Extreme flood sensitivity to snow and forest harvest, western Cascades, Oregon, United States

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[1] We examined the effects of snow, event size, basin size, and forest harvest on floods using >1000 peak discharge events from 1953 to 2006 from three small (<1 km^2), paired-watershed forest-harvest experiments and six large (60–600 km^2) basins spanning the transient (400–800 m) and seasonal (>800 m) snow zones in the western Cascades of Oregon. Retrospectively classified rain-on-snow events delivered 75% more water to soils than rain events. Peak discharges of >10 year rain-on-snow events were almost twice as high as rain peaks in large basins but only slightly higher in small basins. Peak discharges of >1 year rain-on-snow events increased slightly (10%–20%) after logging in small basins, but small basin peaks do not account for the magnitudes of large basin rain-on-snow peak discharges during >1 year floods. In extreme floods, despite very high infiltration capacity, high soil porosity, and steep hillslope gradients, prolonged precipitation and synchronous snowmelt produce rapid, synchronized hydrograph responses to small variations in maximum precipitation intensity. At the large basin scale, forest harvest may increase the area of snowpack and simultaneous snowmelt, especially in elevation zones normally dominated by rain and transient snow, thereby increasing large basin peaks without producing very large percent increases in small basin peaks. Further work is needed to describe water flow paths in melting snowpack, snow cover and the area experiencing snowmelt, synoptic peak discharges, and routing of flood peaks through the stream network during extreme rain-on-snow floods. The evolving structure of the forest on the landscape is a potentially very important factor influencing extreme rain-on-snow floods.

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1. Introduction

[2] Rain-on-snow floods are some of the most extreme precipitation-driven floods that occur on Earth. Climate and topography combine to create extreme floods; the highest 1% of floods on record in >500 km^2 basins in the United States are concentrated in the Oregon Cascade Range and other mountain ranges where large storms produce sustained rainfall and sometimes snowmelt for multiple days over broad areas [*O'Connor and Costa*, 2004]. Rain-on-snow conditions dominate flood-generation processes in mountainous temperate and boreal regions [*Loukas et al.*, 2000; *Merz and Blöschl*, 2003; *McCabe et al.*, 2007; *Yue and Gan*, 2009]. In the Pacific Northwest of the United States (PNW), rain-on-snow floods are responsible for major fluvial modifications affecting channels, riparian zones, and road and bridge infrastructure.

[3] Despite general agreement that rain-on-snow conditions produce extreme floods and that forest harvest alters snowpack dynamics, no satisfactory mechanism has been proposed to connect plot-scale snowpack dynamics to regional forest harvest and extreme rain-on-snow floods. Rain-on-snow events may produce extreme peak discharges because (1) snowmelt runoff augments precipitation and peak discharge magnitudes or (2) simultaneous snowmelt over a large area synchronizes peak discharges among tributary basins. If mechanism 1 drives extreme floods, we would expect to see increased peak discharge magnitudes at all spatial scales during rain-on-snow compared to rain events. On the other hand, if mechanism 2 drives extreme floods, we would expect to see more synchronized peak discharges during extreme rain-on-snow events, higher peak discharges during large rain-on-snow compared to large rain events at the large basin scale, and no differences in peak magnitudes between large rain-on-snow and large rain events at the small basin scale.

[4] The two mechanisms (the rate of snowmelt runoff versus the timing and spatial extent of snowmelt) are evident in observations from a 50 year rain-on-snow flood at Lookout Creek, a 62 km^2 basin in the western Cascades of Oregon (Figure 1) [*Dyrness et al.*, 1996]. In this extreme flood, continuous precipitation over 2 days culminated in maximum intensities of 9.66 mm/h at 7:00 P.M. on 6 February and 10.94 mm/h at 2:00 A.M. on 7 February, 9 h before the 11 A.M. peak at Lookout Creek (Figure 1a).

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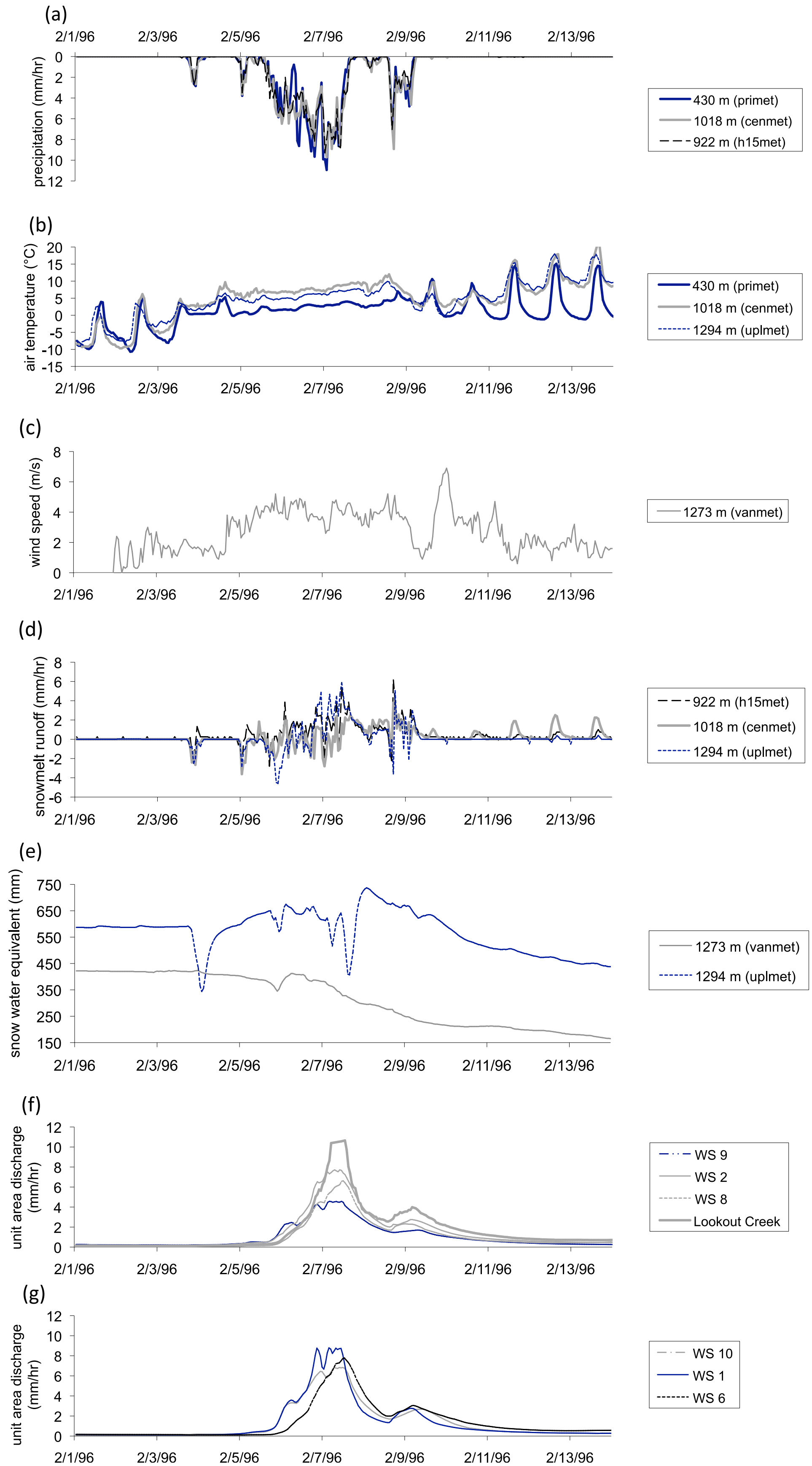
(a)
precipitation (mm/hr)
430 m (primet)
1018 m (cenmet)
922 m (h15met)
(b)
air temperature (°C)
430 m (primet)
1018 m (cenmet)
1294 m (uplmet)
(c)
wind speed (m/s)
1273 m (vanmet)
(d)
snowmelt runoff (mm/hr)
922 m (h15met)
1018 m (cenmet)
1294 m (uplmet)
(e)
snow water equivalent (mm)
1273 m (vanmet)
1294 m (uplmet)
(f)
unit area discharge (mm/hr)
WS 9
WS 2
WS 8
Lookout Creek
(g)
unit area discharge (mm/hr)
WS 10
WS 1
WS 6
2/1/96
2/3/96
2/5/96
2/7/96
2/9/96
2/11/96
2/13/96

Figure 1

Air temperature showed diel fluctuations indicative of clear air until 3 February, then rose above 0°C and remained above freezing. A temperature inversion persisted from 3 to 9 February (Figure 1b). Wind speed rose to 4 m/s late on 5 February and was sustained until midday of 9 February, blowing consistently from the WSW (250°) (Figure 1c). Snowmelt runoff in lysimeters (output > precipitation, values > 0) at 1000–1300 m in the seasonal snow zone began on the afternoon of 6 February; reached rates of up to 4 mm/h at 4:00, 8:00, and 10:00 AM on 7 February; and persisted during the peak at Lookout Creek on 7 February (Figure 1d). Snowmelt runoff reduced snow water equivalent just before the peak on 7 February (Figure 1e). During the peak at Lookout Creek from 11:00 A.M. to 1:00 P.M. on 7 February, discharge (>10.65 mm/h) equaled maximum precipitation intensities and exceeded peak discharges from small control basins (Figures 1a and 1f). Peak discharges from small treated basins exceeded peak discharges from controls but were lower than the peak at Lookout Creek (Figure 1g). At the end of the storm on 9 February, precipitation ceased and wind speed dropped and then increased as the wind shifted to the ENE, bringing a return of clear skies, diel temperature fluctuations, and diel snowmelt pulses (Figures 1a–1d). Snowmelt runoff rates of 2–4 mm/h during the peak (Figure 1e) and higher peaks at harvested versus control small basins (Figure 1g) are consistent with mechanism 1, and the high correlations among stations for precipitation, air temperature, snowmelt runoff, and streamflow (Figures 1a, 1b, 1d, 1f, and 1g) are consistent with mechanism 2. Other mechanisms, such as orographic effects, are not apparent in field observations, and are not explored here.

[5] Clear-cutting of forests and creation of large gaps where young forest plantations are regenerating alter snowpack dynamics and arguably may increase rain-on-snow peak discharges both by increasing snow water storage and melt rates (mechanism 1) or by increasing the area over which a snowpack accumulates and melts synchronously (mechanism 2) [*Harr*, 1986; *Harr and Coffin*, 1992]. Forest harvest has occurred in the PNW since European colonization in the mid-1800s. Clear-cutting of native old and mature age-class forests in the PNW accelerated after World War II but nearly ceased on public forestland in 1990 to afford protection for endangered species. Larger snowpacks accumulate in openings, and during precipitation events, they melt faster than under mature forest [*Marks et al.*, 1998; *Storck et al.*, 2002] (mechanism 1). However, studies using models [*Whitaker et al.*, 2002; *Schnorbus and Alila*, 2004; *Tonina et al.*, 2008] and streamflow records [*Jones and Grant*, 1996; *Thomas and Megahan*, 1998; *Beschta et al.*, 2000; *Bowling et al.*, 2000; *Jones*, 2000] have found mixed responses of large rain-on-snow peak discharges to forest harvest.

[6] Climate variability and warming are expected to modify snowpacks and may alter the frequency and magnitude of rain-on-snow floods in the PNW, western United States, and globally [*Loukas et al.*, 2002; *Hamlet and Lettenmaier*, 2007; *McCabe et al.*, 2007; *Adam et al.*, 2009]. Floods involving snowmelt, including rain-on-snow, tend to display simple scaling over a range of basin sizes [*Gupta and Dawdy*, 1995; *Yue and Gan*, 2009]. Climate warming is expected to affect transient (short-duration, midelevation) snow more than seasonal snow [*Nolin and Daly*, 2006; *Cuo et al.*, 2009; *Adam et al.*, 2009]. To account for climate effects on floods, studies increasingly separate rain-on-snow from rain peak discharge events [*Loukas et al.*, 2000; *Merz and Blöschl*, 2003; *Perkins and Jones*, 2008].

[7] This study examined evidence for mechanism 1 (snowpack effects on peak magnitude) and 2 (snowpack effects on peak timing) to explain extreme rain-on-snow floods using long-term streamflow and meteorological records from three small paired-watershed forest harvest experiments in the H.J. Andrews Experimental Forest and from large basins in the western Cascade Range of Oregon. We asked the following questions.

[8] 1. What are the peak discharge and peak timing of rain versus rain-on-snow events in small (<1 km^2) and large (60–600 km^2) basins in the western Cascades of Oregon?

[9] 2. How does forest harvest affect the relationship between large and small basins during rain-on-snow events of various sizes?

2. Study Site

[10] The study was conducted in a 4500 km^2 area in the western Cascade Range of Oregon containing six large (60–600 km^2) and six small (0.09–1 km^2) basins (Table 1 and Figure 2). The six large basins drain west from the crest of the ancestral (25–35 Ma) western Cascades (the highly dissected area in the center of the image) and in several cases from the young (<2 Ma) high Cascade platform (Figure 2a). The small basins are part of three paired basin experiments in Lookout Creek and Blue River basins, spanning the transient (WS 9, WS 10), transient to seasonal (WS 1, WS 2), and seasonal (WS 6, WS 8) snow zones within Lookout Creek (LO) and Blue River (BR) (Figure 2b). The large basins are the largest unregulated (above dams) basins with gaging records in the Willamette National Forest, and they range from 400 to 3200 m in elevation, encompassing zones with permanent, seasonal, and transient snow (Figure 3).

[11] Mean annual precipitation ranges from 2200 to 2700 mm, depending on orographic and rain shadow effects, and >80% of precipitation occurs from November to April

Figure 1. Hourly values of precipitation, air temperature, wind speed, snowmelt runoff, snow water equivalent, and streamflow at multiple sites during extreme rain-on-snow flood of February 1996 in the Lookout Creek basin, OR. Locations of gaging and meteorological stations are in Figure 2; their elevations are depicted in Figure 3. (a) Event precipitation, (b) air temperature, (c) wind speed, (d) snowmelt runoff (snow lysimeter output minus precipitation), (e) snow water equivalent, and (f and g) unit-area streamflow. Throughout the event (from 5 to 8 February), there were strong correlations among stations for hourly precipitation ($r > 0.90$), hourly air temperatures ($r > 0.77$ for primet versus cenmet, $r > 0.91$ for cenmet versus h15met), hourly snowmelt runoff ($r > 0.53$ for h15met versus cenmet, $r > 0.42$ for cenmet versus uplmet), and hourly streamflow ($r > 0.89$ for WS 9 versus Lookout, $r > 0.95$ for WS 2 versus Lookout, $r > 0.98$ for WS 8 versus Lookout, $r > 0.98$ for WS 9 versus WS 10, $r > 0.92$ for WS 1 versus WS 2, $r > 0.98$ for WS 6 versus WS 8).

Table 1. Characteristics of Study Basins in the Cascade Range of Oregon

Name	Size (km^2)	Elevation (m) Minimum	Elevation (m) Maximum	Area in Seasonal Snow Zone[a] (%)	Streamflow Records[b] (Year)	Treatment (Extent, Type, Year)
Watershed 1	0.96	450	1027	35	1952–2007	100% harvest, 1962–1966
Watershed 2	0.60	572	1079	55	1952–2007	Control
Watershed 6	0.15	893	1029	100	1963–2007	100% harvest, 1974
Watershed 8	0.22	968	1182	100	1963–2007	Control
Watershed 9	0.09	438	731	0	1968–2007	Control
Watershed 10	0.10	471	679	0	1968–2007	100% harvest, 1975
Lookout Creek	62	400	1600	71	1949–2007	23% patch clear-cut, roads, 1950–1990
Upper Blue River	119	400	1600	75	1949–2007	25%, 1957–1990
N. Fork Willamette Middle Fork	637	350	2400	82	(1909) 1935–1994	17%, 1945–1990
Salmon Creek	313	350	2400	83	(1913) 1935–1994	20%, 1948–1990
N. Santiam River	559	400	3200	89	(1907) 1935–1991	12%, 1936–1990
Breitenbush River	280	400	2800	81	1933–1986, 1998–1991	15%, 1930–1990

[a]Defined as area above 800 m.
[b]Year in parentheses is first year of record; years separated by dashes are years of continuous record.

(Figure 4a). Precipitation is higher along the south-bounding ridge of Lookout Creek (uplmet, upper elevations of WS 1 and WS2), compared to north and northeast ridges (h15met, vanmet, cenmet, WS 6, and WS 8). Soil temperature falls below freezing for no more than 1–2 days per year on average at all sites (Andrews Forest, unpublished data, accessed in 2009). Precipitation type (rain, snow) varies with elevation and day of year. In the transient snow zone (400–800 m, primet, cs2met) snowpacks rarely last more than 1–2 weeks; in contrast, in the seasonal snow zone (>800 m), snowpacks persist from November to late April (cenmet) or June (vanmet, uplmet) (Figure 4b) [*Harr and McCorison*, 1979; *Perkins and Jones*, 2008]. Rain shadow effects reduce winter (December–February) streamflow at the small high-elevation basin (WS 8) relative to low-elevation basins (WS 2, WS 9), but snowpack storage and melt augment spring (March–June)

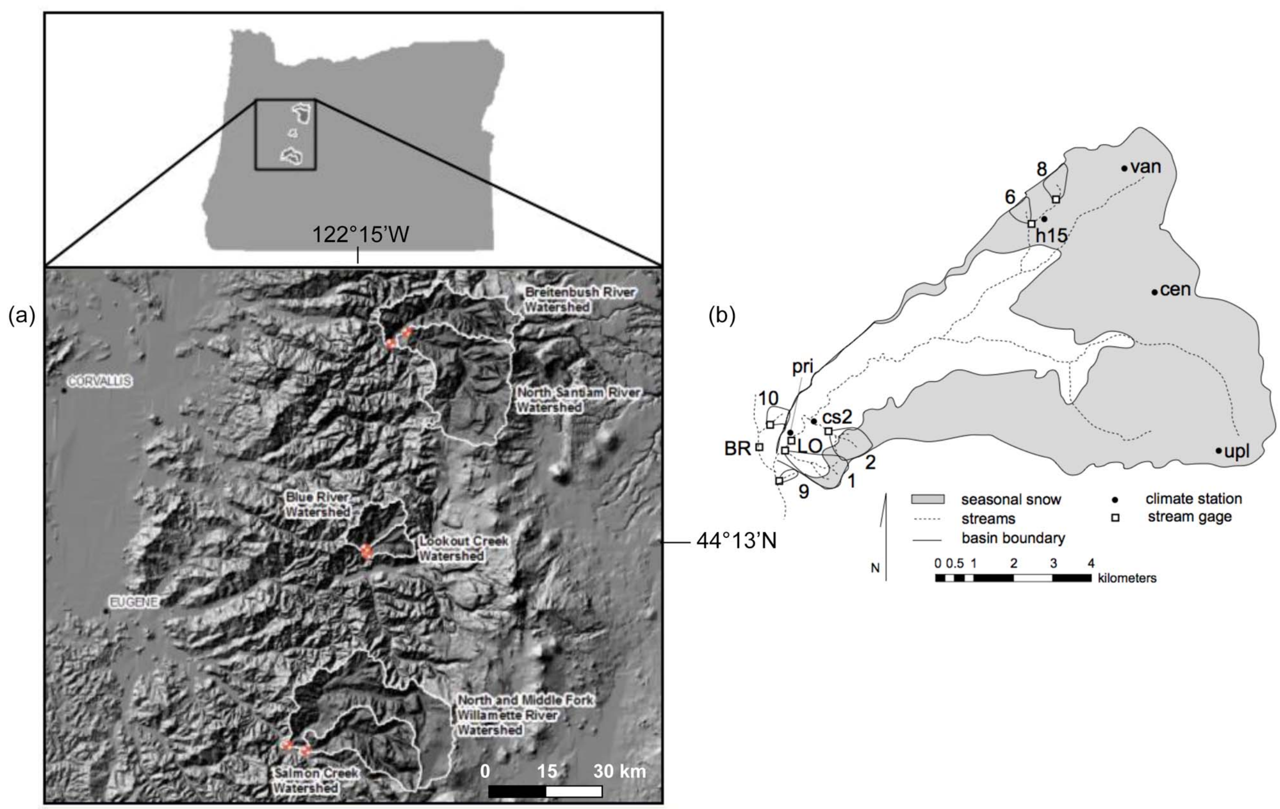

Figure 2. The study site consisted of six large basins and six small basins spanning 400–3200 m elevation on the west slope of the Cascade Range of Oregon. Basin sizes, elevation ranges, streamflow records, and land use histories are in Table 1; elevation ranges of basins and elevations of meteorological stations are in Figure 3. (a) Six large basins and (b) six small basins. Data from study sites in Figure 2a were obtained from USGS, and data from study sites in Figure 3b are at http://andrewsforest.oregonstate.edu/.

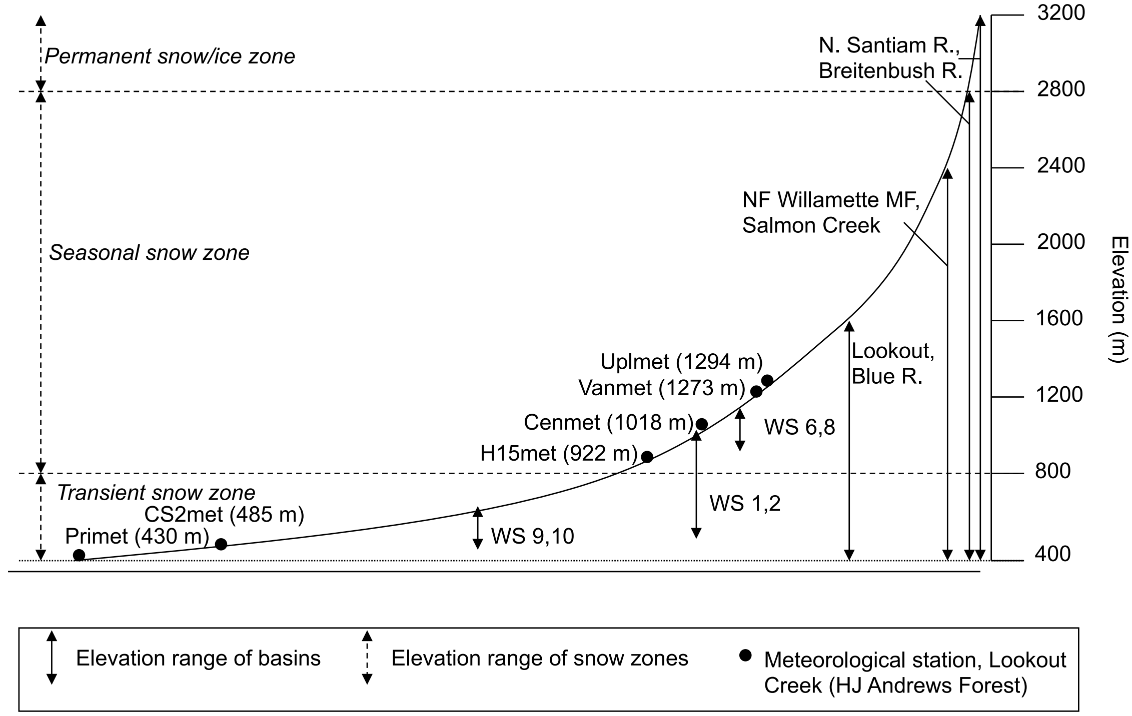

Figure 3. Schematic diagram of the longitudinal profiles of channels in the study basins, showing elevation ranges of study basins and elevation of meteorological stations relative to the elevation zones dominated by transient snow and seasonal snow on the west slope of the Cascade Range, OR. Zones are based on average snow water equivalent and duration of snowpack (see Figure 4).

streamflow from basins draining the seasonal snow zone (WS 8, Lookout) relative to those in the transient snow zone (WS 9) (Figure 4c). Overland flow rarely occurs because soil infiltration capacity (>20 cm h^{-1}) greatly exceeds maximum precipitation intensity (10 mm h^{-1}) [*Dyrness*, 1969; *U.S. Forest Service*, 1973].

[12] Geology and landform evolution in Lookout Creek have produced short, steep slopes on old highly weathered volcanic rocks, short gentle slopes on ridge-capping lava flows, and long steep slopes that span ridge-capping lava flows and highly weathered old volcanics [*Swanson and James*, 1975]. Small study basins represent all slope types in Lookout Creek: WS 9 and WS 10 have short, high-gradient (average 58%) slopes; WS 1 and WS 2 have long, high-gradient slopes (average 53% and 59%, respectively); and WS 6 and WS 8 have short, low-gradient (average 25%) slopes (Figure 2).

[13] Study basins are dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) forests from 400 to 1200 m and by mountain hemlock (*Tsuga mertensiana*) and Pacific silver fir (*Abies amabilis*) above 1200 m (Figure 3) [*Zobel et al.*, 1976]. Small treated basins were harvested in 1962–1966 (WS 1), 1974 (WS 6), and 1975 (WS 10). Up to 25% of large basins was harvested at rates of 0.5%–1% of basin area per year from the 1930s to 1990 (Table 1). Fifteen percent of Lookout Creek was in patch clear-cuts and roads at the beginning of the study (1963); this rose to 23% by the end of the study (2006). Regenerating forest consisted of shrub and deciduous tree species (e.g., *Ceanothus* spp., *Acer* spp., *Alnus rubra*) and planted Douglas-fir [*Dyrness*, 1965, 1973; *Halpern*, 1989; *Halpern and Spies*, 1995]. Many publications from these paired-watershed experiments indicate that forest harvest is associated with persistent increases in water yield in winter and >1 year peak flows in winter and spring, that postharvest summer water yield increases for only a few years and then declines below pretreatment levels, and that snow water storage and melt are significantly altered in clear-cut opening for several decades after forest harvest [*Harr and McCorison*, 1979; *Harr*, 1981; *Harr et al.*, 1982; *Harr*, 1986; *Harr and Coffin*, 1992; *Jones and Grant*, 1996; *Jones*, 2000; *Jones and Post*, 2004].

3. Methods

3.1. Hypotheses

[14] This study tested eight hypotheses.

[15] 1. Controlling for precipitation, more water is delivered to soils under rain-on-snow than rain conditions (H1).

[16] 2. Extreme floods are rain-on-snow events at all basins (H2).

[17] 3. Flood ranking of rain-on-snow events is correlated among basins based on the extent of their snow zones (H3).

[18] 4. Peak discharges of rain-on-snow events exceed those of rain events, controlling for precipitation and basin size (H4).

[19] 5. Peak discharges of extreme floods are less damped (H5) and more synchronized (H6) than small peak discharges as they are routed downstream from small control basins within large basins.

[20] 6. Forest cutting and the first few decades of regeneration increases the magnitude (H7) without altering the timing (H8) of the largest rain-on-snow peaks in small, logged basins relative to control (old-growth) basins.

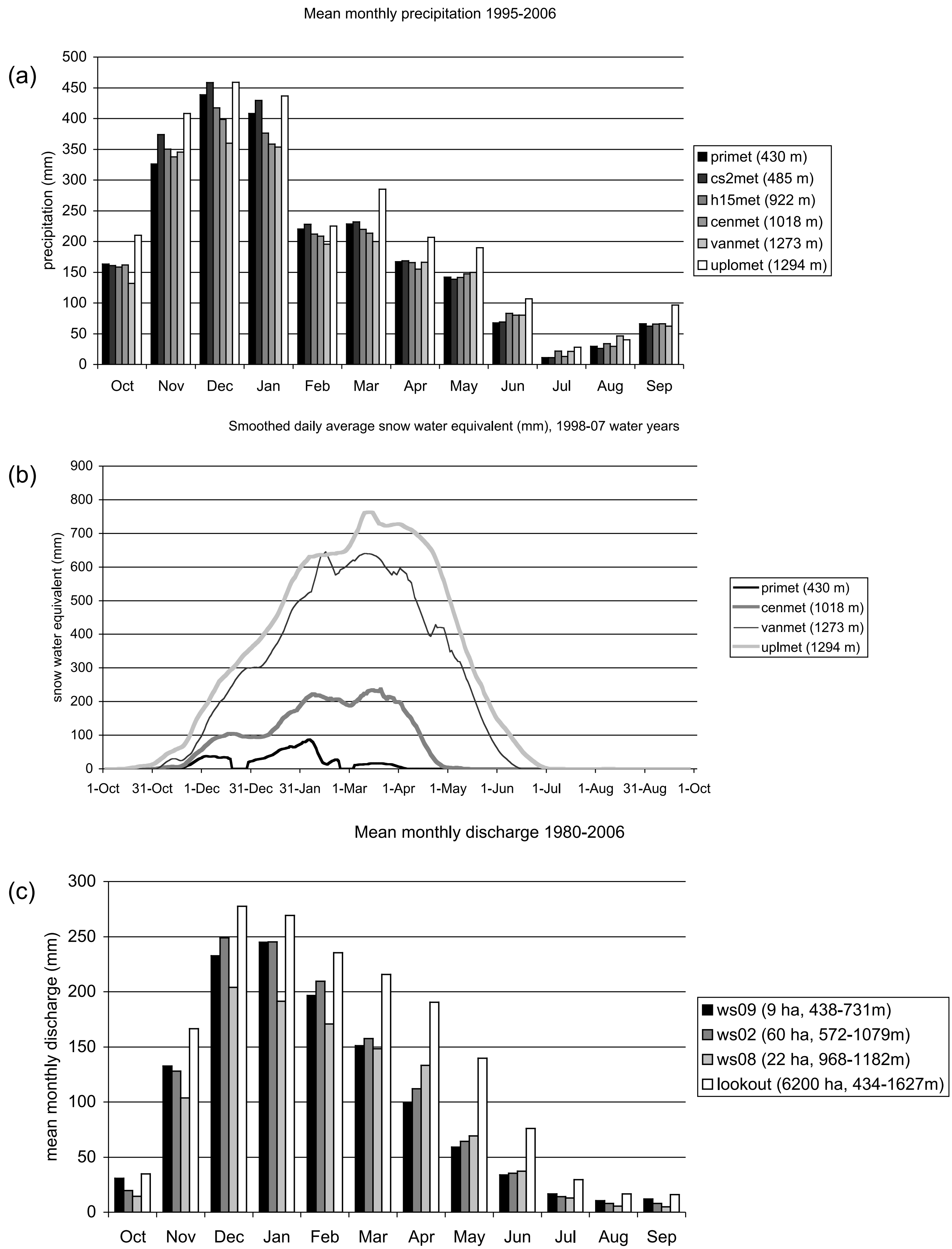

Figure 4. Precipitation, snow, and streamflow in study basins in Lookout Creek. (a) Mean monthly precipitation (1995–2006), (b) mean daily snow water equivalent (1998–2007), and (c) mean monthly streamflow (1980–2006) on a water-year basis (1 October to 30 September). Meteorological station locations and elevations are in Figures 2 and 3.

3.2. Data

[21] This study used data from 6 climate stations and 12 stream gaging stations (Figure 2). Streamflow data for up to 60 year periods (Table 1) were obtained from http://andrewsforest.oregonstate.edu/ (small basins) or original U.S. Geological Survey A-35 strip charts (large basins). Precipitation, air temperature, snow water equivalent, and snowmelt lysimeter data were obtained from meteorological stations (http://andrewsforest.oregonstate.edu/data/abstractdetail.cfm?dbcode=MS001&topnav=135) (Figures 2 and 3). Small basin peak discharge events were selected from continuous records using an automated selection procedure based on stage height changes, and the resulting peak discharges were matched by date and time with events at other basins following procedures in the study by *Jones and Grant* [1996], *Jones* [2000], and *Perkins and Jones* [2008]. Most peak discharges were matched within ±12 h, but some were up to ±36 h apart. For each peak discharge, event precipitation was determined using an automated peak discharge identification procedure and the precipitation record from the site nearest the stream gage (Figure 2) following procedures in the study by *Perkins and Jones* [2008]. In automated procedures, points in the continuous streamflow record were identified as peak discharges based on criteria for changes in stage height; these were corroborated using the Get-PQ routine that identifies peak discharges using stage height and precipitation timing [*Dripchak and Hawkins*, 1992]. The analysis used peak discharges for the period of overlapping records at all basins, including the first two or three decades after logging at the treated basins (1964–1992), supplemented with pretreatment data for WS 1 and WS 2 (1953–1961) and peaks producing >1 year floods at Lookout Creek from 1992 to 2006. Sample sizes of matched events were $n = 131$ (WS 9, WS 10), $n = 223$ (WS 1, WS 2), $n = 100$ (WS 6, WS 8), and $n = 49$ (Lookout Creek, Blue River).

3.3. Peak Discharge Event Classification

[22] Peak discharge events from WS 2, 8, and 9 were classified into categories based on soil moisture and snow water storage following *Perkins and Jones* [2008]. Because soil moisture and snow water equivalent measurements began after 1991, basinwide soil moisture and snow water equivalent were estimated retrospectively using a distributed hydrologic model (PRMS) [*Leavesley et al.*, 1983; *Leavesley and Stannard*, 1995; *Perkins and Jones*, 2008]. Soil water and snowpack modules of PRMS were run for a set of hydrologic response units (HRUs) in each control basin (WS 9, WS 2, WS 8) using climate data extrapolated from the nearest meteorological station (Figure 2). Soil moisture and snow water equivalent values were simulated to determine whether basinwide soil moisture was near saturation (>90% soil moisture), and a minimum snowpack (>2.5 mm snow water equivalent, see below) was present in each study basin on the day of a peak discharge (details of model procedures are in the work of *Perkins and Jones* [2008]). Snow water equivalents estimated using PRMS for the HRU containing vanmet, assuming forest cover, were about eightfold lower than values of snow water equivalent observed at vanmet, in a canopy gap, for October 1987 to September 1992 [*Perkins and Jones*, 2008]. These differences are at the high end or larger than differences in snow water storage under forest cover versus canopy openings reported by *Berris and Harr* [1987], *Marks et al.* [1998] (twofold to eightfold differences), and *Storck et al.* [2002] (fourfold differences).

[23] Peak discharge events were classified as rain and rain-on-snow events on near-saturated soils; other event types (snowfall, mixed rain and snow, pure snowmelt, unsaturated soils) were excluded [*Perkins and Jones*, 2008]. Events classified as "rain" had precipitation >0, minimum daily temperatures >0°C, snow water equivalent <2.5 mm, and basinwide, area-weighted soil moisture was >90% of the estimated moisture storage capacity. Events classified as "rain-on-snow" had the same precipitation, air temperature, and soil moisture as rain events but were preceded by a period of snow (precipitation falling when the maximum daily air temperature was less than 0°C) and the estimated basinwide, area-weighted average value of snow water equivalent exceeded 2.5 mm. Given the uncertainty in snow water equivalent simulation under forest versus canopy gaps and the spatial variability of snow, events classified as rain-on-snow may have had >20 mm of snow water equivalent on the ground [*Perkins and Jones*, 2008].

3.4. Statistical Methods

[24] Hypotheses were tested using linear regression and correlation [*Ramsey and Schafer*, 1997]. Multiple linear regression models (H1, H4, H5, H7) were of the form $y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2$, where y = response variable; α = intercept; β_1, β_2, and β_3 are slope terms; and x_1 and x_2 are explanatory variables. Models related some measure of runoff or peak discharge (y or y_1 for control watersheds, y_2 for harvested watersheds) to event size (x_1) event type (x_2, rain versus rain-on-snow), and the interaction ($x_1\, x_2$). Event size was measured as precipitation during the storm event (H4) or peak discharge at the large basin (H5, H6, H7, H8) (see below). Event type (x_2) was represented by a binary variable (rain = 0, rain-on-snow = 1). Model fit was evaluated using model F statistics, p values, and r^2 values; hypotheses were evaluated based on the significance of individual terms. If the β_1 term was statistically significant ($p < 0.01$), runoff or peak discharge depended on event size; if β_2 and/or β_3 were statistically significant, runoff or peak discharge depended on event type and/or the relationship between event size and event type. Peak discharge and event precipitation were log-transformed prior to model fitting. Models were fitted both with and without the interaction term ($x_1\, x_2$), and the best fit model or both models are presented.

[25] H1 tested how well the event classification worked: classified daily lysimeter output (y) was related to daily precipitation (x_1) and event type (x_2). H4 tested whether event size and event type affected peak discharge: unit-area peak discharge (y) was related to event precipitation (x_1) and event type (x_2) for each small control basin (WS 2, WS 8, WS 9) and two large basins (Lookout Creek, Blue River).

[26] H5 tested whether event size and event type affected peak discharge differences between small and large basins: percent difference in classified unit-area peak discharge at control basin relative to matched peak discharge at Lookout Creek (y) was related to unit-area peak discharge at Lookout Creek (x_1) and event type (x_2). The percent difference $p_{c,l}$ between matched peak discharges a_i and b_i was

$$p_{c,l} = (\exp\{[\ln(a_i) - \ln(b_i)] - d\} - 1)100, \qquad (1)$$

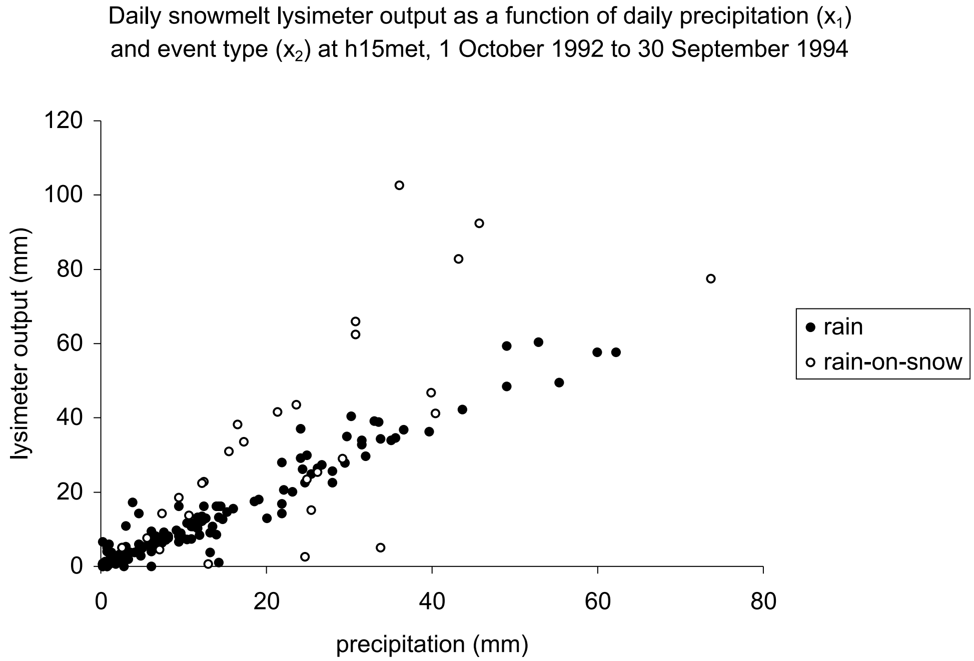

Figure 5. Retrospective classification (rain versus rain-on-snow, see text) distinguishes days when snowmelt runoff augmented precipitation (rain-on-snow) from days with rain only (H1). Snowmelt lysimeter output from h15met in the seasonal snow zone for days classified as rain-on-snow versus rain over the period 1 October 1992 to 30 September 1994 (n = 160 rain days, n = 29 rain-on-snow days). Low outliers for precipitation <35 mm are days that experienced mixed snow and rain or rain absorbed by a snowpack.

where a_i, b_i = unit-area peak discharge of event i at the small control basin (WS 9, WS 2, WS 8) and the large basin (Lookout Creek), respectively, and d = the average of [$\ln(a_i) - \ln(b_i)$] for all events i in the period of record. H7 tested whether peak discharge response to forest harvest was related to event size and event type: percent difference in classified unit-area peak discharge at the treated small basin relative to the average relationship of matched peak discharges between the control basin and Lookout Creek (y) was related to unit-area peak discharge at Lookout Creek (x_1) and event type (x_2). Percent difference $p_{t,l}$ between matched peak discharges c_i and b_i was

$$p_{t,l} = (\exp\{[\ln(c_i) - \ln(b_i)] - d\} - 1)100, \qquad (2)$$

where b_i, c_i = unit-area peak discharge of event i at the large basin (Lookout Creek) and the small treated basin (WS 10, WS 1, and WS 6), respectively.

[27] H2 tested the effect of event type on event size by ranking floods at all study basins and determining event types for the large basins based on event types from small basins. H3 tested the effect of snow zones on flood ranking by correlating flood rankings and peak discharges among pairs of study basins. Flood rankings were correlated using Spearman rank correlations, equivalent to Pearson's r applied to ranked events; peak discharges were correlated using Pearson's r. The effect of event size and event type on peak discharge timing differences (H6 and H8) was tested by plotting the difference in classified peak discharge times at the small basin and Lookout Creek versus unit-area peak discharge at Lookout Creek.

4. Results

4.1. Peak Discharge Classification (H1)

[28] The event classification system correctly identified conditions of snowmelt runoff. Retrospective classification distinguished days when snowmelt runoff augmented precipitation (rain-on-snow) from days with rain only (H1). Daily lysimeter output was significantly related to event precipitation and the interaction between precipitation and event type (Figure 5 and Table 2). Over the range of 1–100 mm of daily precipitation, the lysimeter produced on average 175% of precipitation on rain-on-snow days, and 100% of precipitation on rain days. A few points fall below the 1:1 line, indicating net storage of precipitation in the snow lysimeter.

4.2. Extreme Floods, Regional Rain-on-Snow Conditions, and Snow Zones (H2, H3)

[29] Most extreme floods are regional rain-on-snow events. Extreme peak discharges of record were 10.9 and 10.6 mm/h (22 December 1964, 7 February 1996), and the annual return period event was 2.7 mm/h at Lookout Creek (Figure 6 and Table 2). The 26 largest peak discharges (>1 year events) at Lookout Creek from 1963 to 2006 were rain-on-snow events at basins in the seasonal snow zone (WS2, WS8) and rain-on-snow or rain events at basins in the transient snow zone (Table 3). The top ranked seven events at Lookout Creek also were regional floods (high-ranked events) at all six large basins in the period of record (Table 4).

Table 2. Multiple Regression Models Shown in Figures 5–8[a]

Figure	Model	n	F	$p <$	r^2
5	$y = 0.3 + 0.995x_1 + 2.3x_2 + 0.323x_1x_2$ ns 0.0001 ns 0.004	189	256.3	0.00001	0.80
6a	$y = -2.88 + 0.70x_1 - 0.14x_2 + 0.04x_1x_2$ 0.0001 0.0001 ns ns	127	45.4	0.0001	0.51
6b	$y = -6.05 + 1.22x_1 + 1.76x_2 - 0.31x_1x_2$ 0.0001 0.0001 0.008 0.02	140	95.3	0.0001	0.67
6c	$y = -4.90 + 1.02x_1 + 0.35x_2 - 0.06x_1x_2$ 0.0001 0.0001 ns ns	96	34.7	0.0001	0.51
6d	$y = -3.2 + 0.74x_1 + 0.37x_2$ 0.0001 0.0001 0.005	49	20.8	0.0001	0.45
6e	$y = -1.6 + 0.50x_1 + 0.22x_2$ 0.003 0.0001 0.02	49	17.1	0.0001	0.41
7a	$y_1 = 14.2 - 38.7x_1 + 17.3x_2 - 12.1x_1x_2$ 0.004 0.0001 ns ns	79	25.0	0.0001	0.48
7b	$y_1 = -5.3 + 3.8x_1 + 17.0x_2 - 20.2x_1x_2$ ns ns 0.005 0.02	99	6.0	0.0008	0.13
7c	$y_1 = 15.1 + 14.8x_1 - 5.1x_2 - 16.5x_1x_2$ 0.004 ns ns ns	85	1.3	0.25	0.01
8a	$y_1 = 10.4 - 29.5x_1 + 26.0x_2 - 19.6x_1x_2$ ns 0.04 ns ns	16	2.7	0.09	0.25
8a	$y_2 = 26.0 - 17.7x_1 + 25.1x_2 - 30.8x_1x_2$ ns ns ns ns	16	0.8	0.52	0.0
8d	$y_1 = 15.8 - 42.1x_1 + 14.9x_2 - 8.4x_1x_2$ 0.006 0.0001 ns ns	63	21.5	0.0001	0.50
8d	$y_2 = 39.6 - 29.3x_1 - 4.7x_2 - 3.6x_1x_2$ 0.005 0.01 ns ns	50	6.5	0.0009	0.25
8b	$y_1 = 4.3 - 16.5x_1$ ns 0.0001	78	25.3	0.0001	0.24
8b	$y_2 = 38.7 - 22.7x_1$ 0.0001 0.0004	78	13.8	0.0008	0.14
8e	$y_1 = -5.3 + 3.8x_1 + 17.0x_2 - 20.2x_1x_2$ ns ns 0.005 0.02	99	6.0	0.0008	0.13
8e	$y_2 = 69.9 - 5.6x_1 + 16.0x_2 - 36.7x_1x_2$ 0.0001 ns ns 0.03	99	9.9	0.0001	0.21
8c	$y_1 = -8.1 - 12.8x_1 + 21.1x_2 + 6.4x_1x_2$ ns ns ns ns	27	0.9	0.44	0.0
8c	$y_2 = -6.7 - 14.7x_1 + 17.4x_2 + 14.4x_1x_2$ ns ns ns ns	27	0.4	0.77	0.0
8f	$y_1 = 19.5 + 25.7x_1 - 10.8x_2 - 25.4x_1x_2$ 0.0004 ns 0.02 0.04	58	3.6	0.02	0.12
8f	$y_2 = 38.6 + 30.5x_1 - 8.3x_2 - 35.7x_1x_2$ 0.0001 ns ns ns	58	1.6	0.12	0.03

[a]Here x_1 = event size (mm/h), x_2 = event type, rain equals 0, rain-on-snow equals 1, y = peak discharge, y_1 = peak discharge at control basin, y_2 = peak discharge at treated basin.

[30] Basins that had all or much of their area in the seasonal snow zone had similar rank ordering of the 23 largest floods at Lookout Creek (Table 5). Pairs of adjacent basins with similar snow zone distributions had the highest rank-order correlations (>0.80): North Fork MF Willamette and Salmon Creek (>80% in seasonal snow zone), Breitenbush and North Santiam River (>80% in seasonal snow zone), WS2 and WS9 (>35% in transient snow zone) (Table 1, Table 5, and Figure 2). Flood rankings in the small basin in the seasonal snow zone (WS 8) also were correlated with Lookout Creek, to which it contributes ($r = 0.76$) and the nearest other large basins (Blue River, North Santiam River) ($0.6 \leq r \leq 0.7$). Flood rankings were not correlated in basins with dissimilar snow zone distributions: WS 9 versus WS 8, Blue River, Breitenbush River, and North Santiam River, and WS 2 versus Breitenbush River (Table 5).

4.3. Effect of Snow on Peak Discharge Magnitude in Unharvested Basins (H4)

[31] Controlling for event precipitation, rain-on-snow peak discharges were significantly higher than rain peak discharges in large but not in small, basins, indicating that in most cases snowmelt runoff does not augment peak discharges in small basins. In the transient to seasonal snow zone (WS 2), peak discharges of rain-on-snow events with 100 mm of precipitation were 50% higher than rain events, but peak discharges of larger events at this basin and of events in small basins in the transient (WS9) and seasonal (WS8) snow zones did not differ based on event type (Figures 6a–6c and Table 2). In contrast, in large basins, on average rain-on-snow events were 45% higher than rain events at Lookout Creek and 25% higher at Blue River, and >10 year rain-on-snow events were nearly 2 times higher (Figures 6d and 6e and Table 2).

4.4. Peak Discharge Relationships Between Small and Large Basins (H5, H6)

[32] Peak discharges of large (>1 year) rain-on-snow events in large basins were damped relative to small basins in the seasonal snow zone but amplified relative to small basins in the transient snow zone. In the transient and seasonal snow zones, small (<1 year) peak discharges were

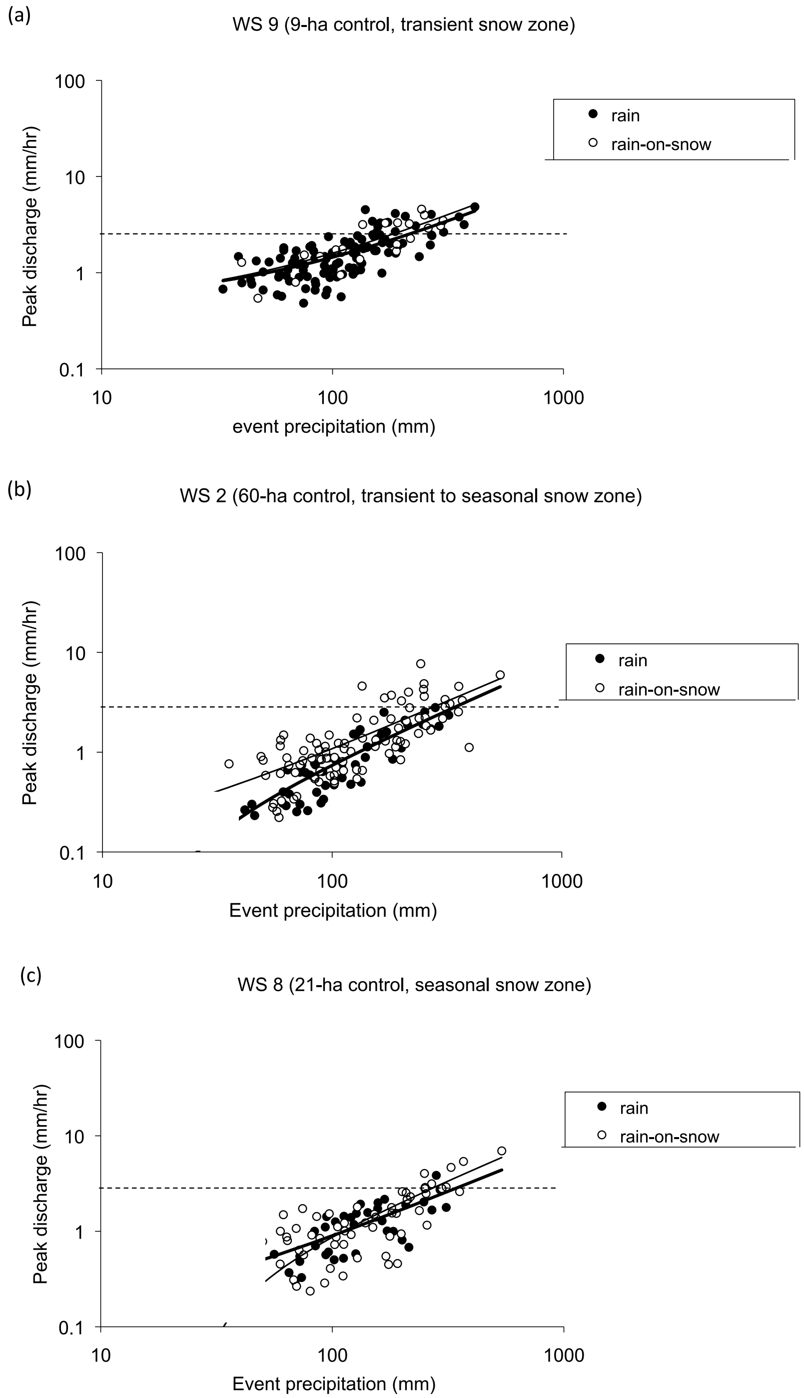

Figure 6. Effect of event size, event type, and basin size on peak discharges, 1963–2007, controlling for precipitation (H4). Event precipitation ranged from 34 to 539 mm. (a) WS 9, 9 ha control, transient snow zone. (b) WS 2, 60 ha control, transient to seasonal snow zone. (c) WS 8, 21 ha control, seasonal snow zone. (d) Lookout Creek, 6200 ha, transient to seasonal snow zones. (e) Blue River, 11,860 ha, transient to seasonal snow zones. Lines are trend lines fit to rain-on-snow days (light lines, normal font equation) and rain days (heavy line, bold font equation). Horizontal dashed line is the 1 year return period peak discharge at Lookout Creek over the 60 year record. Equations are fitted multiple regressions.

higher than matched peaks at Lookout Creek (Figures 7a, 7b, and 7c and Table 2). In small basins in the transient to seasonal zone, small (<1 year return period) peak discharges of rain-on-snow events were significantly higher than rain events relative to peaks at Lookout Creek (Figure 7b). However, >1 year return period peak discharges at small basins (which were almost all rain-on-snow events) were lower than matched peaks at Lookout Creek (Figures 7a, 7b, and 7c). Thus, different flood-generating mechanisms appear to operate in small versus large floods, and snowmelt in the seasonal snow zone influences the magnitude of large rain-on-snow peak discharges in large basins.

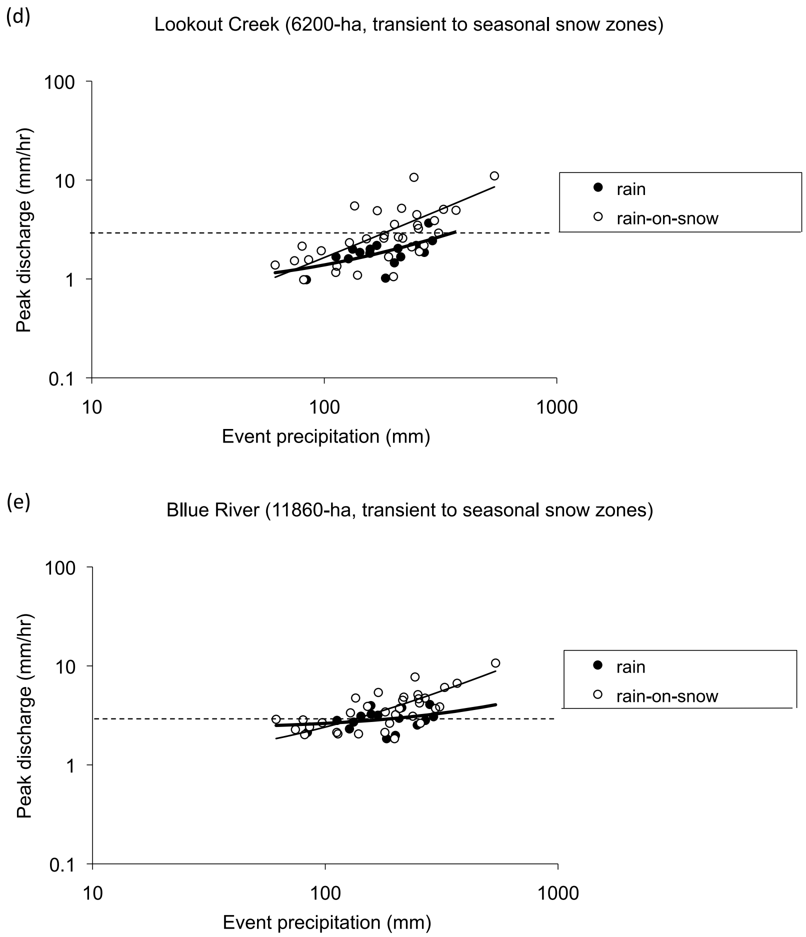

Figure 6. (continued)

[33] Flood peaks from small subbasins became more synchronized with the large basin peak as peak discharge increased at the large basin; peak synchrony influences magnitudes of extreme peak discharges. For <1 year events, many peak discharges from the transient snow zone (WS 9) preceded the peak time at Lookout Creek by ≥6 h, whereas all but a few peak discharges from the transient to seasonal snow zone (WS 2, 86 of 99) and the seasonal snow zone (WS 8, 75 of 85) were within ±6 h (Figures 7d, 7e, and 7f). As event size increased above 1 year events, peak discharges from the small basin in the transient snow zone (WS 9) became more synchronized with the peak time at Lookout Creek (Figure 7d). For >10 year return period events (5 mm/h at Lookout Creek), all small basins had peaks within 1 or 2 h of the peak at Lookout Creek (Figures 7d, 7e, and 7f).

4.5. Peak Discharge Response to Forest Harvest (H7, H8)

[34] After harvest, peak discharges of large (>1 year) rain-on-snow events did not increase significantly in small basins in the transient and seasonal snow zones relative to peaks at the large basin, although peak discharges of small events did increase in the transient to seasonal snow zone; timing was largely unaffected (Figure 8 and Table 2). Thus, a postharvest increase in snowmelt contribution to peak discharges is only apparent in small basins for events that produce small peak discharges at the large basin and not detectable for events that produce large or extreme peak discharges at the large basin. After harvest, small (<1 year) rain-on-snow peak discharges increased in the transient (WS10), transient to seasonal (WS 1), and seasonal snow zones (WS 6). This inference is based on significant values of intercept and interaction terms in regression models for harvested basins (y_2) in postharvest periods versus preharvest periods in harvested basins and postharvest periods in control basins (y_1) (Figure 8 and Table 2).

[35] Forest harvest was associated with some changes in the relative timing of peak discharges at small relative to large basins, but large events remained synchronized after harvest. In the transient snow zone (WS 9 and WS 10), postharvest peak timing differences between the treated basin (WS 10) and Lookout Creek were nearly identical to peak timing differences between the control basin (WS 9) and Lookout Creek (Figure 9a). In the transient to seasonal snow zone (WS 2 and WS 1), three large postharvest events (1–3 year events, 4–6 mm/h at Lookout Creek) occurred 3–10 h earlier at the treated basin (WS 1) relative to the control basin (WS 2) (Figure 9b). In the seasonal snow zone (WS 8 and WS 6), two large postharvest events (between 3 and 6 mm/h at Lookout

Table 3. Rankings of Top 30 Peak Discharge Events at Lookout Creek, 1963–2006, and Their Corresponding Rankings and Event Types at Watersheds 9, 2, and 8[a]

Lookout			Watershed 9				Watershed 2				Watershed 8			
Date/Time	Peak (mm/h)	Rank	Date/Time	Peak (mm/h)	Type	Rank	Date/Time	Peak (mm/h)	Type	Rank	Date/Time	Peak (mm/h)	Type	Rank
12/22/64 11:30	10.9	1	–[b]				12/22/64 9:30	6.0	rs	3	12/22/64 14:00	7.0	rs	1
2/7/96 11:00	10.6	2	2/7/96 11:00	4.6	rs	2	2/7/96 10:00	7.7	rs	1	2/7/96 12:00	6.6	rs	2
1/21/72 2:00	6.8	3	1/21/72 1:55	3.8	r	7	1/21/72 2:30	4.6	rs	5	1/21/72 1:30	5.2	ms	4
2/6/96 22:30	5.8	4	2/6/96 20:30	4.1	rs	3	2/6/96 20:30	6.5	rs	2	2/6/96 22:00	4.6	rs	6
12/28/98 4:00	5.5	5	12/28/98 6:00	3.0	rs	25	12/28/98 4:30	4.8	rs	4	12/28/98 3:00	3.3	rs	12
11/25/99 23:30	5.2	6	11/25/99 22:30	3.1	rs	22	11/25/99 23:30	4.0	rs	10	11/25/99 23:00	3.0	rs	15
12/30/05 16:00	5.0	7	12/30/05 14:30	3.4	r	8	12/30/05 15:30	4.2	rs	9	12/30/05 14:00	3.8	rs	11
11/25/77 18:00	5.0	8	11/25/77 15:58	3.1	rs	20	11/25/77 16:28	3.1	rs	20	11/25/77 18:24	4.7	rs	5
11/19/96 8:00	4.9	9	11/18/96 21:00	3.1	rs	18	11/19/96 5:30	3.5	rs	14	11/19/96 6:30	4.5	rs	7
12/13/77 11:30	4.9	10	12/13/77 5:13	3.2	r	16	12/13/77 15:16	3.3	rs	17	12/13/77 14:18	5.4	rs	3
1/28/65 11:30	4.6	11	–[b]				1/28/65 14:00	4.2	rs	8	1/28/65 17:00	2.8	rs	18
2/23/86 7:30	4.4	12	2/23/86 4:10	4.0	rs	5	2/23/86 8:01	4.3	rs	7	2/23/86 7:27	4.0	rs	9
1/10/06 22:30	4.4	13	1/10/06 22:00	2.5	rs	34	1/10/06 21:00	3.1	rs	19	1/10/06 21:00	4.3	rs	8
2/9/96 4:00	4.1	14	2/9/96 7:00	1.7	rs	68	2/9/96 3:00	2.8	rs	28	2/9/96 3:00	2.3	rs	30
12/26/96 5:30	3.9	15	12/26/96 1:30	3.0	rs	24	12/26/96 4:30	3.7	rs	12	12/26/96 7:30	3.2	rs	13
1/18/71 1:00	3.9	16	1/18/71 3:57	3.3	rs	13	1/18/71 5:00	2.8	rs	19	1/18/71 5:00	2.8	rs	19
1/31/97 12:30	3.6	17	1/31/97 11:00	2.5	rs	36	1/31/97 17:30	2.8	rs	27	1/31/97 18:00	2.7	rs	21
12/4/68 22:30	3.5	18	12/4/68 16:00	3.3	r	14	12/4/68 21:45	3.3	rs	18	12/4/68 19:45	2.6	rs	24
2/13/84 10:00	3.5	19	2/13/84 10:39	3.4	o	9	2/13/84 9:49	3.6	rs	13	2/13/84 9:34	2.9	rs	17
12/13/03 16:30	3.4	20	12/13/03 8:00	2.5	r	32	12/13/03 15:00	2.8	ms	24	12/13/03 14:30	2.6	ms	22
12/4/96 19:30	3.3	21	12/4/96 17:30	3.0	r	26	12/4/96 19:30	2.8	rs	29	12/4/96 19:30	2.5	rs	26
2/23/68 5:30	3.2	22	–[b]				2/23/68 6:00	2.1	rs	41	2/23/86 7:27	4.0	rs	9
1/7/90 21:30	3.2	22	1/7/90 19:55	3.1	r	21	1/7/90 20:39	2.2	rs	35	1/7/90 22:22	2.5	rs	28
12/13/01 22:00	3.0	24	12/13/01 20:30	2.4	r	39	12/13/01 21:00	2.9	ms	21	12/13/01 21:00	2.2	ms	33
1/13/95 20:30	2.9	25	1/13/95 19:00	3.1	r	19	1/13/95 18:00	2.9	rs	22	1/13/95 19:30	2.5	rs	27
12/6/81 6:30	2.9	26	12/6/81 6:46	3.3	r	12	12/6/81 5:09	3.4	rs	15	12/6/81 4:04	2.9	rs	16
11/8/68 22:30	2.8	27	11/8/68 17:42	3.2	o	15	11/9/68 0:45	2.5	r	31	11/8/68 22:45	2.2	o	32
12/5/71 21:00	2.8	27	12/5/71 18:33	3.3	r	10	12/5/71 19:30	2.9	rs	23	12/5/71 20:00	1.8	r	45
11/26/71 12:00	2.7	29	11/26/71 9:43	3.2	o	17	11/26/71 17:45	2.4	r	33	11/26/71 10:30	2.2	ms	31
1/9/89 22:30	2.7	29	1/9/89 18:46	3.9	r	6	1/9/89 21:27	3.7	rs	11	1/9/89 21:37	1.6	rs	55

[a]Here rs, rain-on-snow; r, rain; ms, mixed rain and snow on snow; o, other, including snowfall, mixed rain and snow, pure snowmelt, unsaturated soils. Rank order correlations of Lookout versus WS 9 = 0.07, versus WS 2 = 0.70, versus WS 8 = 0.81; peak discharge correlations of Lookout versus WS 9 = 0.37, versus WS 2 = 0.86, versus WS 8 = 0.88. Date format is month/day/year. Lookout is transient to seasonal, Watershed 9 is transient, Watershed 2 is transient to seasonal, and Watershed 8 is seasonal.

[b]No record; WS 9 gaging record started in 1968.

Creek) occurred 6 to 12 h later at the treated basin (WS 6) than at the control basin (WS 8) (Figure 9c).

5. Discussion

[36] Using long-term records from a limited sample of six small, experimental basins and six large basins spanning the transient and seasonal snow zones in the central western Cascades of Oregon, this study provides evidence about two mechanisms for generating the extreme rain-on-snow floods in western Oregon noted by *O'Connor and Costa* [2004]. The first mechanism is based on plot-scale studies [e.g., *Harr*, 1981; *Berris and Harr*, 1987; *Marks et al.*, 1998; *Storck et al.*, 2002] and involves augmentation of peak discharges by snowmelt runoff increasing the local runoff rate, which depends on snow water equivalent and the capacity of the snowpack to melt rapidly. The second mechanism is based on snow-covered area [e.g., *Harr*, 1986; *Jones and Grant*, 1996; *Whitaker et al.*, 2002; *Schnorbus and Alila*, 2004; *Tonina et al.*, 2008] and involves simultaneous snowmelt over large areas, which synchronizes peak discharges from tributary basins and augments peaks in large basins.

[37] This study provides evidence that small rain-on-snow peak discharge magnitudes are sensitive to snowmelt runoff rate (mechanism 1). Snowmelt runoff from snowmelt lysimeters was about 75% higher on rain-on-snow days than rain days with precipitation <100 mm, and rain-on-snow peak discharges were 50% higher than rain events for precipitation events of <100 mm in the transient-seasonal snow zone (WS2). However, these small peak discharges were desynchronized among tributary basins, precluding large floods at the large basin scale. During an extreme event (Figures 1 and 2), the snowmelt runoff rate in three lysimeters (2–4 mm/h) augmented maximum precipitation rate (8–10 mm/h) by a similar proportion (25%–50%) as the observed increases of rain-on-snow events compared to rain events in large basins (25%–45%) (Figures 6d and 6e). However, large rain-on-snow peak discharges were no higher than rain peaks in small study basins (Figures 6a, 6b, and 6c and Table 2). This suggests that snowmelt runoff rate in small basins does not explain rain-on-snow peak discharge magnitudes in large basins.

[38] Rather than depending on the rate of snowmelt runoff, extreme rain-on-snow peak discharge magnitudes in large basins appear to depend on the extent of snow-covered area and timing of melt (mechanism 2). Extreme floods are regional events involving rain-on-snow conditions at a range of elevations spanning the transient and seasonal snow zones, implying large snow-covered areas. Strong cor-

Table 4. Ranks of Top 23 Peak Discharge Events at Lookout Creek and Corresponding Ranks at Five Large Basins on the Western Slope of the Cascade Range, Oregon, for the Period of Overlapping Record (1963–1992)[a]

Date	Lookout Creek Event Type	Lookout Creek Rank	Blue River Rank	North Fork Middle Fork Willamette River Rank	Salmon Creek Rank	North Santiam River Rank	Breitenbush River Rank
12/22/64	rs	1	1	1	1	1	1
1/21/72	o	2	2	4	5	5	3
11/25/77	rs	3	4	8	4	4	2
12/13/77	r/rs	4	3	12	3	3	4
1/28/65	rs	5	–[b]	–[b]	–[b]	10	13
2/23/86	rs	6	5	25	6	6	5
1/18/71	rs	7	17	2	12	12	16
12/4/68[c]	rs	8	26	40	79	46	81
2/13/84[c]	r/rs	9	8	11	19	39	59
2/23/68[c]	rs	10	47	27	11	11	22
1/7/90	r/rs	10	10	22	32	–[d]	–[d]
12/6/81	r/rs	12	15	3	6	15	20
11/8/68	o	13	35	15	15	36	10
12/5/71[c]	o	13	29	17	20	50	60
11/26/71	o	15	19	9	17	44	43
1/9/89	r/rs	15	21	19	21	–[d]	–[d]
1/8/76	o	17	22	10	11	48	52
11/24/70[c]	r/rs	18	17	24	26	25	20
12/1/64[c]	rs	19	33	34	50	33	8
1/28/67[c]	rs	20	62	39	56	52	44
1/12/80	rs	20	6	14	16	16	19
2/14/82[c]	rs	20	22	27	34	37	32
4/27/90	r/rs	23	14	6	5	–[d]	–[d]

[a]Here rs, rain-on-snow event at all elevations; r/rs, rain event below 800 m, rain-on-snow events above 800 m; o, other combination of event type (see Table 3). Date format is month/day/year.
[b]Not recorded; gage destroyed by flood of December 1964.
[c]Events have a ranking that is more than five ranks lower at three or more of the five other basins than at Lookout Creek.
[d]Not recorded; gage no longer functioning.

relations among observed hourly snowmelt runoff rates in lysimeters, synchronized timing of >1 year peak discharges among small and large basins, near-equal magnitudes of peak discharges in the small basin in the seasonal zone and the large basins during >1 year events, and the strong correlations of peak discharge magnitudes and rankings between the small basin in the seasonal snow zone and the large basins all indicate that simultaneous snowmelt occurs throughout the snow-covered area in extreme flood events.

[39] Extreme rain-on-snow floods involve a set of factors that distinguish them from other rain-on-snow and rain events (Figure 10). Rain peak discharge events may occur over a range of event precipitation sizes, rain may fall over part or all of the basin, and soils may be unsaturated or near saturation, but there is no snowpack or snowmelt contribution (solid lines, Figure 10). A variety of conditions may produce rain-on-snow peak discharge events that are not extreme floods (dashed lines, Figure 10). Event precipitation may be low, or only part of the basin area may experience rain (as opposed to snow). Or, only part of the basin may experience snowmelt runoff, either because snow cover is partial or because the basin has a complete snowpack but part of the snow-covered area is too cold to melt. For these reasons, snowmelt timing and peaks from tributary basins are desynchronized in a rain-on-snow flood that does not produce an extreme flood peak. An extreme rain-on-snow flood requires high event precipitation with rain falling over the entire basin, complete snowpack cover in the basin, a snowpack that is warm enough to melt, snowmelt runoff from the base of the snowpack, near-saturated soils, and simultaneous melt in most or all of the basin (dotted lines, Figure 10).

[40] We infer from this limited sample that in an extreme rain-on-snow flood, hillslopes and snowpacks become gradually saturated by prolonged rainfall, and snowmelt enhances the saturation of the hydrologic system so that discharge responds very rapidly to small pulses of relatively high-intensity precipitation (e.g., Figure 1). Pistonlike pulses or pressure waves [*Torres et al.*, 1998; *Torres*, 2002; *Ebel and Loague*, 2008] transmitted through nearly continuously

Table 5. Correlations Among Rankings of Top 23 Events at Lookout Creek, 1963–1992, With Those at Other Basins

	Blue River	North Fork Middle Fork Willamette	Salmon Creek	North Santiam River	Breitenbush River	Watershed 9	Watershed 2	Watershed 8
Lookout	0.49	0.35	0.28	0.68	0.36	0.50	0.57	0.76
Blue River		0.64	0.55	0.61	0.37	0.04	0.42	0.60
N. Fork Willamette			0.81	0.48	0.37	0.41	0.41	0.36
Salmon Creek				0.65	0.60	0.46	0.27	0.33
North Santiam River					0.82	0.02	0.25	0.70
Breitenbush River						−0.12	0.03	0.40
Watershed 9							0.85	0.05
Watershed 2								0.42

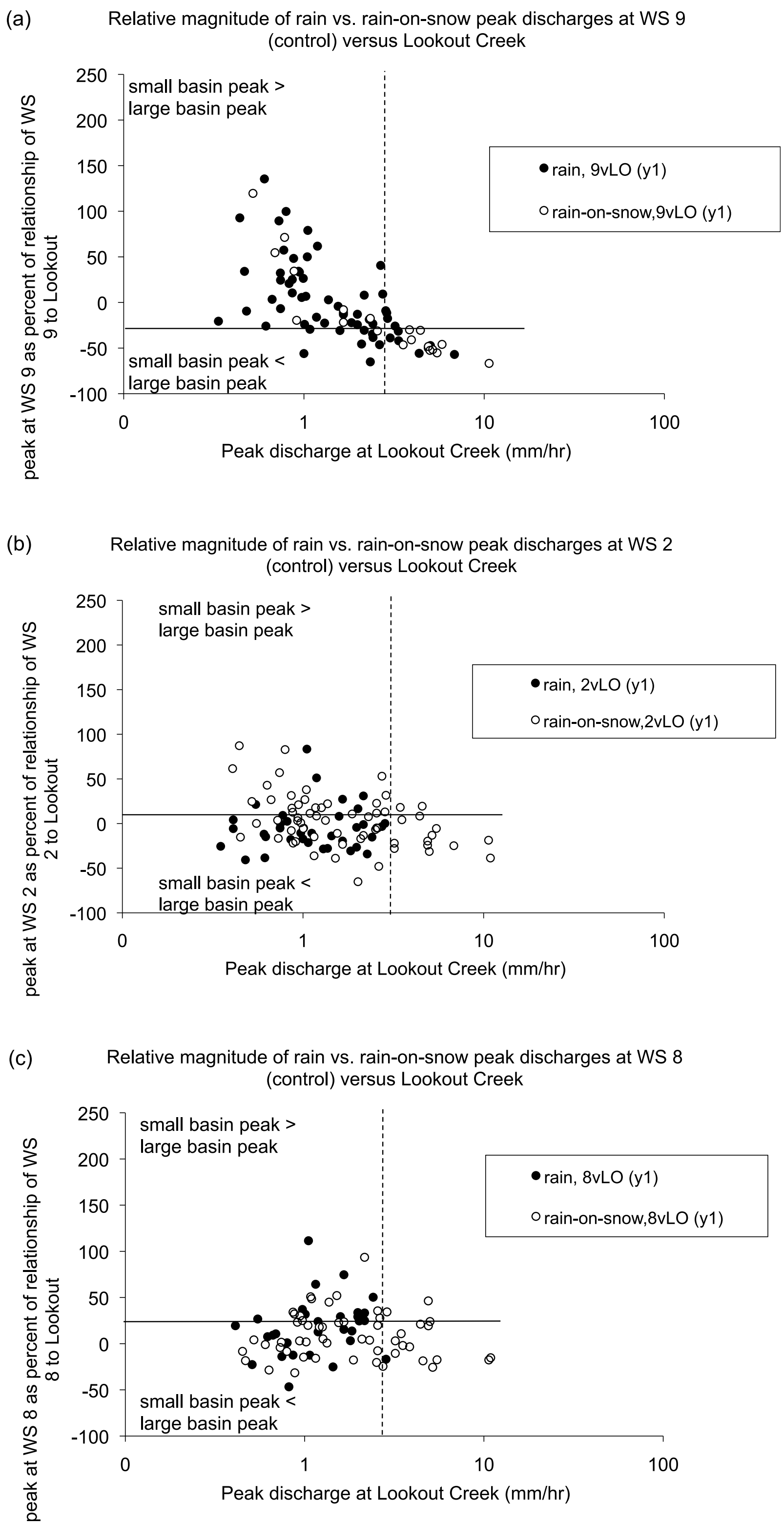

Figure 7. Effect of event size at the large basin (x_1) and event type (x_2, rain, rain-on-snow) on the magnitude (H5) and timing (H6) of peak discharges from three small control basins spanning the transient, transient to seasonal, and seasonal snow zones in the Andrews Forest, Cascade Range, western Oregon. (a, b, and c) Peak discharge as a percent of the average relationship of matched peak discharges at the control basin and Lookout Creek. (d, e, and f) Time difference of matched peak discharges between the control basin and Lookout Creek. Solid horizontal lines represent equal unit-area peak discharges at small basins and Lookout Creek in Figures 7a, 7b, and 7c and synchronous peak timing at small basins and Lookout Creek in Figures 7d, 7e, and 7f. Vertical dashed line is the 1 year event at Lookout Creek. Equations are fitted multiple regressions. See Table 1 for basin details.

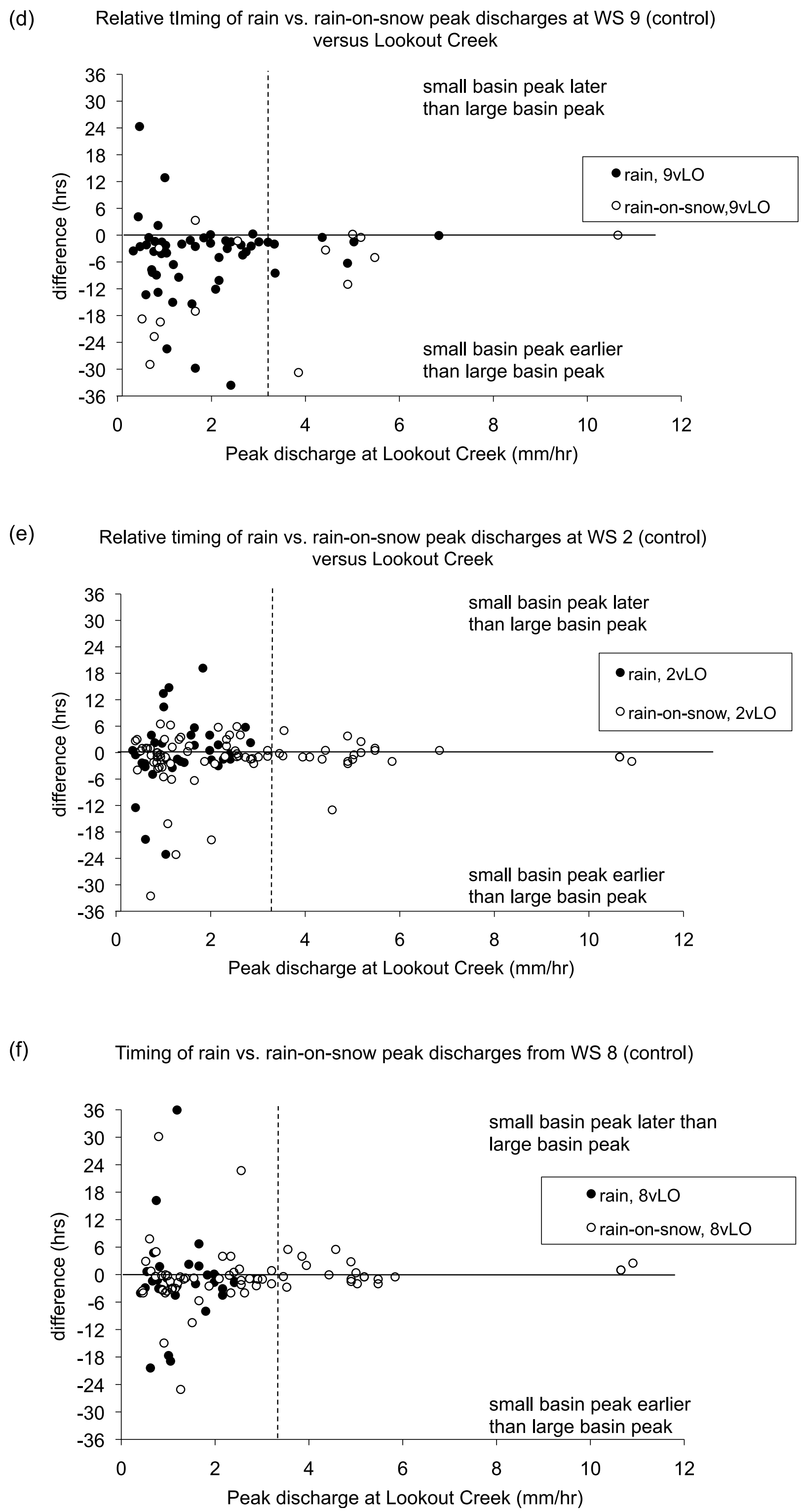

Figure 7. (continued)

saturated snowpacks, soils, and stream channels are a possible mechanism to explain rapid discharge responses during extreme flood events. In addition, the simultaneous peak discharges throughout the stream network may produce some kind of constructive reinforcement that amplifies the peak in the downstream basin. In either case, the area experiencing simultaneous snowmelt runoff, rather than the melt rate per se, is the key driver of extreme rain-on-snow floods.

[41] Simultaneous melt over a large snow-covered area during extreme rain-on-snow floods also explains the

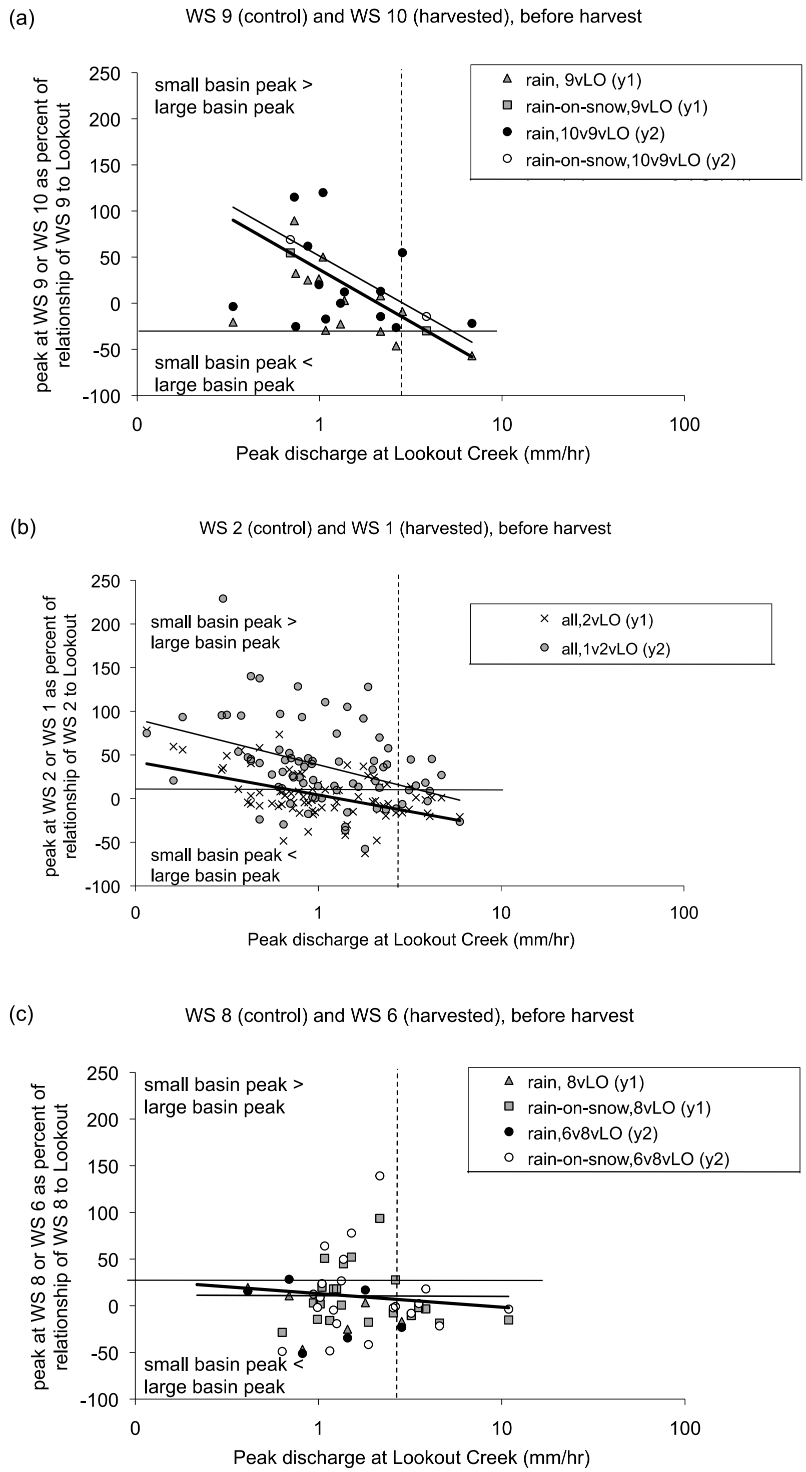

Figure 8. (a–f) Effect of event size at the large basin (x_1), event type (x_2), and forest harvest (preharvest versus postharvest regressions) on the magnitude of rain and rain-on-snow peak discharges from three small experimental basin pairs spanning the transient, transient to seasonal, and seasonal snow zones in the Andrews Forest, Cascade Range, western Oregon (H7). WS 9 (control, y_1, heavy line) and WS 10 (harvested, y_2, light line) in the transient snow zone before (Figure 8a) and after (Figure 8d) harvest. WS 2 (control, y_1, heavy line) and WS 1 (harvested, y_2, light line) in the transient to seasonal snow zones before (Figure 8b) and after (Figure 8e) harvest. WS 8 (control, y_1, heavy line) and WS 6 (harvested, y_2, light line) in the seasonal snow zone before (Figure 8c) and after (Figure 8f) harvest. Solid horizontal line represents equal peak discharges at small basins and Lookout Creek. Vertical dashed line is the 1 year event at Lookout Creek.

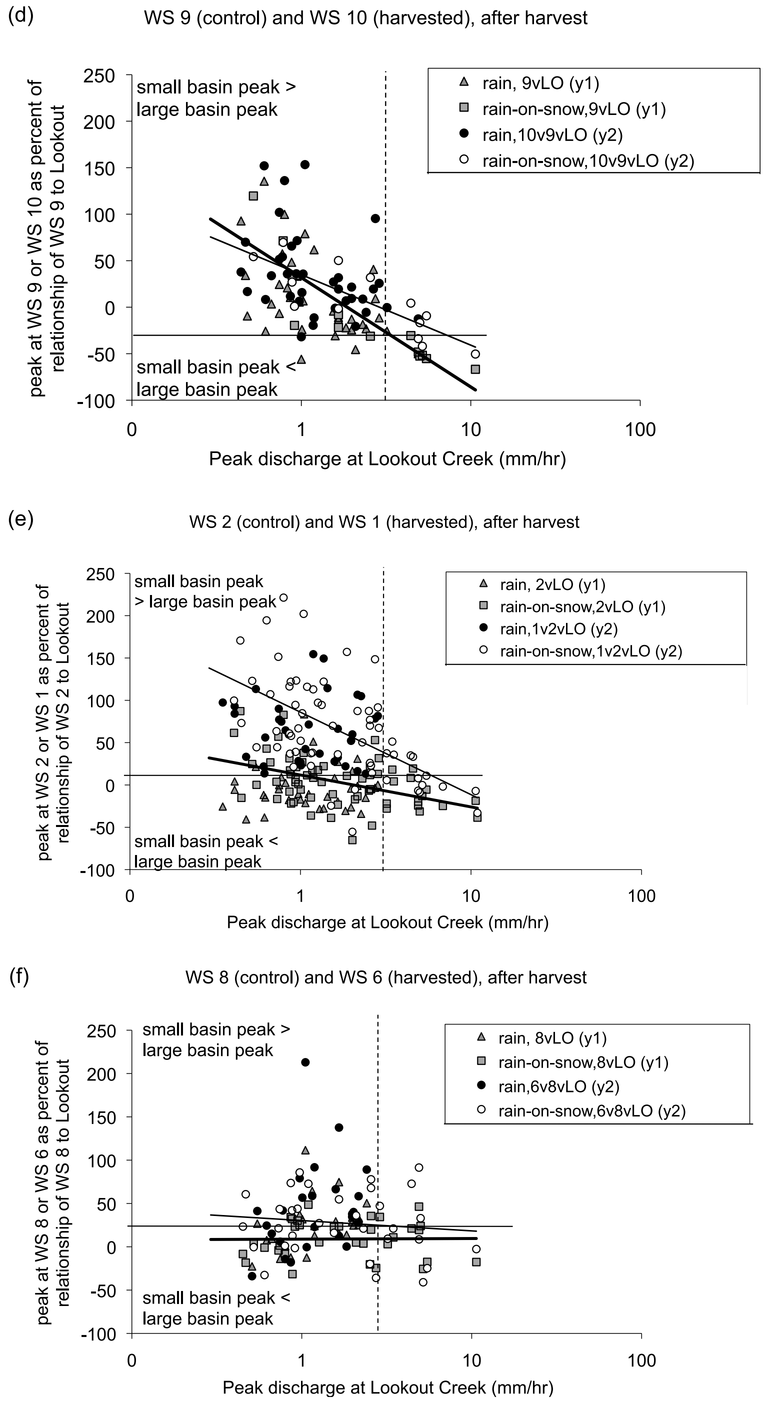

Figure 8. (continued)

puzzling finding that cumulative forest harvest increases the magnitude of peak discharges of large (>1 year) events in large basins [*Jones and Grant*, 1996; *Thomas and Megahan*, 1998], without increasing the magnitude of large peak discharge events in small basins very much [*Harr and McCorison*, 1979; *Harr et al.*, 1982; *Beschta et al.*, 2000; *Jones*, 2000; *Grant et al.*, 2008]. In this study forest harvest increased the magnitude of small rain-on-snow peak discharges in small basins in the transient and transient to seasonal snow zones, but it did not increase the magnitude of large peak discharges by more than ~15% in the transient or seasonal snow zones. Because forest harvest increases snow-covered area through creation of canopy openings, including clear-cuts and roads (noted by *Berris and Harr* [1987], *Marks et al.* [1998], *Pomeroy et al.* [2002], *Storck et al.* [2002], and *Murray and Buttle* [2003]), it could increase in the area of simultaneously melting snowpack, the synchronization of peak discharges from small basins, and the magnitude of large basin peaks.

[42] Forest harvest does not always synchronize snowmelt timing between small and large basins. After harvest, increased moisture storage in soils and snowpack could expand contributing area and delay peak timing; this apparently happened in some postharvest >1 year rain-on-snow

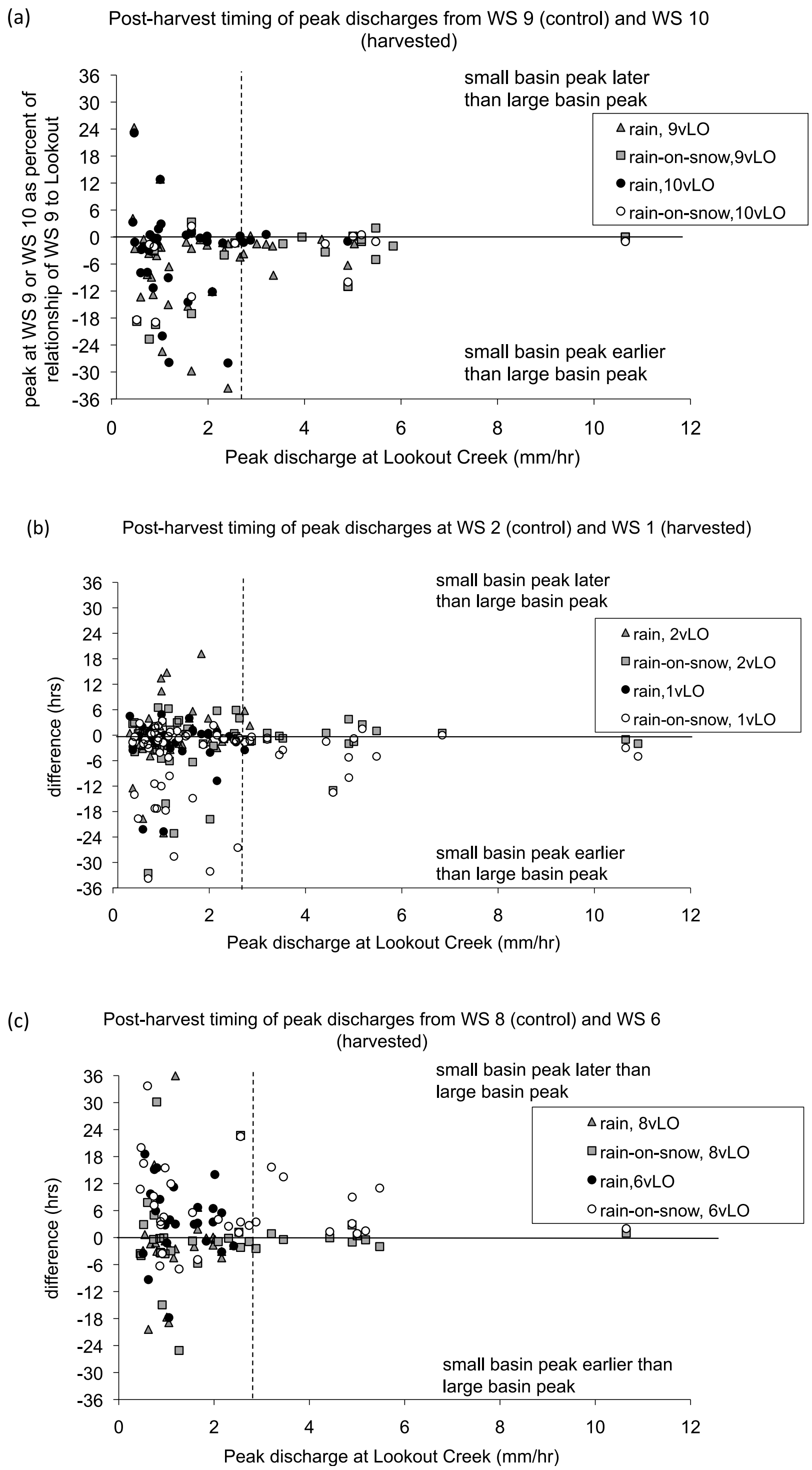

Figure 9. Effect of event size at the large basin, event type (rain versus rain-on-snow), and forest harvest on timing of peak discharges from three small control basins spanning the transient, transient to seasonal, and seasonal snow zones in the Andrews Forest, Cascade Range, western Oregon (H8). (a) WS 9 and WS 10, 9 and 10 ha basins in the transient snow zone. (b) WS 2 and WS 1, 60 and 101 ha basins in the transient to seasonal snow zone. (c) WS 8 and WS 6, 21 and 15 ha basins in the seasonal snow zone. Plots show the time difference of matched peak discharges between the control basins (gray triangles and squares) and treated basins (solid and open circles) and Lookout Creek. Solid horizontal line (at zero) represents synchronous timing at small basins and Lookout Creek. Vertical dashed line is the 1 year event at Lookout Creek.

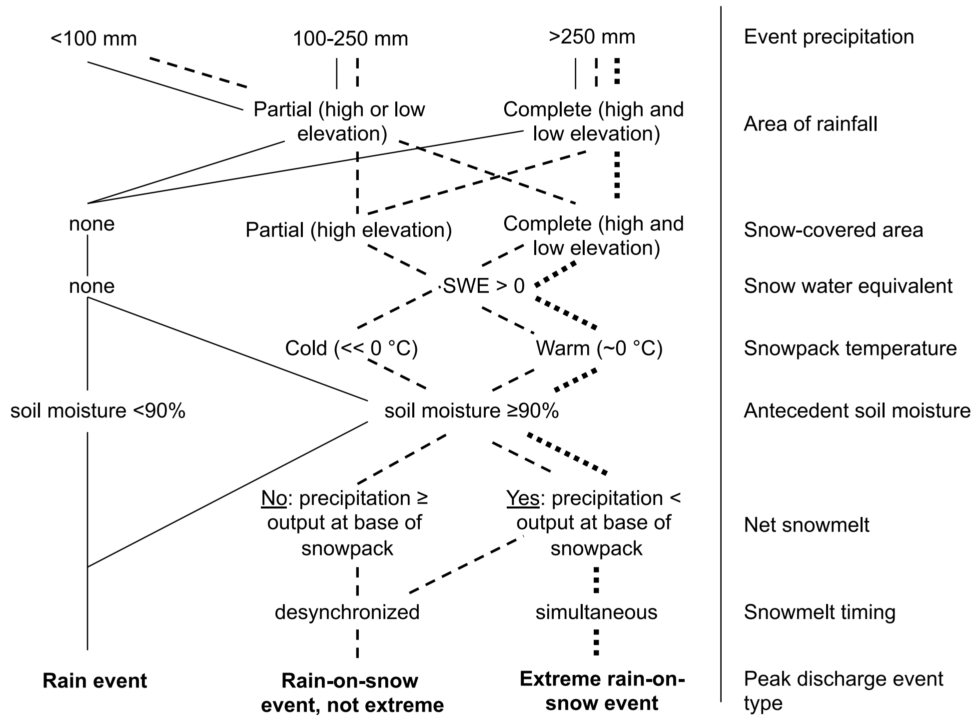

Figure 10. A particular set of conditions produces extreme rain-on-snow floods; some of these conditions are not met during rain events or rain-on-snow events that do not produce extreme floods. Extreme floods require certain conditions of event precipitation, area of rainfall, snow-covered area, snow water equivalent, snowpack temperature, antecedent soil moisture, snowmelt runoff, and snowmelt timing.

events in the low-gradient basin in the seasonal snow zone (WS 6 versus WS 8). On the other hand, increased snowpacks and wind speeds in harvested areas [*Harr*, 1981] could speed snowmelt, producing saturated areas that could advance peak timing; this apparently happened for some postharvest >1 year rain-on-snow events in the high-gradient basin in the transient to seasonal snow zone (WS 1 versus WS 2). A variety of mechanisms associated with forest harvest effects on snowpacks and snowmelt timing could in some cases desynchronize melt (as noted by *Harr and McCorison* [1979]) and small basin peaks, reducing large basin peaks.

[43] In addition to forest harvest, other very large forest disturbances, such as volcanic eruptions or wildfire, may influence snow-covered area and extreme rain-on-snow peak discharges. A forest removal effect on snow might explain posteruption increases in moderate to large peak discharges in rivers draining Mount St Helens [*Major and Mark*, 2006]. Such a mechanism might also have contributed to floods of record in the Willamette River basin study area in the late 1800s, which occurred when much of the basin area had been affected by forest fires following the arrival of Europeans [*Weisberg and Swanson*, 2003].

[44] These findings also are consistent with physical mechanisms predicted to govern simple scaling versus multiscaling of floods. In this context scaling theory expresses the distribution of peak discharges as a function of drainage area, e.g., if the pth quantile of peak flow for an area A is denoted by $q_{p(A)}$, then this quantity has been observed to scale in proportion to $A^{\theta(p)}$ where the exponent is a function $\theta(p)$ of the return period $1/p$ [*Gupta and Dawdy*, 1995]. A large exponent $\theta(p)$, often exceeding 0.9, indicates that runoff is almost directly predicted by basin size, which occurs in basins where floods are dominated by snowmelt [*Yue and Gan*, 2009]. In this study scaling relationships inferred (but not calculated) by comparisons of small and large basin peak magnitudes differed not only by the size (return period) of the event but also by event type (rain versus rain-on-snow). We conjecture that if conditional distributions are evaluated for scaling, the conditional distribution of the peaks given the type of event (rain-on-snow) should have a larger exponent than the unconditional scaling distribution.

[45] If extreme rain-on-snow events are sensitive to the area of simultaneous snowmelt, climate warming may have little effect on extreme floods, which depend on rare conditions, rather than on average snowpacks as considered by *Hamlet and Lettenmaier* [2007]. To affect extreme rain-on-snow floods, climate warming would have to alter the joint probability of a marine polar air mass producing a large snow-covered area, followed by a continental polar air mass to maintain a large snow-covered area, followed by a marine tropical air mass bringing heavy rain and warm winds and widespread simultaneous snowmelt.

6. Conclusion

[46] Extreme rain-on-snow floods in the Oregon Cascade Range produce the highest 1% of floods on record in >500 km^2 basins in the United States, associated with large storms, sustained rainfall, and snowmelt over broad areas. Although most extreme floods in the Pacific Northwest are rain-on-snow events, not all rain-on-snow events produce extreme peak discharges, and the specific mechanisms linking precipitation, snowmelt, and extreme peak discharges remain controversial. Prior work on rain-on-snow floods in

the Pacific Northwest has examined plot-scale snowpack dynamics and models to understand regional rain-on-snow floods, whereas a large, separate literature has explored forest harvest effects on peak flows at small, experimental basins.

[47] Taking advantage of records from the H.J. Andrews Experimental Forest, this study brought together plot-scale observations of snow water equivalent and snowmelt from snow lysimeters, long-term records of peak discharges from six large basins (60–600 km^2) and forest-harvest experiments in six small basins (9–100 ha), and retrospective modeling of rain versus rain-on-snow conditions, to test mechanisms that generate extreme rain-on-snow floods. Evidence from these analyses indicates that extreme rain-on-snow events in the western Cascades of Oregon over the period 1963–2007 apparently depended on simultaneous melt from a large snow-covered area, such that peak discharges at small and large basins were tightly synchronized and occurred within an hour or two of maximum precipitation intensities and snowmelt runoff. Forest harvest may have augmented extreme flood peak discharges in large basins by increasing the snow-covered area that experienced synchronized melt; this provides a mechanism to explain a forest-harvest effect on extreme flood peaks at large basins, despite the lack of observed response of large peak discharges to forest harvest at the small basin scale. Therefore, it is important to consider the evolving structure of the forest on the landscape as a potentially very important factor influencing extreme rain-on-snow floods.

[48] Further work is needed on snowpack dynamics during rain-on-snow, especially (1) detailed observations of water routing within and underneath melting snowpacks under varying temperature and forest cover conditions to explain how rapid flood responses are generated in hillslopes and (2) synoptic analyses of snow-covered area and peak discharges to reveal snowmelt and peak discharge timing during flood events. Because future climate and wildfires are likely to continue to alter snow-covered area, snow water equivalent, and melt timing, improved understanding of rain-on-snow events should remain a key priority for hydrologists and watershed managers.

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