	75	1.02b	31
				Andrews 10 (100% Clear-Cut, No Roads) Versus 2 (Control)						
1968–1975	P	9	−1.34a	0	22	−1.14a	0	12	−1.24a	0
1975–1996	R	20	−1.05a	34	16	−1.15a	−1	37	−1.11a	13
				Andrews 6 (100% Clear-Cut, Roads) Versus 8 (Control)						
1963–1973	P	10	−0.52a	0	8	−0.49a	0	34	−0.58a	0
1974–1996	R	19	−0.49a	3	15	−0.59a	−10	39	−0.36b	25
				*Andrews 7 (50% Selection Cut, No Roads) Versus 8 (Control)**						
1963–1973	P	10	−0.70a	0	11	−0.47a	0	36	−0.72a	0
1974–1996	R	20	−0.56a	15	18	−0.62a	−14	33	−0.46b	30
				Andrews 3 (25% Patch Cut With Roads) Versus 2 (Control)						
1952–1958	P	9	0.56a	0	9	0.48a	0	9	0.36a	0
1959–1996	R	40	0.65a	10	62	0.67a	22	60	0.59b	26

P, pretreatment, and R, posttreatment periods of record. 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 $p < 0.10$. Calculations for "Mean" and "Change, %" are explained in the text.
*The canopy at Andrews 7 was removed in two cuts, 50% in 1974 and the remaining 50% in 1984.

peak discharges by 47% (at Fox 1, $p < 0.0003$) and 46% (at Fox 3, $p < 0.003$).

At the Andrews basins (the only basins for which events could be retrospectively classified as rain or rain-on-snow), rain-on-snow events of all sizes in winter (December–February) increased significantly after forest canopy removal, but other types of winter events did not change (Table 5). When the entire posttreatment period was compared to the pretreatment period, rain-on-snow peak discharge events in winter increased by 31% ($p < 0.0004$) at Andrews 1, 26% ($p < 0.07$) at Andrews 3, 25% ($p < 0.07$) at Andrews 6, and 30% ($p < 0.01$) at Andrews 7, but winter rain events and winter mixed events did not change significantly at any of these four basins (Table 5). At Andrews 10 no type of winter event increased significantly (Table 5).

Large (>1 year) events increased significantly after treatment in 8 of 10 basin pairs, and the magnitudes of significant increases in large events in the four 25%-cut basins with roads were as great as those in 100%–clear-cut basins (Table 6). In 100%–clear-cut basins, large events increased by 25% at Andrews 1 ($p < 0.01$), 16% at Andrews 6 ($p < 0.01$), and 26% at Coyote 3 ($p < 0.08$) but did not change at Andrews 10 (Table 6). In 50%-cut basins with roads, large events increased by 27% at Andrews 7 ($p < 0.08$) but did not change at Coyote 1 (Table 6). In 25%-cut basins with roads, large events increased by 16% at Andrews 3 ($p < 0.01$), 36% at Coyote 2 ($p < 0.10$), 13% at Fox 1 ($p < 0.04$), and 13% at Fox 3 ($p < 0.01$) (Table 6). Although sample sizes are too small to test for significance by time period after treatment, increases in >1-year events appeared to persist, and even increase, over the periods of posttreatment records (Figure 6c).

Increases in large (>1 year) events after treatment were attributable to both rain and rain-on-snow events; large rain-on-snow events increased less than rain events at low elevations but similarly to or more than rain events at high elevations. The following comparisons were made using the Andrews basins and retrospective characterization of rain-on-snow conditions [*Perkins*, 1997]. Sample sizes were too small to test for significance. At Andrews 1, >1-year rain events increased by 25% ($n_{pre} = 6$, $n_{post} = 4$), and >1-year rain-on-snow events increased 13% ($n_{pre} = 5$, $n_{post} = 12$). At Andrews 3, >1-year rain events increased 10% ($n_{pre} = 5$, $n_{post} = 9$), and >1-year rain-on-snow events increased 2% ($n_{pre} = 2$, $n_{post} = 10$). At Andrews 6, >1-year rain events increased 11% ($n_{pre} = 4$, $n_{post} = 6$), and >1-year rain-on-snow events increased 16% ($n_{pre} = 7$, $n_{post} = 8$). At Andrews 7, >1-year rain events increased 12% ($n_{pre} = 4$, $n_{post} = 5$), and >1-year rain-on-snow events increased 29% ($n_{pre} = 7$, $n_{post} = 9$). At Andrews 10, >1-year rain, mixed, and mixed-on-snow events decreased 18% ($n_{pre} = 10$ for all event types, $n_{post} = 4$), and >1-year rain-on-snow events increased 4% ($n_{pre} = 10$ for all event types, $n_{post} = 9$).

5. Discussion

The behavior of these 10 paired basins illustrates that many different components of the water balance are affected by forest canopy removal, forest regrowth, and roads and that these effects can, to some degree, be understood according to how they affect water in the forest canopy, the snowpack, and the soil (Figure 1). Viewing streamflow response to forest removal, regrowth, and roads from this perspective provides plausible explanations for much of the observed variability in responses among these basins, which are located within a single climatic region and forest vegetation zone (Figure 2). In addition, the collective behavior of these 10 basins lends itself to the formulation of qualitative predictions about the magnitude, seasonal timing, and duration after treatment of peak discharge response to forest removal, regrowth, and roads under a range of conditions within the Pacific Northwest and in similar areas. These ideas merit further exploration and testing through focused field measurements, experiments, and modeling.

This paper advocates a conceptual model, namely, that

Table 6. Peak Discharge Response to Forestry Treatments, for >1 year Events, in 10 Pairs of Small Experimental Basins in the Western Cascades of Oregon

Years	Treatment	*n*	Mean	Change, %
		Andrews 1 (100% Clear-Cut, No Roads) Versus 2 (Control)		
1952–1961	none	16	0.73a	0
1962–1996	cut, 0–30 years postcut	25	0.87b	25
		Andrews 10 (100% Clear-Cut, No Roads) Versus 2 (Control)		
1968–1974	none	10	−1.30a	0
1975–1996	0–22 years postcut	15	−1.38a	−8
		Andrews 6 (100% Clear-Cut, Roads) Versus 8 (Control)		
1963–1973	none	16	0.73a	0
1974–1996	0–23 years postcut	25	0.87b	16
		Coyote 3 (100% Clear-Cut, Roads) Versus 4 (Control)		
1963–1969	none	4	−0.12a	0
1970–1981	0–12 years postcut	13	0.12b	26
		*Andrews 7 (50% Selection Cut, No Roads) Versus 8 (Control)**		
1963–1973	none	12	−0.72a	0
1974–1996	0–10, 0–12 years postcut	20	−0.48b	27
		Coyote 1 (50% Selection Cut, Roads) Versus 4 (Control)		
1963–1969	none	4	0.08a	0
1970–1981	0–12 years postcut	11	0.17a	10
		Andrews 3 (25% Patch Cut With Roads) Versus 2 (Control)		
1952–1958	none	11	0.36a	0
1959–1996	roads, 0–33 years postcut	30	0.51b	16
		Coyote 2 (25% Patch Cut With Roads) Versus 4 (Control)		
1963–1969	none	4	−0.10a	0
1970–1981	0–12 years postcut	13	−0.21b	36
		Fox 1 (25% Patch Cut With Roads) Versus 2 (Control)		
1958–1964	none	6	−1.30a	0
1965–1988	roads, 0–20 years postcut	24	−1.18b	13
		Fox 3 (25% Patch Cut With Roads) Versus 2 (Control)		
1958–1964	none	9	−1.13a	0
1965–1988	roads, 0–20 years postcut	21	−1.01b	13

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 $p < 0.10$. Calculations for "Mean" and "Change, %" are explained in the text.

*The canopy at Andrews 7 was removed in two cuts, 50% in 1974 and the remaining 50% in 1984.

streamflow response can be explained, or predicted, according to the magnitude and duration of the effect of forest treatment(s) upon water balance components associated with the forest canopy, the snowpack, and the soil (Figure 1). Responses may vary according to the absolute magnitude of the capacity or change in a water balance component, as well as its magnitude relative to other storage components (equations (1)–(4)). Variations in streamflow response over time (e.g., as forests regrow) or in space (e.g., in basins differing in latitude, elevation, soil depth, or topographic exposure) can be explained or predicted following the same logic. Such an approach lends itself to more in-depth study of the coupling between forest ecosystems and water, recently termed "ecological hydrology" [*Post et al.*, 1998].

This analysis of 10 treated-control basin pairs focused on four hydrologic mechanisms (Figure 1). After forest canopy removal, two potentially offsetting changes apparently occurred: an evapotranspiration effect whereby peak discharges increased, and a countervailing cloud water interception effect. In addition, forest canopy removal apparently modified snowpack dynamics in such a way as to increase snowmelt contributions to peak discharges during winter rain-on-snow events. Moreover, soil drainage may have been modified by forest roads so as to increase peak discharges of large (>1 year) events.

5.1. Evapotranspiration, Cloud Water Interception, and Forest Canopy Removal and Recovery

Evapotranspiration influences upon peak discharges are the most obvious, but not necessarily the most important, streamflow responses to forest removal. Forest canopy removal effects on transpiration, soil moisture storage, and streamflow have been noted in many studies [*Rothacher*, 1970, 1973; *Harr et al.*, 1975, 1982, 1979; *Harr*, 1976a]. In this study, when old-growth conifer forests in the Pacific Northwest were removed, the evapotranspiration effect produced large increases in peak discharge events, but the affected events were quite small, and increases tended to disappear as forest canopies regrew. Moreover, the magnitude, timing, and duration of the evapotranspiration effect varied according to the climatic setting, the size of the soil moisture reservoir, the type and leaf area of vegetation removed, and the type and timing of vegetation recovery.

In order for evapotranspiration to affect the peak discharge signal, interception, canopy evaporation, and transpiration must be large relative to other water balance components

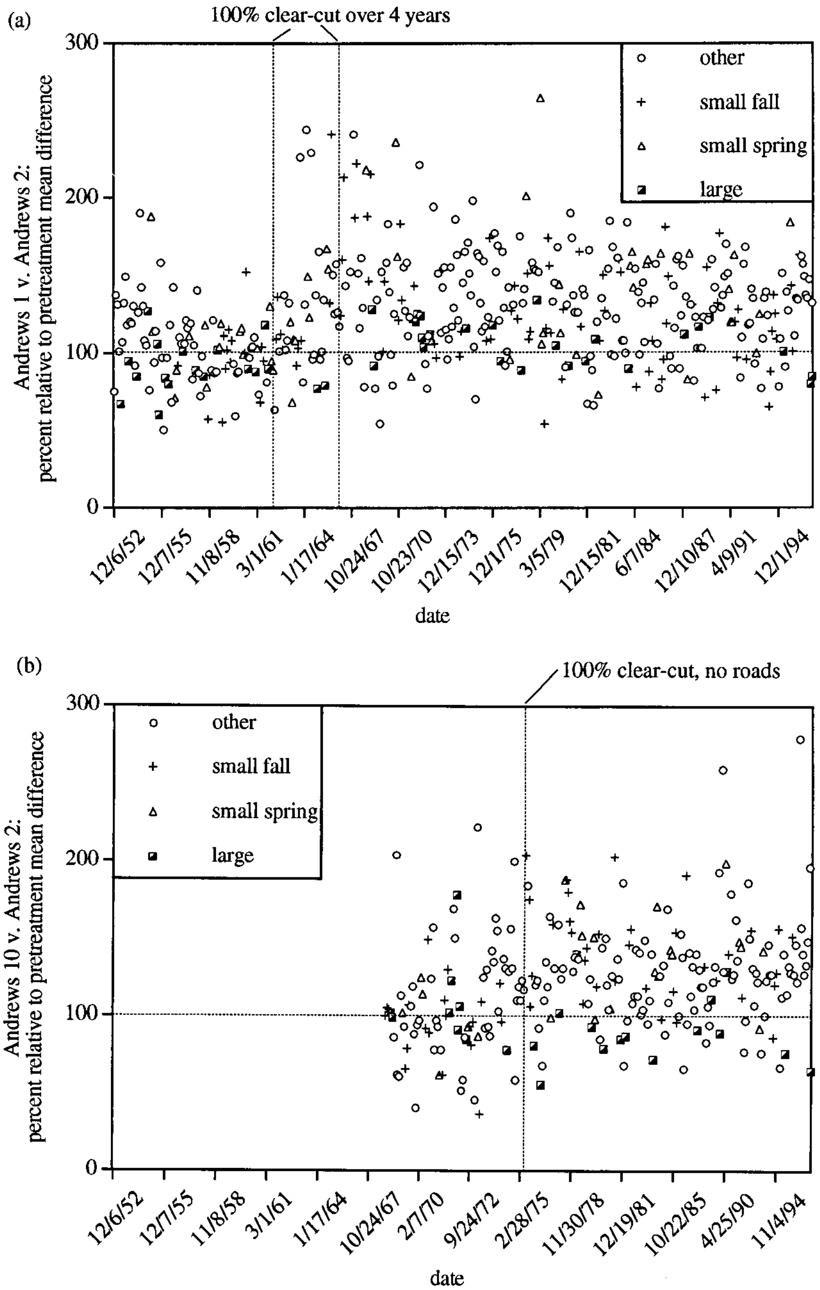
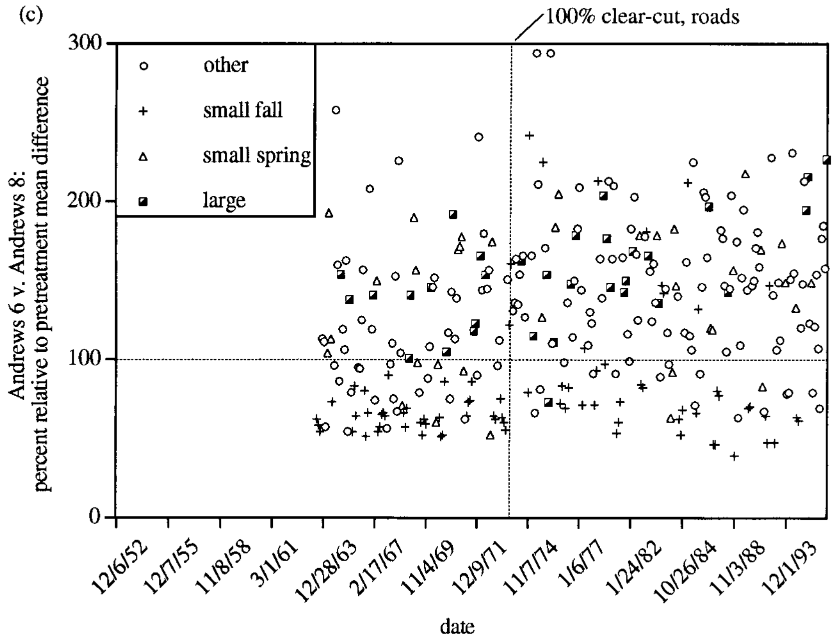


Figure 5. Matched peak discharge events by date and event type for 10 treated-control basin pairs used in the trends in Figure 6 and the statistical analyses in Tables 2–6. Each point represents one matched peak discharge event and is expressed as a percent, calculated as $e^{(A-B)} \times 100$, where $A = \log_e(t_n) - \log_e(c_n)$, pretreatment mean difference $B = 1/m \; \Sigma_{i \text{ to } m} [\log_e(t_n) - \log_e(c_n)]$, where t_n is the peak discharge in the treated basin, c_n is the matched peak discharge in the control basin, and peak discharge events are indexed $i = 1, 2, \ldots, m, \ldots, n$, where m is the number of events in the pretreatment period and n is the number of events in the entire record. Thirty events are plotted between each tick mark on the abscissa. Basin pairs are as follows: (a) Andrews 1 versus Andrews 2, (b) Andrews 10 versus Andrews 2, (c) Andrews 6 versus Andrews 8, (d) Coyote 3 versus Coyote 4, (e) Andrews 7 versus Andrews 8, (f) Coyote 1 versus Coyote 4, (g) Andrews 3 versus Andrews 2, (h) Coyote 2 versus Coyote 4, (i) Fox 1 versus Fox 2, and (j) Fox 3 versus Fox 2 (see Table 1).

(Figure 1). In conifer forests of the Pacific Northwest, evapotranspiration losses are relatively large during the fall when precipitation events are relatively small, and trees are actively transpiring, but soil moisture storage is low. After forest canopy removal, small, fall peak discharge events increased in 8 of 10 basin pairs by 53–116% averaged over the first posttreatment decade (Table 3), and by larger percents for shorter periods (Figures 5 and 6). In five of these basin pairs, small, spring peak discharges did not increase, apparently because the evapotranspiration effect was overwhelmed by other components of the water balance, such as large precipitation event size, large soil moisture storage volume, or large snowmelt inputs.



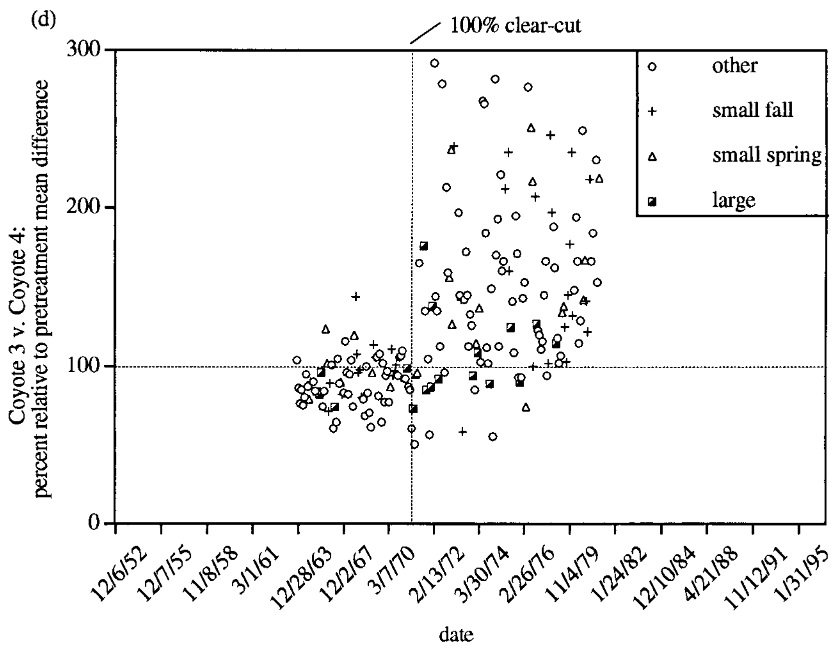
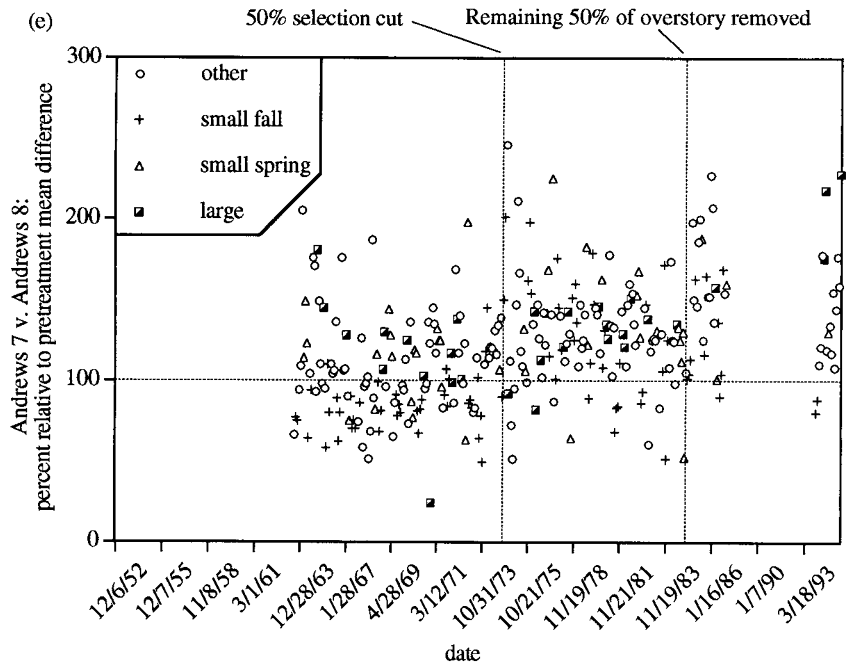


Figure 5. (continued)

The greater the role of transpiration in the water balance in a particular location, season, or time after treatment, the greater is the evapotranspiration effect. Thus in three of the four 100%-cut basin pairs which had south facing exposures (Andrews 6 and half of Andrews 10, Figure 4) or were in drier climate settings (Coyote 3, Figure 2), small, spring discharges increased significantly for the first decade after cutting (Table 4). Also, the magnitude of increase in small, fall peak discharges was greater in basins with relatively dry climates (Coyote versus Andrews) and greater in 100%-clear-cut than 50%- or 25%-cut basins at a given latitude. Increases in small, fall events were transitory, and, where records were long enough to discern it, the timing of the return of small, fall peak discharge events to pretreatment levels coincided with forest canopy regrowth in the treated basins [*Halpern*, 1989; *Halpern and Spies*, 1995; *Bredensteiner*, 1998]. Moreover, in those basins where small, fall peak discharges increased initially and records were collected for two or more decades after treatment (Andrews basins), small, fall peak discharge events returned to pretreatment levels where relatively little forest canopy had been removed (Andrews 3) or where conifer canopy recovery was vigorous (Andrews 6) but recovered more slowly or not at all where conifer canopy recovery was slow (Andrews 1 and Andrews 10).

The greater the role of cloud water interception in the water balance prior to forest canopy removal, the greater is the reduction in moisture inputs after forest removal, offsetting the evapotranspiration effect. Thus in the Fox Creek basins, where low cloud is common and measurable cloud water interception (fog drip) occurs [*Harr*, 1982], small, fall peak dis-



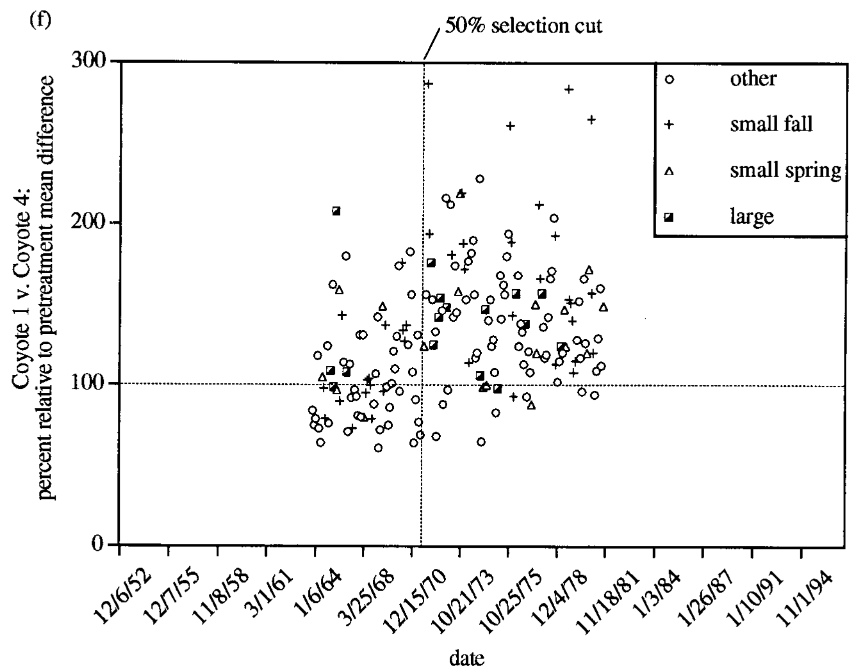


Figure 5. (continued)

charge events did not increase significantly after 25% patch cutting, whereas the same treatment produced 31–71% increases in other sites (Andrews 3 and Coyote 2, Table 3). Moreover, very small, summer events decreased by more than 40% in the first 2 years after forest canopy removal in the Fox Creek basins.

5.2. Snowpack Dynamics and Forest Canopy Removal and Recovery

An effect of forest canopy removal upon snowpack dynamics and, consequently, upon peak discharges has been inferred or predicted for Pacific Northwest forests, where snowpacks frequently are melted by warm, rain events [*Harr*, 1981, 1986]. If forest canopy removal increases snowpacks and snowmelt in these gaps is synchronized with the peak precipitation, forest canopy removal may increase peak discharges [*Harr*, 1986]. However, increases in snowpack depth without synchronized melting might not affect peak discharges, and precipitation absorbed by the snowpack along with delayed melting could even decrease peak discharges [*Harr and McCorison*, 1979]. In this study, when old-growth conifer forests in the Pacific Northwest were removed, the snowpack dynamics effect produced moderate increases in peak discharges of rain-on-snow events. However, the snowpack dynamics effect varied according to the susceptibility to melting of the snowpack and the relative volumes of the snowmelt, the precipitation event, and the soil moisture reservoir.

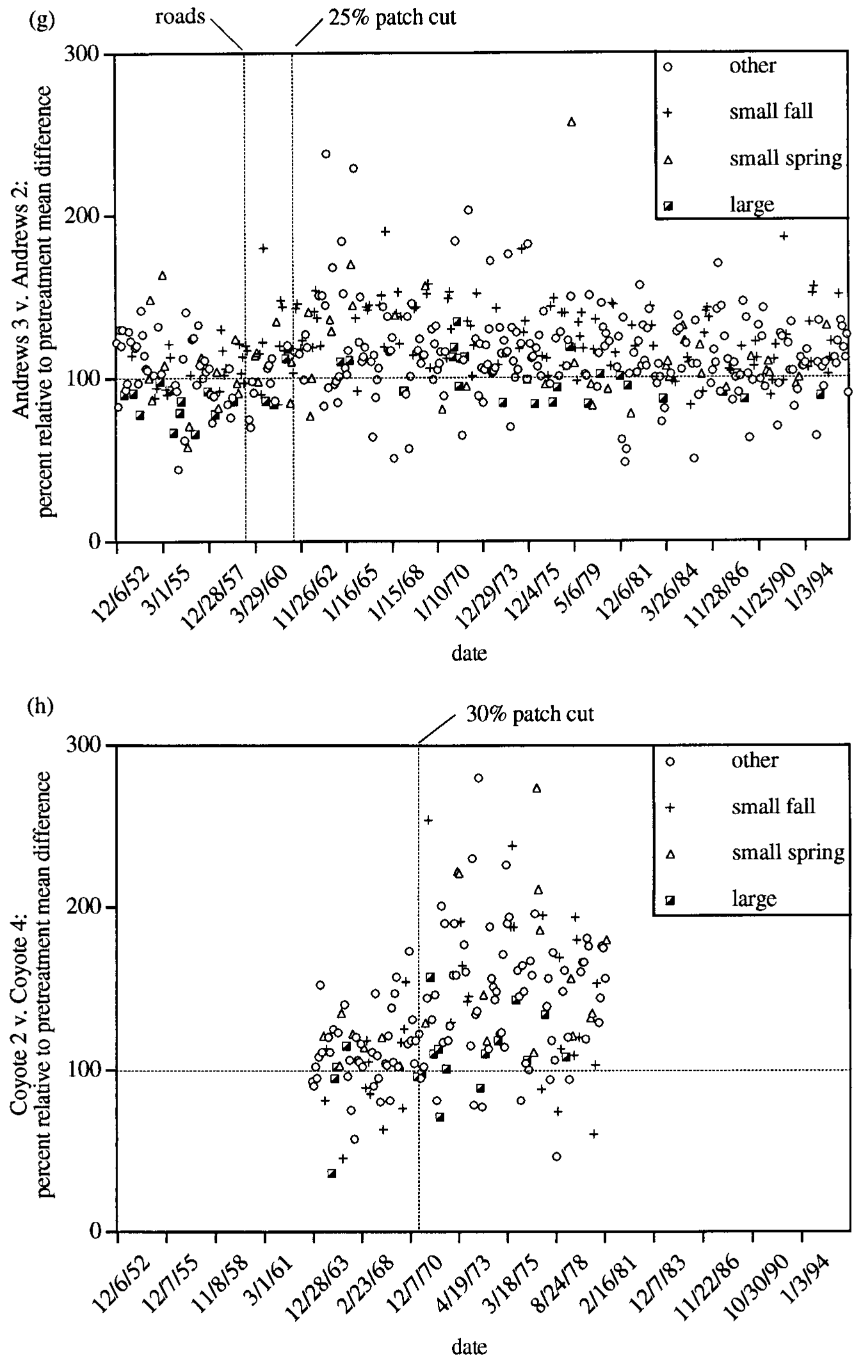
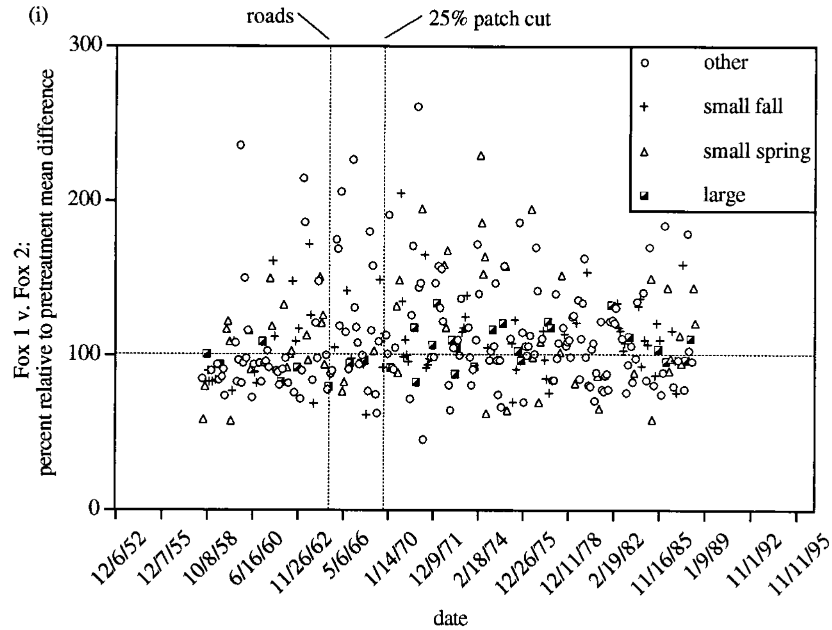


Figure 5. (continued)

To affect the peak discharge signal, snowpack melting must be large relative to other water balance components, such as precipitation event inputs, evapotranspiration losses, and soil moisture storage (Figure 1). In conifer forests of the Pacific Northwest this occurs during the winter when warm windy conditions induce snowpack melting coincident with rainfall [*Harr*, 1981]. After forest canopy removal, peak discharges classified as rain or mixed events did not change significantly, but rain-on-snow events increased by 26–31% in four of five treated basins in the Andrews. This result indicates, as suggested by *Harr* [1986], that snowpack volume, or at least the amount of snowmelt coinciding with the peak discharge, was increased after forest canopy removal. This finding is consistent with the notion, suggested by *Harr* [1986] and quantified by *Marks et al*. [1998], that energy exchanges between the snowpack and warm winds during rain-on-snow events involve greater latent heat releases from condensation on snow in canopy gaps than on snow under forest canopies, enhancing snowmelt and contributing to greater peak discharges from clear-cuts than from adjacent forests.

The greater the role of snowmelt in runoff from a particular location, season, or time after treatment, the greater is the snowpack dynamics effect. Thus, holding the amount of forest canopy removal constant (100% clear-cut), at low elevations



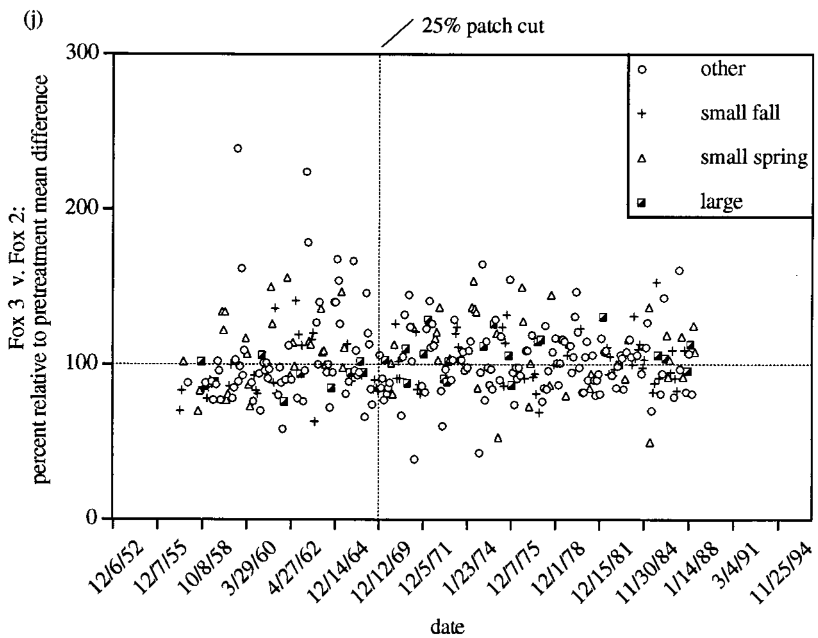


Figure 5. (continued)

(Andrews 1), winter rain-on-snow events increased by only a few percent more than winter rain events, but at high elevations (Andrews 6), winter rain-on-snow events increased by several times more than winter rain events. Although small sample sizes precluded statistical tests of rain-on-snow events by event size, percent increases of large rain-on-snow events appeared to be smaller than for rain-on-snow events of all sizes in the three 100%–clear-cut basins in the Andrews basins. If so, this indicates that the influences of snowmelt and changes in snowpack dynamics decline with increasing size of peak discharge event, as precipitation inputs and stored soil moisture increase.

5.3. Subsurface Flow Interception, Roads, and Stream Networks

Some studies have proposed that forest roads on steep slopes may intercept subsurface flow and hasten its arrival as surface flow in stream channels [*Burroughs et al.*, 1971; *Megahan and Clayton*, 1983; *King and Tennyson*, 1984; *Montgomery*, 1994; *Wemple et al.*, 1996; *Bowling and Lettenmaier*, 1997; *Wemple*, 1998], possibly contributing to increased peak discharges [*Jones and Grant*, 1996]. In basins with roads in this study, the subsurface flow interception effect produced moderate (13–36%) increases of peak discharge events with >1-year return periods, and increases persisted for decades. However, road effects on subsurface flow interception appeared to vary according to road design and placement relative to soil depth and hillslope position.

To affect large peak discharge events, subsurface flow interception by roads must be large relative to other water balance components, such as precipitation event inputs, snowmelt, and soil moisture storage (Figure 1). During peak discharge events in these landscapes, a transient, heterogeneous saturated zone

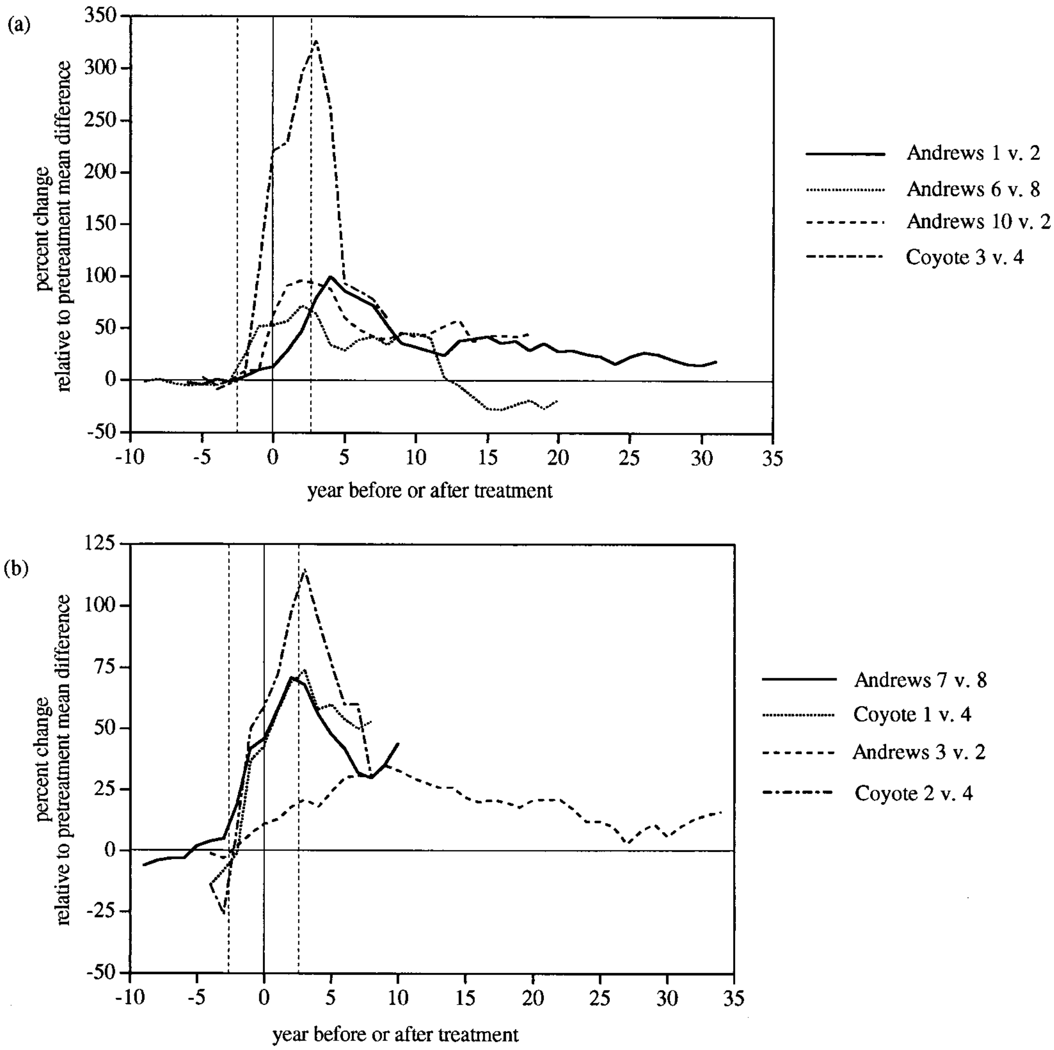


Figure 6. Smoothed trends in peak discharge events by year before or after forestry treatment, expressed as percent change, and grouped by event type, percent forest canopy removed, and presence of roads: (a) small, fall events in 100%–clear-cut basins, (b) small, fall events in 25–50%-cut basins with roads, (c) large events in 50–100%-cut basins with roads, and (d) large events in 25%-cut basins with roads. Each smoothed line is a running mean (5 years for small events and 7 years for large events) of percent change for a given subpopulation of events in a treated-control basin pair. Percent change was calculated as described in the text. Widths of moving windows (indicated by vertical dashed lines) make the treatment effect appear before year 0.

develops in soil profiles, as shown by *Harr* [1977] in Andrews 10. Road cuts intercept water flowing in this zone, and road ditches route the intercepted water to stream channels, as shown by *Wemple* [1998] in Andrews 3. However, overland flow from road surfaces in Andrews 3 was equivalent to less than 5% of runoff measured at road culverts [*Wemple*, 1998]. After road construction in conjuction with forest canopy removal, large (>1 year) peak discharges increased by 13–36% in seven of eight basins with roads. Thus during large events, roads may intercept sufficient water from the saturated soil zone to affect peak discharges.

Road configuration along hillslopes may influence the magnitude of the subsurface flow interception effect. Of the subsurface flow in Andrews 3 that was intercepted along roads and delivered to channels coincident with the peak discharge, the greatest amounts were contributed by midslope road segments (i.e., segments perpendicular to subsurface flow paths, midway between ridges and major stream channels) whose road cuts intersected most of the soil profile [*Wemple*, 1998]. Densities of midslope roads may explain why large peak discharges increased by 16% after 25% forest removal at Andrews 3, which has two tiers of midslope roads with many deep road cuts [*Wemple*, 1998], whereas large peak discharges increased by only 25% after 100% clear-cutting at Andrews 1, which lacks roads (Figure 4). Relative densities of midslope roads also may explain why large events increased by 27% at Andrews 7 (100% cut in two cuts separated by a decade, one tier of midslope road constructed in 1984), whereas they increased by only 16% at Andrews 6 (100% clear-cut, partial tier of midslope roads) (Figure 4). Higher densities of midslope roads also may explain 36% increases in large events at Coyote 2 (25% cut, three tiers of midslope roads) compared to 26% increases in large events in Coyote 3 (100% cut, no midslope roads) (Figure 4).

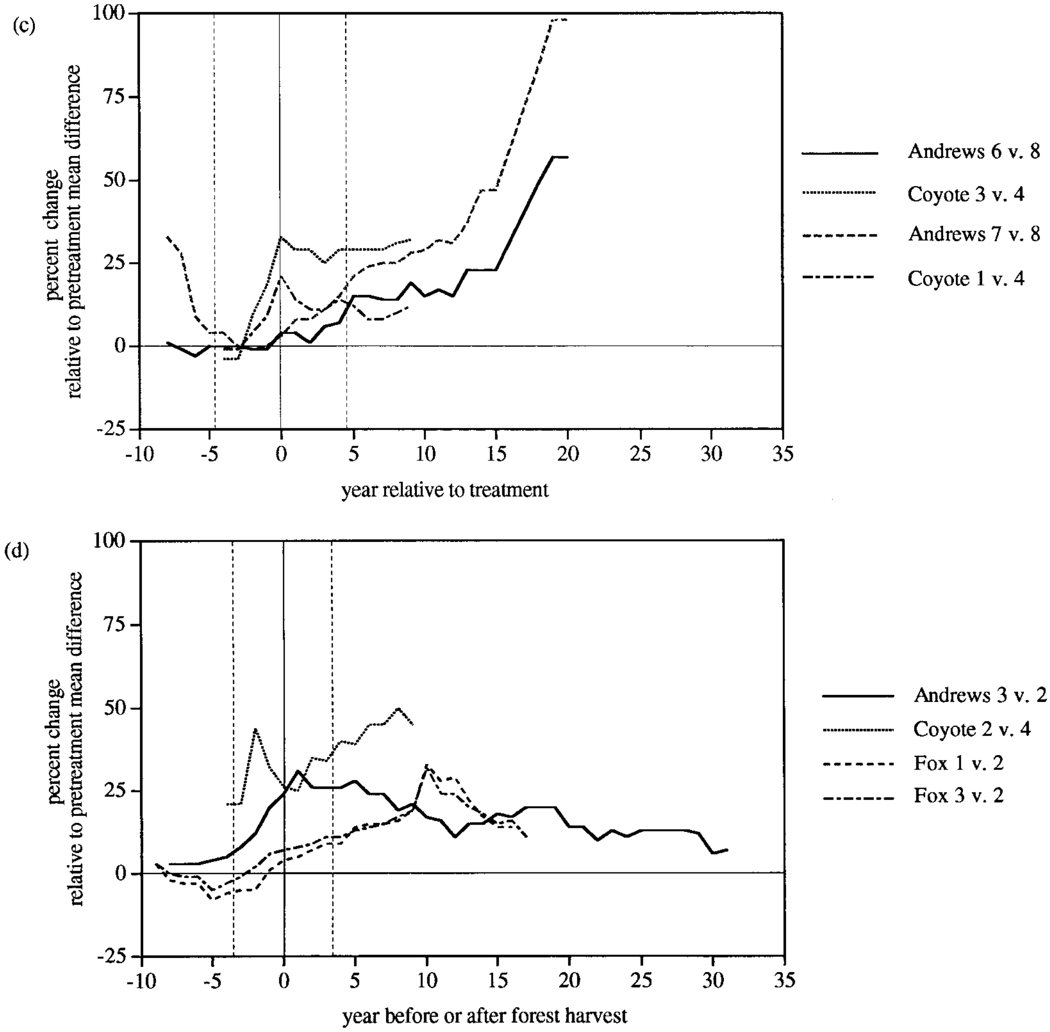


Figure 6. (continued)

5.4. Future Work

The basins examined in this study represent only a portion of the range of geographic and climatic conditions under which forest removal and roading occur, and therefore they illustrate only some of the possible hydrologic mechanisms that may be affected. Despite 50-year records some important classes of events, such as extreme floods or large rain-on-snow events, are so rare that it is difficult to assess the statistical significance of changes. Moreover, forest removal and road construction practices are quite different today than in the past. Even within the Pacific Northwest, for example, different hydrologic responses than found in this study may occur where the snowpack is not melted by rain (e.g., eastern Oregon and Washington, Idaho), large rain events occur without snow (e.g., Oregon Coast Range), or cloud water interception is an important component of forest hydrology (e.g., coastal fog zone). Also, forestry treatments have evolved from clear-cutting of old-growth forests and ambitious road construction projects, common in the 1950s and 1960s when these experiments were begun, to thinning of second-growth stands, ridgetop roads, and road restoration programs today. Forestry treatments in small experimental basins involve two kinds of change, namely, canopy reduction and changes in drainage. Examination of carefully segregated event types over time, such as in this study, reveals magnitudes and directions of responses of various hydrologic processes operating at the scale of small basins.

This study focused upon causes of peak discharge responses to forestry treatments, but the geomorphic and biological consequences of hydrologic responses are important, too. Ecological implications of streamflow changes on stream and riparian habitat depend upon interactions among flood peaks, sediment, wood, and riparian vegetation. As this study showed, streamflow is inherently variable, and disentangling complex natural from human-induced effects represents a continuing challenge for hydrologists, geomorphologists, and ecologists.

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References

Adams, P. W., A. L. Flint, and R. L. Fredriksen, Long-term patterns in soil moisture and revegetation after clearcut of a Douglas-fir forest in Oregon, *For. Ecol. Manage.*, *41*, 249–263, 1991.

Bowling, L. C., and D. P. Lettenmaier, Evaluation of the effects of forest roads on streamflow in Hard and Ware Creeks, Washington, *Water Resour. Ser.*, *Tech. Rep. 155*, 189 pp., Dep. of Civ. Eng., Univ. of Wash., Sept., 1997.

Bredensteiner, K. C., A distributed-parameter hydrologic model approach to evaluate vegetation succession interactions with hydrology in two small experimental basins, western Cascades, Oregon, M.S. thesis, Dep. of Bot. and Plant Pathology, Oreg. State Univ., Corvallis, 1998.

Burroughs, E. R., Jr., M. A. Mardsen, and H. F. Haupt, Volume of snowmelt intercepted by logging roads, paper presented at American Society of Civil Engineers National Water Resources Engineering Meeting, Phoenix, Ariz., 1971.

Dunne, T., and L. B. Leopold, Water in environmental planning, W. H. Freeman, New York, 1978.

Dyrness, C. T., The effect of logging and slash burning on understory vegetation in the H. J. Andrews Experimental Forest, *Res. Note PNW-31*, U.S. For. Serv. Pac. Northwest For. and Range Exp. Stn., Corvallis, Oreg., 1965.

Dyrness, C. T., Hydrologic properties of soils on three small watersheds in the western Cascades of Oregon, *Res. Note PNW-111*, U.S. For. Serv. Pac. Northwest For. and Range Exp. Stn., Corvallis, Oreg., 1969.

Dyrness, C. T., Early stages of plant succession following logging burning in the western Cascades of Oregon, *Ecology*, *54*, 57–69, 1973.

Eberhardt, L. L., and J. T. Thomas, Designing environmental field studies, *Ecol. Monogr.*, *61*(1), 53–73, 1991.

Faustini, J. M., Stream channel response to peak flows in a fifth-order mountain watershed, Ph.D. dissertation, Dep. of Geosci., Oreg. State Univ., Corvallis, 2000.

Grant, G. E., and A. L. Wolff, Long-term patterns of sediment transport after timber harvest, western Cascade mountains, Oregon, USA, in *Sediment and Water Quality in a Changing Environment: Trends and Explanation*, *Publ. 203*, pp. 31–40, Int. Assoc. of Hydrol. Sci., Gentbrugge, Belgium, 1990.

Haan, C. T., *Statistical Methods in Hydrology*, Iowa State Univ. Press, Ames, 1977.

Halpern, C. B., Early successional patterns of forest species: Interactions of life history traits and disturbance, *Ecology*, *70*, 704–720, 1989.

Halpern, C. B., and T. A. Spies, Plant species diversity in natural and managed forests of the Pacific Northwest, *Ecol. Appl.*, *5*(4), 913–934, 1995.

Harr, R. D., Forest practices and streamflow in western Oregon, *Gen. Tech. Rep. PNW-49*, U.S. For. Serv. Pac. Northwest For. and Range Exp. Stn., Corvallis, Oreg., 1976a.

Harr, R. D., Hydrology of small forest streams in western Oregon, *Gen. Tech. Rep. PNW-55*, U.S. For. Serv. Pac. Northwest For. and Range Exp. Stn., Corvallis, Oreg., 1976b.

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

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

Harr, R. D., Fog drip in the Bull Run municipal watershed, Oregon, *Water Resour. Bull.*, *18*(5), 785–789, 1982.

Harr, R. D., Effects of clearcutting on rain-on-snow runoff in western Oregon: A new look at old studies, *Water Resour. Res.*, *22*, 1095–1100, 1986.

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, *Res. Pap. PNW-249*, U.S. For. Serv. Pac. Northwest Res. Stn., Corvallis, Oreg., 1979.

Harr, R. D., A. Levno, and R. Mersereau, Streamflow changes after logging 130-yr-old Douglas-fir in two small watersheds, *Water Resour. Res.*, *18*, 637–644, 1982.

Hewlett, J. D., and A. R. Hibbert, Increases in water yield after several types of forest cutting, *Q. Bull. Int. Assoc. Sci. Hydrol.*, *6*(3), 5–17, 1961.

Hicks, B. J., R. L. Beschta, and R. D. Harr, Long-term changes in streamflow following logging in western Oregon and associated fisheries implications, *Water Resour. Bull.*, *27*, 217–226, 1991.

Holland, P. W., Statistics and causal inference, *J. Am. Stat. Assoc.*, *81*, 945–960, 1986.

Jones, J. A., and G. E. Grant, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon, *Water Resour. Res.*, *32*, 959–974, 1996.

Jones, J. A., F. J. Swanson, B. C. Wemple, and K. Snyder, Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks, *Conserv. Biol.*, *14*(1), 76–85, 2000.

King, J. G., and L. C. Tennyson, Alteration of streamflow characteristics following road construction in North Central Idaho, *Water Resour. Res.*, *20*, 1159–1163, 1984.

Law, F., Measurement of rainfall, interception, and evaporation losses in a plantation of Sitka spruce trees, *Publ. 44*, pp. 397–411, Int. Assoc. of Sci. Hydrol., Gentbrugge, Belgium, 1958.

Leavesley, G. H., R. W. Lichty, B. M. Troutman, and L. G. Saindon, Precipitation-runoff modeling system: User's manual, *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *83-4238*, 207 pp., 1983.

Lee, R., The hydrologic importance of transpiration control by stomata, *Water Resour. Res.*, *3*, 737–752, 1967.

Leopold, L., Hydrologic research on instrumented watersheds, paper presented at New Zealand Symposium on Experimental and Representative Research Basins, Int. Assoc. of Sci. Hydrol., Wellington, Dec. 1–14, 1970.

Marks, D., J. Kimball, D. Tingey, and T. Link, The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: A case study of the 1996 Pacific Northwest flood, *Hydrol. Processes*, *12*, 1569–1587, 1998.

Marshall, J. D., and R. H. Waring, Comparative methods of estimating leaf area in old-growth Douglas-fir, *Ecology*, *67*, 975–979, 1986.

Megahan, W. F., and J. L. Clayton, Tracing subsurface flow on road-cuts on steep forested slopes, *J. Soil Sci.*, *SA 47*(6), 1063–1067, 1983.

Miller, R. G., Jr., *Simultaneous Statistical Inference*, Springer-Verlag, New York, 1980.

Montgomery, D. R., Road surface drainage, channel infiltration, and slope instability, *Water Resour. Res.*, *30*, 1925–1932, 1994.

Neter, J., W. Wasserman, and M. H. Kutner, *Applied Linear Statistical Models: Regression, Analysis of Variance, and Experimental Design*, 3rd ed., Irwin, Homewood, Ill., 1990.

Oberlander, G. T., Summer fog precipitation on the San Francisco peninsula, *Ecology*, *37*, 851–852, 1956.

Patric, J. H., Rainfall interception by mature coniferous forests of southeast Alaska, *J. Soil Water Conserv.*, *21*, 229–231, 1966.

Perkins, R. M., Climate and physiographic controls on peakflow generation in the western Cascades, Oregon, Ph.D. dissertation, Dep. of For. Sci., Oreg. State Univ., Corvallis, 1997.

Post, D. A., G. E. Grant, and J. A. Jones, Ecological hydrology: Expanding opportunities in hydrologic sciences, *Eos Trans. AGU*, *79*(43), 517, 526, 1998.

Rothacher, J., Net precipitation under a Douglas fir forest, *For. Sci.*, *9*, 423–429, 1963.

Rothacher, J., Streamflow from small watersheds on the western slope of the Cascade Range of Oregon, *Water Resour. Res.*, *1*, 125–134, 1965.

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

Rothacher, J., Does harvest in west slope Douglas-fir increase peak flow in small forest streams?, *Res. Pap. PNW-163*, U.S. For. Serv. Pac. Northwest For. and Range Exp. Stn., Corvallis, Oreg., 1973.

Sherrod, D. R., and J. G. Smith, Preliminary map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon, *U.S. Geol. Surv. Open File Rep.*, *89-14*, 1989.

Sinton, D. S., J. A. Jones, F. J. Swanson, and J. Ohmann, Windthrow disturbance, forest composition and structure in the Bull Run basin, Oregon, *Ecology*, in press, 2000.

Thomas, R. B., and W. F. Megahan, Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion, *Water Resour. Res.*, *34*, 3393–3403, 1998.

Thornthwaite, C. W., and J. R. Mather, The water balance, *Lab. of Climatol. Publ. 8*, Centerton, N. J., 1955.
U.S. Forest Service, Soil resources inventory, Willamette National Forest, Pacific Northwest Region, Eugene, Oreg., 1973.
Waring, R. H., and J. F. Franklin, Evergreen coniferous forests of the Pacific Northwest, *Science*, *204*, 1380–1386, 1979.
Waring, R. H., and W. H. Schlesinger, *Forest Ecosystems: Concepts and Management*, Academic, San Diego, Calif., 1985.
Wemple, B. C., Investigations of runoff and sediment production from forest roads in western Oregon, Ph.D. dissertation, Dep. of For. Sci., Oreg. State Univ., 1998.
Wemple, B. C., J. A. Jones, and G. E. Grant, Hydrologic integration of forest roads with stream networks in two forested basins in the western Cascades of Oregon, *Water Resour. Bull.*, *32*, 1195–1207, 1996.
Wilkinson, L., G. Blank, and C. Gruber, Desktop data analysis with Systat, Prentice-Hall, Englewood Cliffs, N. J., 1996.

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