FLOOD OF FEBRUARY 1996 IN THE H. J. ANDREWS EXPERIMENTAL FOREST

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INTRODUCTION

This paper is a preliminary look at some of the climatic, hydrologic, and geomorphic aspects of the flood event of February 6-9, 1996 on the H.J.Andrews Experimental Forest (HJA). A wealth of geophysical and ecological information, including long-term observations, set the stage for interpretation of effects of this important disturbance event/process on terrestrial, riparian, and aquatic systems. Comparison with the major floods of 1964-1965 provides perspectives on effects of watershed conditions on ecosystem responses to extreme climatic events. The distinctive, well-known forest management history of HJA provides insights concerning effects of changes in forest management on watershed responses to floods.

STUDY AREA

The HJA encompasses the entire 15,000 acre (6075 ha) drainage of Lookout Creek, a tributary of Blue River which flows into the McKenzie River. It is located in the western Cascades about 40 miles (65 km) east of Eugene and has an elevational range of about 1200 to 5000 ft. (365 to 1525 m). In the unlogged portions of the HJA the vegetation is largely old-growth Douglas-fir-hemlock at low to mid-elevations and true firs (Pacific silver fir and noble fir) at high elevations. Clearcut logging in the 1950's and 1960's created a patchwork of plantations covering about 25% of the area. Young, shallow soils derived from tuffs and breccias predominate at low elevations, while deeper soils from andesite lava flows and volcanic ash are generally found at higher elevations. Established in 1948, the HJA has come to be a very intensively used research area--each year over 125 research projects are underway involving scientists from all over the U.S. and abroad. To facilitate this research 6 weather stations and 9 gauged watersheds are maintained, providing valuable documentation of the flood (Fig. 1).

FEBRUARY 1996 STORM

Until the middle of January, the winter of 1995-96 was characterized by very low snowpacks in the Cascades of Oregon. During the last two weeks of January, however, prodigious amounts of snow fell in the Cascades, more than making up for the previous lack of snow. By January 31 the Willamette basin had a snowpack that was 112% of the long-term average for that date. This period of snow accumulation was followed by five days of intensely cold weather, with daily low temperatures in the low teens in much of western Oregon. The cold spell came to a close on February 3 and 4 with an episode of freezing rain in the Willamette Valley.

On February 6 a strong southwestern jet stream began to bring subtropical moisture into northwestern Oregon. This subtropical storm track stayed in place for 4 days and brought record amounts of rainfall. Twenty-four hour rainfall totals were as high as 3.26 inches (83 mm) for Corvallis and 5.17 inches (131 mm) for Eugene, with much higher amounts in the Coast Range. Very warm temperatures accompanied this moist air mass and snow began to melt quickly in the Coast Range and Cascades. Throughout this episode the freezing level remained at about 7000 to 8000 feet (2100-2400 m) in elevation.

Streams began rising very quickly on the 6th and 7th of February, and flood stage was reached on many streams. For example, the McKenzie River at Vida was at 4000 cfs (113 m^3/s) on the 5th and had increased to 20,000 cfs (566 m^3/s) on the 6th (the peak, reached on the 9th, was at 25,800 cfs [730 m^3/s)]). Near-record flood peaks were reached on the Willamette and Columbia Rivers on Feb. 9. At Portland where the Willamette River flood stage is 18.0 ft. (5.5 m), the peak for this flood event was 28.6 ft. (8.7 m).

The last major flood event in western Oregon occurred in 1964 (Waananen et al. 1971). Peak flows for most major streams in western Oregon were slightly lower in 1996 than in 1964. Notable exceptions were the Tualatin, Clackamas, and Mohawk Rivers where all-time flood records were set at some stations in 1996. The 1964 flood was also more wide-spread, affecting northern California, Oregon, and Washington and on into Idaho.

CLIMATIC CONDITIONS AT THE H.J. ANDREWS

Precipitation and air temperatures for periods before, during, and after the flood event are shown in Figs. 2 and 3. During the last half of January temperatures were at or below average and precipitation was above average with considerable snow accumulation. By the end of January daily temperatures were averaging 23° F (-5° C) or colder at the Upper Lookout Creek station at 4250 ft. (1300 m) elevation (Fig. 1), and snow depth totaled 8 to 10 feet (2.5 to 3 m). The first hint of the weather changes to come was a rapid increase in the temperature starting Feb. 4. This, combined with greatly increased precipitation, almost all in the form of rain, beginning on Feb. 5 led to the flooding which occurred on the HJA on the 6th to 8th of February. Starting Feb. 10, a high pressure system moved into the area bringing clear skies, warm days, and cool nights.

Weather conditions at 3 representative stations in the HJA (at high, mid, and low elevations) during the flood event are summarized in Table 1. In a rain-on-snow episode, such as this, the amount of water contributed by snowmelt is always of great interest. After the 1964 rain-on-snow event at HJA, Fredriksen (1965) stated that peak flows in watersheds 1, 2, and 3 were the result of a 3-day input of over 12 inches (300 mm) of water: 8.25 inches (210 mm) of rain and an estimated 3 to 4 inches (75 to 100 mm) from snowmelt. However these figures involve substantial uncertainty. Fortunately today we are in a much better position to estimate snowmelt quantities due to the installation of lysimeters and snow pillows at selected HJA weather stations. The highest water input for the 1996 HJA flood event occurred at the Hi-15 station at 3025 ft. (922 m) elevation, where a total of 17.33 inches (440 mm) of water reached the soil surface over a 9 day period from Feb. 2 to Feb. 10 (Table 1). Almost one-third of this total (5.15 inches [130mm]) came from melted snow. Total amounts of melted snow and precipitation were lowest at the high-elevational (4250 ft. [1300 m]) Upper Lookout Station in the southeast HJA, although total input was still over 13 inches (330 mm)(Table 1).

Negative snowmelt values in Table 1 represent amounts of rain water stored in the snowpack. As would be expected, rain storage amounts were highest during the early stages of the storm. By Feb. 6 and 7 warm temperatures had taken effect and relatively large amounts of water were released from the snowpack. It is interesting to note that apparently throughout this whole episode mineral soils were not frozen at 10 cm depth. Even at the high elevation Upper Lookout Station soil temperatures were consistently above zero (Table 1). Evidently the heavy snowpack provided sufficient insulation to prevent soil freezing even during the cold period of late January and early February.

Table 1. Weather conditions during the flood at three HJA weather stations representing low, mid, and high elevations. The Primary Station is at 1430 ft. (436 m), Hi-15 at 3025 ft. (922 m), and Upper Lookout Station is at 4250 ft. (1300 m) elevation. Air temperatures (°C) were taken at a height of 4.5 m above ground surface and soil temperatures at a depth of 10 cm. An estimate of 1.25 inches (32 mm) snowmelt at the Primary Station was made using snow core depth measurements.

Date	Primary Station				Hi-15 Station				Upper Lookout Station				
	Air Temp Min	Max	Precip	Soil Temp	Air Temp Min	Max	Precip	Snow Melt	Air Temp Min	Max	Precip	Snow Melt	Soil Temp
Feb 1996	°C	°C	Ins.	°C	°C	°C	Ins.	Ins.	°C	°C	Ins.	Ins.	°C
2	-11.8	7.0	0.00	1.4	-10.3	-0.1	0.00	0.02	-4.0	2.0	0.03	-0.03	0.4
3	-8.8	4.8	0.37	1.2	-5.8	2.8	0.28	-0.07	-2.9	5.6	0.31	-0.31	0.4
4	-0.8	7.1	0.06	1.2	1.1	6.8	0.06	0.07	1.1	7.1	0.04	-0.04	0.4
5	-0.4	4.2	1.46	1.1	3.0	6.1	1.85	-0.07	3.0	6.3	1.27	-1.26	0.4
6	0.8	4.4	5.18	0.5	4.3	7.0	4.69	1.34	4.2	6.5	3.93	0.35	0.4
7	2.4	5.3	3.53	4.2	5.1	8.6	3.65	1.79	5.2	8.0	3.43	2.29	1.2
8	2.3	10.0	1.44	4.0	4.9	9.4	1.34	1.20	4.2	10.4	1.81	0.61	1.2
9	-0.8	13.6	0.42	4.1	2.7	7.1	0.31	0.65	-0.4	7.4	0.58	0.21	1.2
10	-0.6	12.4	0.00	4.2	2.7	7.8	0.00	0.22	0.6	10.7	0.00	0.00	0.7
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Total			**12.46**				**12.18**	**5.15**			**11.40**	**1.82**	
Precip+Snowmelt			**13.71 est.**				**17.33**				**13.22**		

STREAMFLOW IN THE H.J. ANDREWS

Starting in the 1950's, nine experimental watersheds have been established in the HJA. These watersheds vary greatly in size, elevation, and land management treatment (Table 2). The February 1996 flood provides insight into the dominant controls on hydrologic response of HJA watersheds to extreme water inputs. These controls include snowpack dynamics, precipitation quantity and intensity, watershed condition (i.e., harvested, old-growth, presence of roads), and channel routing. Here we examine some of these effects in light of preliminary data from HJA; some of these interpretations may evolve as more regional data becomes available.

Table 2. Characteristics of gauged watersheds on the H.J. Andrews Experimental Forest.

Watershed	Year Establ.	Area (Acres)	Elevation Range (ft.)	Mean Slope (%)	Treatment
1	1953	237	1500 - 3350	55	100% Clearcut (1962-1966)
2	1953	149	1800 - 3510	51	Control
3	1953	250	1370 - 3540	48	25% Clearcut (1963) with 1.6 miles of roads (1959)
6	1964	32	2940 - 3310	26	100% Clearcut (1974)
7	1964	38	3080 - 3610	30	90% Shelterwood (1974) w/Overstory removal(1984)
8	1964	53	3260 - 3840	26	Control
9	1969	21	1420 - 2300	60	Control
10	1969	25	1550 - 2230	55	100% Clearcut (1975)
Mack	1980	1436	2490 - 5280	47	15% Clearcut and Salvage (1962)
Lookout	1950	15424	1440 - 5310	36	30% Clearcut and Salvage (1950-1970)

Effects of snowpack dynamics on runoff

Differences in the amount of water stored in the snowpack were a primary factor influencing the relative size and timing of peak flows in small watersheds. A key aspect was whether the snowpack acted as a source for runoff water or a sink for precipitation. Snowpack and streamflow dynamics appear to be closely correlated and can be indexed by the distribution of watershed area with elevation for particular watersheds.

The role of snowpack dynamics is revealed in an examination of flood hydrographs for undisturbed watersheds WS 2 and 9 (median elevations of 2620 and 2000 ft [800 and 610 m], respectively), which have quite similar shapes, although unit peak flows for WS 2 were approximately 30 - 40 % higher than WS 9 (Fig. 4). Notable in both watersheds is an initial peak that occurred early in the evening of Feb. 6th and appears to be associated with an increase in precipitation intensity from 0.25 to 0.33 in/hr (0.65 to 0.85 cm/hr) during that period. The highest peak for both watersheds, which was one of a broad series of peaks extending over 12 hours, occurred the following morning (Feb. 7th), again in response to high rainfall intensities during the previous night. We believe that the smaller snowpack in these lower elevation basins (Table 3) did not permit substantial storage of incoming precipitation, and that streamflow in these basins was therefore tightly coupled with rainfall intensity and amount. Unfortunately we do not have accurate low-elevation snowpack measurements and can only estimate that snowpack contribution to runoff for these watersheds was relatively small (Table 1). It is worth noting that patchy snow was still present at the Primary Meteorological Station (lowest elevation) even after the storm was over.

Table 3. Summary of daily precipitation, snow pillow (snow water), and lysimeter (snow melt plus precipitation) from Upper Lookout, Hi-15, Vanilla Leaf, and Central Meteorological Stations, H.J. Andrews Forest, for February 1-10, 1996. Snowmelt is calculated as the difference between lysimeter outflow and precipitation; negative snowmelt represents snowpack storage of water. Total water available is calculated as the sum of previous day's snow water plus current day's precipitation.

		Upper Lookout								HI-15		
	Ppt.	Snow melt +ppt	Snow melt	Snow water	Total water avail.	Percent snow melt	Runoff/ Total avail.		Ppt.	Snow melt +ppt	Snow melt	Percent snowmelt
Date(Feb.)	(in.)	(in.)	(in.)	(in.)	(in.)			Date (Feb.)	(in.)	(in.)	(in.)	
1	0	0	0	23.1	23.10		0.00	1	0	0.02	0.02	100
2	0.03	0	-0.03	23.1	23.13		0.00	2	0	0.02	0.02	100
3	0.31	0	-0.31	23.3	23.41		0.00	3	0.28	0.21	-0.07	-33
4	0.04	0	-0.04	23.5	23.34		0.00	4	0.06	0.13	0.07	54
5	1.27	0.01	-1.26	23.6	24.77		0.00	5	1.85	1.78	-0.07	-4
6	3.93	4.28	0.35	24.3	27.53	8.2	0.16	6	4.69	6.03	1.34	22
7	3.43	5.72	2.29	28.7	27.73	40.0	0.21	7	3.65	5.44	1.79	33
8	1.81	2.42	0.61	26.3	30.51	25.2	0.08	8	1.34	2.54	1.20	47
9	0.58	0.79	0.21	23.3	26.88	26.6	0.03	9	0.31	0.96	0.65	68
10	0	0	0	20.2	23.30		0.00	10	0	0.22	0.22	100

		Vanilla Leaf				Central		
	Ppt.	Snow water	Total water avail.		Ppt.	Snow melt +ppt.	Snow melt	Percent snowmelt
Date(Feb.)	(in.)	(in.)	(in.)	Date (Feb.)		(in.)	(in.)	(in.)
1	0	16.5	16.50	1	0			
2	0	16.6	16.60	2	0			
3	0.29	16.6	16.89	3	0.28			
4	0.06	15.8	16.66	4	0.06			
5	1.91	14.8	17.71	5	1.94	1.4	-0.54	-38.6
6	4.85	15.0	19.65	6	4.84	4.9	0.06	1.2
7	4.03	11.7	19.03	7	3.61	4.4	0.79	18.0
8	1.61	9.8	13.31	8	1.71	3.1	1.39	45.0
9	0.37	8.5	10.17	9	0.55	1.0	0.45	45.0
10	0	8.3	8.50	10	0	0	0	

The hydrograph for the undisturbed, high-elevation WS 8 (median elevation 3520 ft [1075 m]), in contrast, shows that only one peak occurred, and that this peak was delayed and smaller than the peaks in WS 2 and 9 (Fig. 4). Unit peak flow for WS 8 was 117.6 $ft^3/s/mi^2$ (1.3 $m^3/s/km^2$), which was 30% lower than WS 9 and 40% lower than WS 2. The peak in WS 8 occurred 1 hour after the peak in WS 9 and 1.5 hours after the peak in WS 2, but the broad peak plateau for the lower elevation watersheds makes this rather arbitrary. The pattern of streamflow in WS 8 closely corresponds with the *total* input of water to the ground at the nearby Hi-15 gage, which includes both rainfall and snowmelt. Total available water increased more or less monotonically from Feb. 6th to mid-day Feb. 7th. Snowmelt measurements for Hi-15 confirm that the extensive snowpack at elevations from 2600 - 4000 ft (800-1200 m) was storing water during the early part of the storm and releasing it during the middle and later part of the storm as warm rain continued and snowpack moisture holding capacity was exceeded (Table 1). The WS 8 hydrograph tracked this trend closely, with short-term increases in rainfall intensity not reflected in changes in hydrograph shape. Release of snowpack-stored water was delayed approximately one day, however, until after the peak rainfall had passed (Fig. 6). In essence, the snowpack at upper elevations buffered the streamflow response to direct precipitation.

At elevations above 4000 ft (1200 m), the deep snowpack (measured at 23 in. [585 mm] snow water equivalent at Upper Lookout prior to the storm) effectively absorbed much of the incoming precipitation. In fact, snow moisture went from 23.6 in. (600 mm) on Feb. 5 to 28.7 in. (730 mm) on Feb. 7, declining back to 23 in. (585 mm) on Feb. 9 and continuing to decline thereafter (Fig. 6, Table 3). The moisture holding capacity of the snow and delayed melt resulted in only moderate streamflow rises. Peak runoff for Mack Creek (median elevation 3860 ft [1180 m]) was 107 $ft^3/s/mi^2$ (1.2 $m^3/s/km^2$), 11% less than at WS 8 and 46% less than at WS 2. A key factor in the delayed snowmelt from this elevation may have been the absence of strong winds that typically drive melt processes (Harr 1981). Maximum wind speeds measured during the period February 5-7 were 9.5 ft/s (2.9 m/s) at Upper Lookout and 11.5 ft/s (3.5 m/s) at Central.

In summary, this analysis points to the strong control on pattern of runoff generation from the February 1996 storm due to the interaction of snowpack dynamics with incoming precipitation and the changing nature of this interaction with elevation. Three distinct elevation zones were present: a lower elevation zone extending from approximately 1300 - 2600 ft (400 - 800 m) where melting from a relatively shallow snowpack directly augmented very high precipitation intensities, resulting in sharp peaks and record streamflows; a middle elevation zone from 2600 - 4000 ft (800 - 1200 m) where a deeper snowpack first stored then released water, so that maximum snowmelt and maximum precipitation were out of phase by approximately one day -- this resulted in proportionately lower but more sustained peak flows than in the lower elevation basins; and an upper elevation zone above 4000 ft (1200 m) where a very deep snowpack stored much of the direct precipitation throughout the storm, beginning to melt only during the latter stages of the storm, and resulting in proportionately lower streamflows than at lower elevations.

It is interesting to speculate how much larger streamflows could have been if precipitation had continued at approximately the same intensity for an additional day or two, as was originally forecast. First we assume that additional precipitation coupled with warm temperatures would have driven rapid snowmelt to increasingly higher elevations. At the end of February 7th, the last day of precipitation greater than 3 in. (76 mm), Vanilla Leaf Met Station had 11.7 in. (297 mm) of snow water remaining, while Upper Lookout Met Station had 28.7 in. (729 mm) (HI-15 does not have a snow pillow). The ratio of runoff (snowmelt + precipitation) to total water available (snow water equivalent + precipitation) at Upper Lookout was 0.16 on Feb. 6th and 0.21 on Feb. 7th (Table 3). Assuming this ratio remained at 0.20 (a conservative estimate due to snowpack ripening), and that Upper Lookout received an additional 3 in. (76 mm) of rainfall on Feb. 8th, runoff at Upper Lookout on that day would be predicted at 6.0 in. (152 mm), a 150% increase over the 2.4 in. (61 mm) actually recorded and a greater amount than on any previous day. This upper elevation melt would now be additive with mid-elevation melt, which at Vanilla Leaf was approximately equal to precipitation input. Although actual streamflows would be difficult to predict without a spatially-distributed model, peak flow increases in small watersheds 50-100% higher than those recorded on Feb. 7th seem reasonable. The synchrony of snowmelt plus precipitation from all elevation zones would have had a devastating effect on larger streams, already at record peak flows.

Peak flow at Lookout Creek crested at 10.12 feet (3.1 m), which corresponds to a flow of 9800 ft^3/s (278 m^3/s), as estimated from the 1988 rating curve. This results in a unit discharge of 406 $ft^3/s/mi^2$ (4.5 $m^3/s/km^2$), which is twice as high as any of the other watersheds (Table 4). Examination of USGS gage sites reveals at least a meter of gravel deposition in the control section for the gage, suggesting that the rating curve is probably overestimating discharge. Resurvey of the cross-section site and recalibration of the stage to discharge relation is necessary in order to get an accurate estimate of discharge for Lookout Creek.

Effects of forest practices

The overall patterns of runoff from experimental watersheds that had been clearcut in the 1960's and 1970's were similar to those observed in neighboring control watersheds, except that the peak flows were higher in all cases (Fig. 5). Unit peak flows from the lower elevation paired watershed studies showed peak flows at Watershed 1 (100% clearcut in 1962-66) were 14% greater than at Watershed 2 (control) and 66% higher at Watershed 10 (100% clearcut in 1975) than at Watershed 9 (control). Unfortunately, the discharge record was lost in Watershed 3 (25% patchcut with 6% roads) when a debris flow destroyed the gaging station. For the upper elevation pairs, peak flows were 32% higher at Watershed 6 (clearcut in 1974) compared with Watershed 8 (control), while Watershed 7 (selection cut in 1974) had peak flows 46% higher than Watershed 8.

The distinctly higher unit peak flows from harvested watersheds is somewhat surprising. Recent analyses of long-term streamflow records from Watersheds 1, 2, and 3 showed that peak flows on average may increase as much as 40% in the first five years after clearcutting, as compared to the forested control, declining to an average increase of 25% in the subsequent 25 years, with the largest storms only showing minor increases above pre-treatment levels (Jones and Grant 1996). The comparatively large increases in peak flows from all logged watersheds (14 to 66% above forested controls) for the February 1996 storm suggest that effects of forest cutting may be larger and more persistent during larger storms than previously recognized.

Forest harvesting also appears to advance the time to peak for harvested watersheds. Peak flows in Watershed 1 and 10 occurred several hours before peaks were reached in Watershed 2 and 9 (Figs. 4, 5). Watershed 1 similarly peaked several hours before Watershed 2 during during the 1964 storm. The two high elevation treated watersheds (WS 6,7) also peaked 1 to 7 hours before their forested control (WS 8). Faster rates of snowmelt from young stands regenerating in clearcuts may be responsible for these differences.

Comparison with 1964 flood

The 1996 storm is the largest storm of record for Watersheds 1, 2, (and presumably 3), 9, and 10 (Table 4). The 1996 storm discharges at Watersheds 1 and 2 were 40% and 33% higher than the 1964 storm, the previously largest storm (Figs. 7,8). The two storms hydrographs had surprisingly similar shapes, although the 1996 storm had a broader peak plateau than the 1964 storm, which had a broader base with several secondary peaks, extending 3 days longer than the 1996 event (Figs. 7,8). Gaging stations had not yet been established at Watersheds 9 and 10 at the time of the 1964 storm; the 1996 storm is, however, 31% and 28% higher at Watersheds 9 and 10 than the next highest storm of record, which occurred on January 11, 1972, prior to treatment at Watershed 10. The stage for Lookout Creek in the 1996 storm was 1.15 ft. higher than in 1964; the February, 1996 discharge is, however, suspect, as previously noted.

Table 4. Comparison of the December 1964 and February 1996 peak streamflows for the HJA gauged watersheds. When instrument malfunctions have occurred, peaks have historically been estimated using past relationships with peak flows from other similar watersheds.

Gaging Station	Year	Day	Peak Flow Time	Peak Flow Cfs	Peak Flow Cfsm[1]		Rank	Return Interval[2]	Comments
WS 1	1964	22 Dec	0500	61.2	165.2		2	22	
	1996	7 Feb	0320	84.3	227.6		1	44	
WS 2	1964	22 Dec	0950	35.0	150.4		2	22	
	1996	7 Feb	0950	46.0	197.4		1	44	Peak from PG3 recorder
WS 3	1964	22 Dec	0900	66.4	169.8	est.	1	44	Debris slide, record estimated
	1996	7 Feb	0330	56.5	144.6	est.	2	22	Debris slide, record estimated
WS 6	1964	22 Dec	1230	10.1	201.6	est.	1	34	Malfunction, record estimated
	1996	7 Feb	1210	10.0	200.4	est.	2	17	Debris filled flume, peak estimated
WS 7	1964	22 Dec	1400	11.7	197.7	est.	1	34	Malfunction, record estimated
	1996	7 Feb	1025	10.1	170.2		2	17	
WS 8	1964	22 Dec	1400	14.3	173.0	est.	1	34	Malfunction, record estimated
	1996	7 Feb	1135	13.9	168.4		2	17	
WS 9	1964	--------	------	------	--------		-	---	Gaging Station not established
	1996	7 Feb	1030	4.7	142.0		1	26	
WS 10	1964	--------	------	------	--------		-	---	Gaging Station not established
	1996	7 Feb	1130	8.7	221.6	est.	1	26	Debris slide, peak estimated
Mack Cr	1964	--------	------	------	--------		-	---	Gaging Station not established
	1996	7 Feb	1035	330.2	147.2		1	18	
Lookout	1964	22 Dec	1100	6660.	276.		2	---	
	1996	7 Feb	1100	8000.	332.	est.	1	---	USGS estimate

[1] Cubic feet per second per square mile

[2] Weibull plotting position (m/n+1) used, where m=event rank (ie., 1=largest) and n=number of events. Note that the estimated return interval for the 7 Feb storm is constrained by the period of record, which varies from 18 years at Mack Creek to 44 years at WS 2.

Comparison of the 1996 storm with the 1964 storm is limited by the lack of upper elevation meteorological data for the earlier event. A comparison of unit discharges for the lower and upper elevation basins reveals that the 1964 storm may have involved more uniform and longer runoff from all elevations within HJA. Unit area peak discharges for the 1996 storm averaged 194 $ft^3/s/mi^2$ (2.15 $m^3/s/km^2$) from the low elevation watersheds and 149 $ft^3/s/mi^2$ (1.65 $m^3/s/km^2$) at the upper elevation watersheds. Unit area discharges for the 1964 storm were 160 $ft^3/s/mi^2$ (1.77 $m^3/s/km^2$) and 191 $ft^3/s/mi^2$ (2.12 $m^3/s/km^2$) for the low and high elevation watersheds, respectively; the upper elevation peaks may be overestimated, however. The average peak discharges at the low-elevation basins were therefore 84% of the peaks for the upper elevation basins in 1964 but 130% in 1996. This implies a greater contribution from high-elevation snowmelt in 1964, possibly driven by higher wind speeds.

Overall, the 1996 storm was apparently a larger event at low elevations and a smaller event at higher elevations than in 1964. Delivery of water (and presumably sediment and wood) was more asynchronous in 1996 with less of the total watershed contributing. The 1996 event was also shorter by several days. All of these factors may have contributed to the lesser extent of geomorphic disturbance noted in the Feb. 1996 storm.

GEOMORPHIC PROCESSES AND ECOSYSTEM DISTURBANCE

Detailed study of the geomorphic and disturbance consequences of the February 1996 climatic events has not been completed. Here we describe some initial observations and present plans to capitalize on research opportunities provided by the storm. Our study objectives are to learn about disturbance regimes of debris slides, debris flows, and fluvial processes in the Andrews Forest and neighboring areas and to assess ecosystem responses to these geomorphic processes.

Our overall perspective in assessing ecosystem effects of floods is in terms of a disturbance cascade from hillslopes to small and then large streams. Debris slides on hillslopes can enter channels, triggering debris flows down small, steep channels. Debris flows deliver pulses of sediment and large woody debris to large channels. Mobilization of this and other material in large channels can contribute to channel and riparian zone disturbance. The amount and size distribution of large woody debris in small and large channels greatly affects the extent and location of disturbance. Therefore, we can assess conditions in each element of the landscape before, during, and after the flood and how disturbances cascaded through the system in order to interpret landscape patterns of ecosystem change.

Debris slides and flows

Inventories of debris slides (rapid soil mass movements on hillslopes) and debris flows (rapid movements of soil, alluvium, and organic matter down stream channels) have documented events involving more than 2,650 ft^3 (75 m^3) in the HJA and upper Blue River since 1950 (Dyrness 1967, Swanson and Dyrness 1975, Marion 1981). Prior to the 1996 storm a total of 147 debris slides were inventoried in the HJA; all but one occurred before 1976 and approximately (not all could be dated to the year) 50% were triggered in the December 1964 and January 1965 storms.

The February 1996 event was the first, major slide-triggering storm in two decades. Six mass movement events with known time of occurrence took place between about 1600 hrs Feb 6 and 0900 hrs Feb 7. Time of occurrence ranged from before the peak of streamflow in first-order streams to the time of peaks in third-order channels.

Based on incomplete inventory of slides and debris flows triggered by the 1996 event (using fixed-wing, helicopter, and field surveys), we know of 35 events exceeding 100 yd^3 (75 m^3) in the HJA. The number of slides in forest areas in 1996 is similar to that in the 1964 flood, which is consistent with similar peak flows in small watersheds at low elevations where most of the sliding occurs in HJA. The similarity of hydrology, but difference in management history leading to the 1996 and 1964 floods, presents opportunity to compare management effects on sliding. Only 4 slides that occurred in 1996 have been observed in clearcuts/plantations in comparison with 16 slides in plantations in 1964, which probably reflects the much larger area in plantations less than 15 yrs old at the time of the 1964 flood. The slides that did occur in 1996 took place in the few plantations in HJA that are younger than 20 yrs. Younger plantations are thought to have higher susceptibility to sliding because of reduced root strength and possible hydrologic effects. A total of 18 slides from the 1996 event have been observed in road rights-of-way, which is half the number observed in the 1964 flood. This may indicate that old roads have some lingering vulnerability to sliding, but at a rate lower than in the first years after construction. Further analysis and inventory are underway for HJA and neighboring upper Blue River where the management history has been different.

Roads were made impassable at 8 locations in the HJA. Large debris flows blocked culverts and spilled deposits of wood and sediment onto roads at four locations. A small, organic-matter-rich debris flow plugged a culvert, leading to erosion of a large road fill. A simple road cut-slope failure in an older plantation (1960's) and a debris slide from a younger plantation deposited soil at two sites on roads. A bridge also collapsed as a result of fluvial erosion.

Initial observations suggest that the extent of mass soil movements during the February 1996 event was less than in 1964-1965. We will examine effects of properties of the storm event (e.g., duration of exceptionally high moisture conditions as indexed by streamflow in small watersheds) and the state of the landscape (e.g., extent of recent cut areas and roads). Further field studies will complete documentation of slide and debris flow frequency with respect to plantation age and stage of vegetation succession interpreted from remote sensing (Nesja 1996), as well as road age and construction practices. These data can be used to evaluate effects of changes in forest management and policy on occurrence of debris slides and flows. We will also assess slide frequency as a function of type of slide, e.g., planar slope, channel head, streamside, and earthflow-associated.

Stream channel/riparian vegetation change

Stream and riparian zones exhibited quite a range of responses to the events of February 1996. Small channels, such as those in the experimental watersheds, experienced major debris flows (WS 3), minor debris flows (WS 10), or simply high streamflow (e.g., WS 1, 2, 9). The major debris flow in WS 3 (Fig. 9) sent a flow several meters thick (9 to 15 ft.) and probably more than 10,000 yd^3 (7500 m^3) in volume down the channel, removing riparian vegetation, scouring the base of hillslope, and mobilizing alluvium. Secondary streamside slides and slumps followed, beginning the process of replenishing sediment and woody debris stored in the narrow valley floor of this small drainage. The minor debris flow in WS 10 had a volume of only 100-300 yd^3 (75-225 m^3) and included snow. It modified the streambed but did not extensively scour the banks (some areas were protected with snow). The debris flow also damaged, but did not destroy, the gage house. WS 3 experienced multiple, major debris flows in 1964 (Fredriksen 1965) (Fig. 9) and WS10 also had one 900 yd^3 (700 m^3) debris flow in 1986. The 1996 flows appear to have been less voluminous in part because inorganic and woody material had recently been scoured from the channels.

Small channels not experiencing debris flows, such as WS1 and Mack Creek, had channel form, woody debris configuration, and riparian vegetation remain largely unchanged except for very local modifications. Damage was interpreted in part by distinguishing patches of freshly moved, moss-free sediment from the mossy rocks that had not moved during the event. Sites of long-term woody debris observations, especially Mack Creek, did not experience major modification.

The mainstem of Lookout Creek (fifth-order) experienced boulder transport audible for more than 24 hrs (morning of 2/7 to midday 2/8) and movement of large logs (morning of 2/7). G.Grant videotaped some of this movement during the morning of Feb 7. Maps of the lower 3.7 mi. (6 km) of the Lookout valley floor, channel cross section sites, riparian vegetation plots, and data from the Stream Nutrient Addition Experiment will provide important reference points for assessing changes in channel and aquatic and riparian ecosystem conditions. Initial impressions are that there are zones of major and more minor change in channel and riparian conditions. Greatest change appears to have occurred in areas of wide valley floor above and below the Concrete Bridge and below the confluence with WS3 near the HJA Headquarters and the Nutrient Addition Experiment. In these cases the flood removed much of the vegetation on the 1964 flood surfaces (commonly alder or willow covered), but erosion was limited on higher and older, conifer-covered floodplain surfaces. Woody debris was mobilized, generally washed downstream and deposited on mid-channel bars or at the channel margin above low flow levels. The entire channel bed appears to have been reworked and local aggradation and/or degradation may exceed 3 ft. (1 m). Determination of the exact change in channel level awaits resurvey of channel cross sections; surveys began in 1978 and were last surveyed in 1995. Elsewhere along the mainstem of Lookout Creek disturbance was less extensive, generally modifying some of the 1964 flood-initiated surfaces, but not completely resetting them.

Mobility of large woody debris is a crucial aspect of channel and riparian change--it appears that greater wood movement corresponds with greater channel and floodplain disturbance. We can assess wood mobility in many areas based on repeated mapping and resurvey of tagged logs, including sites where wood has been placed in channels as part of stream habitat restoration experiments. In lower Lookout large wood pieces up to 100 ft. long (30 m) moved downstream on Feb. 6 and Feb. 7 oriented longitudinally along the channel. In many cases this appeared to be material which had fallen into the channel since 1964 (e.g., see Nakamura and Swanson 1993, Fig. 7) and material delivered by the 1996 debris flow(s) in Watershed 3. At other sites, such as Mack Creek where we annually observe location of over 1500 marked pieces of woody debris, there was little movement.

Our overall impression is that valley floor disturbance was less extensive in the 1996 event than in 1964-1965. In Lookout Creek, channel and channel unit (e.g., pool, riffle) positions generally remained in place with some important exceptions at the sites mentioned. We will attempt to determine the extents to which these patterns were controlled by differences in properties of the storms or in watershed conditions. It does appear that mobilization of woody debris in small and large channels was less extensive in 1996 which may be a critical factor in overall watershed response. Lower woody debris mobilization can arise from: (1) fewer debris slides to trigger debris flows which entrain and transport woody debris from small to large channels, (2) less wood in channels because of changes in logging practices since 1965 and flushing of channels by debris flows in 1964-1965, or (3) lower and/or less sustained high flows which transport woody debris.

STREAM ECOLOGY

Alteration of stream channels and riparian vegetation by the February flood was extremely patchy. Some reaches exhibited major channel shifts, with channels moving laterally more than 160 ft. (50 m). Other reaches experienced extensive movement of sediments through existing pools and riffles. Even though flows were 3-10 ft. (1-3 m) above the winter base flow, bedforms and riparian plants communities in some reaches showed only minor changes, such as removal of organic litter. This mosaic of disturbance patches of differing intensity created a complex picture of biotic responses to a major flood.

The response of critical ecological components (populations, functional groups, communities, ecosystem processes) to the flood may playout over weeks to months, but others require years to decades for recovery (Table 5). In frequently disturbed systems, such as streams, life history and behavioral adaptations emphasize rapid dispersal, recolonization, and reproduction. Past studies of flood and debris flows at HJA have shown that the initial biotic response of aquatic systems to disturbance is extremely rapid (Lamberti et al. 1991), but this research focused on debris flows that occurred during a relatively small flood (9-yr recurrence interval). The flood of 1996 was much larger, and disturbance patches were more extensive over the landscape.

Table 5. Examples of hypothetical species response to flood disturbances. Refugia and life history characteristics that determine resilience to flooding are identified for examples of organisms that we hypothesize will exhibit slow, intermediate, and rapid rates of recovery.

Taxa	Refugia	Dispersal	Reproduction	Recovery Time
Slow (>5 yr)				
• Conifers	Floodplains Upland Undisturbed riparian patches	Fall seed dispersal	Seeds	>30 yr
• Aquatic lichens	Boulders, bedrock	Dispersal by spores	Low spore production	>10 yr
• Giant salamanders	Secondary channels Streambed interstices Tributaries	Limited crawling Terrestrial phase	Long egg development Nest guarding	>5 yr
• Sculpins	Streambed interstices	Weak benthic swimmer No leaping ability	Low fecundity	>5 yr
Intermediate (1-5 yr)				
• Cutthroat trout	Secondary channels Channel margins Floodplains	Strong swimmer Leap over small waterfalls	High fecundity	1-3 yr
• Upland early successional plant species	Upland logged areas Roadsides	Wind dispersed seeds	Seeds	1-2 yr
• Willow	Floodplain margins Higher terraces Undisturbed riparian zones		Beaver cuttings Agressive sprouter Spring seed dispersal	<5 yr
• Red alder	Upland Undisturbed riparian patches		Fall seed dispersal	
• Caddisflies	Shallow margins Floodplains	Behavioral drift Catastrophic drift	Terrestrial mating 26-52 wk generation time	1-3 yr

	Hyporheic zone	Aerial dispersal		
• Stoneflies	Shallow margins Floodplains Hyporheic zone	Crawling Catastrophic drift Aerial dispersal	Terrestrial mating 52-104 wk generation time	3-6 yr
• Dragonflies	Shallow margins Floodplains Hyporheic zone	Behavioral drift Catastrophic drift Aerial dispersal	Terrestrial mating 52-104 wk generation time	3-6 yr
Fast (<1 yr)				
• Aquatic algae	Crevices in rocks	Sloughed cells	Vegetative reproduction Sexual reproduction Auxospores	<3 months
• Midges	Crevices in rocks Shallow margins Hyporheic zone	Behavioral drift Catastrophic drift Aerial dispersal	Terrestrial mating 4-12 wk generation time	3-6 months
• Mayflies	Shallow margins Floodplains Hyporheic zone	Behavioral drift Catastrophic drift Aerial dispersal	Terrestrial mating 8-24 wk generation time	6-12 months

Physical processes of erosion and deposition during a flood create disturbance patches on which aquatic and riparian communities either survive or recolonize (Townsend 1989). Biotic responses are characterized by both resistance to change during the event and resilience after the event (Sousa 1984, Pickett and White 1985). Post-disturbance biological responses will be determined by 1) patchiness of the disturbance across the landscape, 2) habitat relationships, 3) dispersal processes, 4) reproductive strategies, 5) biotic interactions and competition, and 6) links between patches through the river network. The following observations are preliminary indications of the responses of aquatic biota to the flood, but we will be able to present a more accurate perspective after the research this summer and fall.

Aquatic plant communities

Aquatic plant communities in Cascade Mountain streams are characterized by thin films of benthic algae. These microscopic plants reproduce rapidly (24-48 hr) and occupy microscopic crevices in the surfaces of rocks and wood. These algal communities have recovered rapidly to pre-flood abundances in many reaches. By early summer, different reaches and streams differ greatly in algal abundance. This may be related to local physical or chemical factors, or it may reflect differences in the abundance of herbivorous invertebrates.

Mosses and aquatic lichens grow more slowly and must establish more complex basal cells and stems. Where these plants have been scoured from boulders and bedrock, recovery will be much slower and may require several years to attain pre-flood abundances.

Aquatic invertebrate communities

Aquatic insects and other invertebrates exhibit a wide range of life history characteristics that allow them to survive the flood or recover after the flood. Many of these invertebrates have early life history stages that live deep within the streambed or along the margins of the stream. Many of these individuals may have a greater probability of surviving the flood than those associated with sediment surfaces along the streambed. After the flood, patterns of dispersal and reproduction are important factors in recovery.

As aquatic invertebrate adults lay eggs, their offspring can reoccupy stream habitats. Species with very short generation times (e.g., midges, mayflies, blackflies, mosquitos) may be able to increase their populations very rapidly. Species with one-year generation times (e.g., caddisflies, snails, crayfish) will recover over the next 2-5 years. Species with longer generation times (e.g., stoneflies, dragonflies, wood-eating beetles) may require 5-10 years to recover to pre-flood abundances.

Recolonization of stream habitats by invertebrates will be determined by dispersal behavior. Species that drift in the current as a method of movement (e.g., midges, mayflies) will quickly re-occupy the open habitats, but slow moving or attached species (e.g., caddisflies, clams) will take months to years to spread throughout the stream network. Other crawling species (e.g., stoneflies) will disperse to empty habitats at intermediate rates.

Our observations in Summer 1996 indicate that invertebrate abundances vary greatly among streams or reaches. Many streams contain substantial numbers of caddisflies along the margins and backwaters, but other streams have very few caddisflies. Stonefly populations are patchy throughout most reaches, with very low numbers in many areas but average densities of older nymphs in other patches. We will be quantitatively sampling invertebrates later in the summer.

Aquatic vertebrate communities

Aquatic vertebrates, both salamanders and fish, are affected by the same controls of survival and dispersal described for the invertebrates. Trout fry have been found in all stream reaches, though they emerged from the gravels several weeks later than normal. This indicates that surviving adults were able to spawn successfully in March-May 1996. Adult salmonids are present in all stream reaches and appear to have lower populations than pre-flood years. We will quantify these population in mid to late summer. Sculpins live in or on the streambed and their numbers are much lower than pre-flood abundances. Surprisingly, Pacific giant salamanders appear to have population sizes that are equal to the pre-flood levels, and there are many young salamanders in the populations.

Stream restoration projects

Effects of the 1996 flood on stream habitat restoration projects can be assessed by examining two habitat restoration experiments. A total of 27 stream habitat structures were placed in Lookout, Tidbits, and Quartz (N) Creeks in 1994 as part of the Pool Complexity study. These structures consisted of 2 to 8 pieces of conifer wood with length 20+ ft. (6+ m) and 2 to 4 30-yr-old alder trees in some treatments. Most structures were cabled in place and configured with standing streamside trees or large (diameter > 3 ft. [1 m]) boulders to enhance stability. The wood in Tidbits and Quartz Creek sites experienced very minor change during the flood, although there was significant change in pool morphology in some cases. The 9 wood structures in Lookout Creek were washed away, experienced removal of most pieces, or abandoned by the channel when change in channel position took place. In another experiment in Quartz (South) Creek 48 structures were placed in 1988, a third were cabled fully, a third cabled at one end, and the remainder were uncabled. During the 1996 flood none was removed and one new debris accumulation was created naturally.

RESEARCH OPPORTUNITIES

Obviously the flood of February, 1996 in the H.J. Andrews Forest presents us a wide range of research challenges. Soon after the flood we began to record research opportunities which were immediately apparent. Some of these ideas, but by no means all, are listed below:

- Detailed examinations of stream hydrographs during the flood should be conducted in order to further define relationships with logging treatments and vegetation successional stage and roads.
- We need to carefully document changes in stream channel characteristics and riparian vegetation caused by the flood. Vegetation recovery rates should be monitored, at least on an annual basis.
- Channel units should by mapped in three dimensions to test hypotheses on long-term stability/persistance of channel units in relation to formative events and determine the proportion of the valley floor reset by this flood versus earlier disturbances.
- For the several major stream restoration projects installed prior to the flood:
    1. To what degree did different restoration projects survive the flood event and why?
    2. How did restoration features modify the physical and biological effects of the flood?
    3. Did aquatic communities within the range of the restoration projects respond differently to the flood event than communities in degraded reaches?
- Fish and amphibian populations have been studied in many stream reaches within the HJA (Lookout Creek, Mack Creek, etc.). What effect did the flood event have on these populations and what are the immediate post-flood changes?
- Much of the woody debris in several stream reaches has been tagged, affording an excellent opportunity to study the effects of a major flood event on the distrubution of the deposition of new wood and previously incorporated wood elements. The principle hypothesis is vulnerability for wood transport is a function of geomorphic location, accumulation, and stabilizing factors.
- Algal and invertebrate trophic responses have been studied for several years in reaches of Lookout and Mack Creeks. How did the flood affect degree of change in abundance and rate of recovery? How does rate of recovery differ in different habitats (pool, riffle) and different riparian reaches (clearcut, old-growth)?
- How did the flood affect particle size distributions (frequency of large boulders, fines, etc.) in various stream reaches? These measurements will test hypotheses on relative strength of fluvial versus exogenous controls on grain-size distribution, particularly the input of large boulders to the channel.
- A complete inventory of landslides and debris flows should be made for the HJA and the entire Blue River drainage. Size, morphology, vegetation, soils, geologic characteristics, as well as any possible contributing factors should be noted. Number and characteristics of landslides can then be compared to those which occurred during the 1964-65 flood and other events.

SUMMARY AND CONCLUSIONS

The flood of February 7-9, 1996 produced record peak discharges in much of the H.J. Andrews Experimental Forest. Like other major floods in this region which are typically caused by "rain-on-snow" conditions, this peak discharge occurred when a subtropical storm dropped rainfall and melted a previously accumulated snowpack. In this storm event, peak discharges at small low-elevation basins were up to 40% higher than the next highest storm which occurred in December 1964, but at small high-elevation basins peak discharges were as much as 30% lower than the storm of 1964. This spatial pattern of runoff, combined with data on storm event duration, soil temperature, snowpack moisture storage and melt rates at low and high elevations, supports the hypothesis that the high-elevation snowpack contributed less to peak discharge in the 1996 event than it had in the 1964 event.

Unit area peak discharges in the 1996 event were higher in harvested basins than in control basins for all five treated/control basin pairs, but unit area discharges also were higher prior to treatment in treated versus control basins for large peak discharge events such as those of 1953, 1964, and 1972. Very small sample sizes, especially of pre-treatment large peak discharges, limit our ability to detect and quantify the effect of forest harvest on peak discharges.

Disturbance effects of this flood and earlier large floods such as the 1964 event are not directly related to the magnitude of peak discharge. Based on an initial assessment, this flood produced fewer debris slides and debris flows, moved less large wood, destroyed less riparian vegetation, and reworked fewer riparian surfaces than the flood of December 1964. Disturbances were patchy, with greatest changes in debris-flow affected small channels and in the unconstrained reaches of the main stem. Changes in stream organism populations reflected this patchiness, with large changes in some areas and no detectable changes on others; organisms able to escape the immediate flood effects showed the least response. Of the populations depressed by the flood those with short generation times (e.g. insects) or those whose competitors were reduced (e.g. some fish) are expected to recover most rapidly.

Two factors may explain the overall lesser extent and severity of the 1996 flood compared to the 1964 event. First, the lower peak discharges in high elevation sub-basins may have contributed to lower peak discharges and less disturbance in the main stem of Lookout Creek. Second, in 1964 as much as 15% of the basin area had <15 year-old clearcuts and there were ~80 km of roads <15 years old, whereas in 1996 there were only 2% of the clearcuts and <20 km of roads <15 yrs old. In addition, harvest and road-building methods had been modified to mitigate prior flood impacts. Hence, we infer that there was less available large wood in clearcuts and less length of unstable roads during the 1996 compared to the 1964 event.

LESSONS FROM THE STORM

Our observations from the most recent storm event provide an opportunity to consider how to best measure and monitor future large storm events. Some lessons gained from the 1996 storm include:

1. **Importance of snowpack dynamics:** Much of the story of the 1996 storm is in how the snowpack responded to precipitation. Given that most major events in the Oregon Cascades are likely to be rain-on-snow, accurate measurements of snowpack dynamics, including areal extent of snow depths, snow water equivalent, and melt rate, are vital. All meterological stations should be equipped with snow pillows, snow lysimeters, and heated rain gages. Some redundancy in data recording should be considered to minimize loss of data. Snow course measurements should be a regular part of field routine during winter months.

2. **Difficulty of access:** During major storms, access within the watershed may be extremely limited. Key measurement stations need to be able to function for extended periods without servicing, while providing continuous remote access to data. Radio telemetry at HJA was very useful in providing snow water availability values for the two high elevation meteorological stations, however key snowpack data were missing from the two lower elevation stations. Streamflow information should also be telemetered.

3. **Prioritize and assign observations for storm periods:** We missed opportunities to have additional detail on storm dynamics and landscape responses by not having decided prior to the storm what was important to measure. Some additional measurements/observations for major storms might include: 1) Snowpack sampling for water content at 2 hour intervals to calibrate lysimeters; 2) Observations on extent of snow cover in forest, plantation, and open areas at 6 hour intervals; 3) observations on interactions between roads and streams (i.e., where is water flowing down road beds?); 4) suspended sediment samples from accessible streams, including Lookout Creek; 5) video and still photography from key reference locations (i.e., below Administrative Site, concrete bridge, small watersheds).

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Figure 1. Map of the H.J.Andrews Experimental Forest showing locations of experimental watersheds and weather stations.

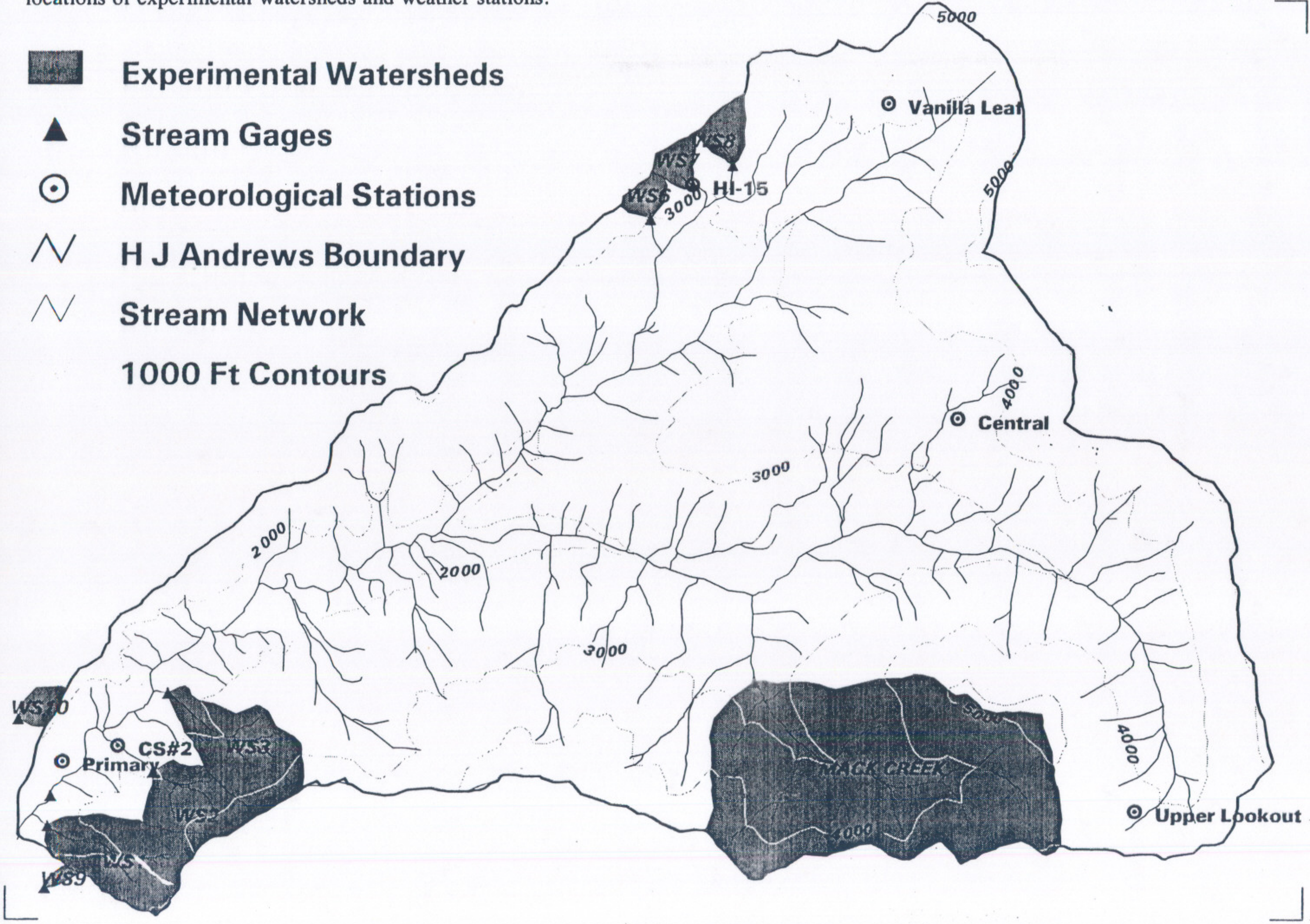


Figure 2. Daily precipitation and average air temperatures during the period of Jan. 13-Feb. 13, 1996 at Primary Weather Station elev. 1,430 ft. (436 m) in the HJA.

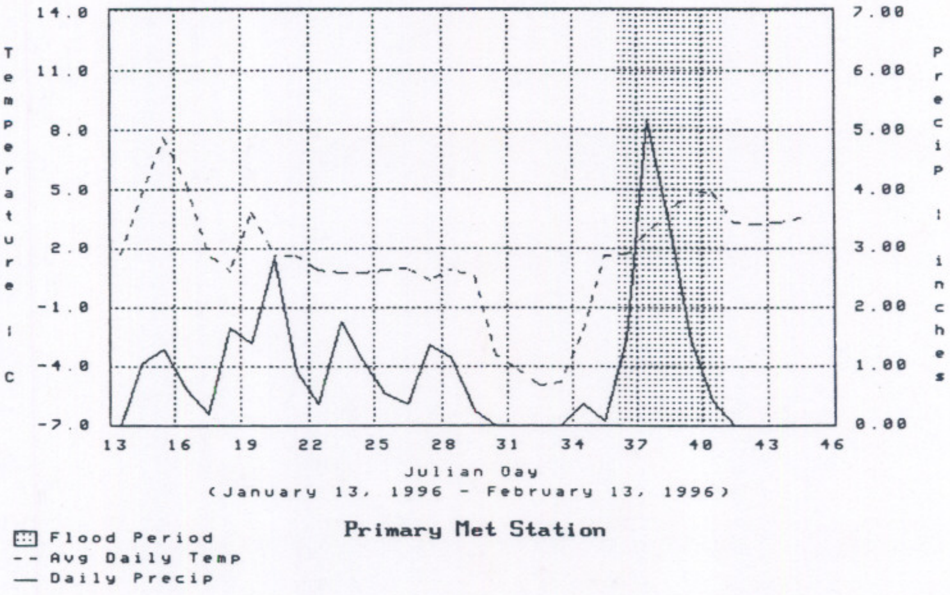


Figure 3. Daily precipitation and average air temperatures during the period of Jan. 13-Feb. 13, 1996 at Upper Lookout Weather Station elev. 4,250 ft. (1300 m) in the HJA.

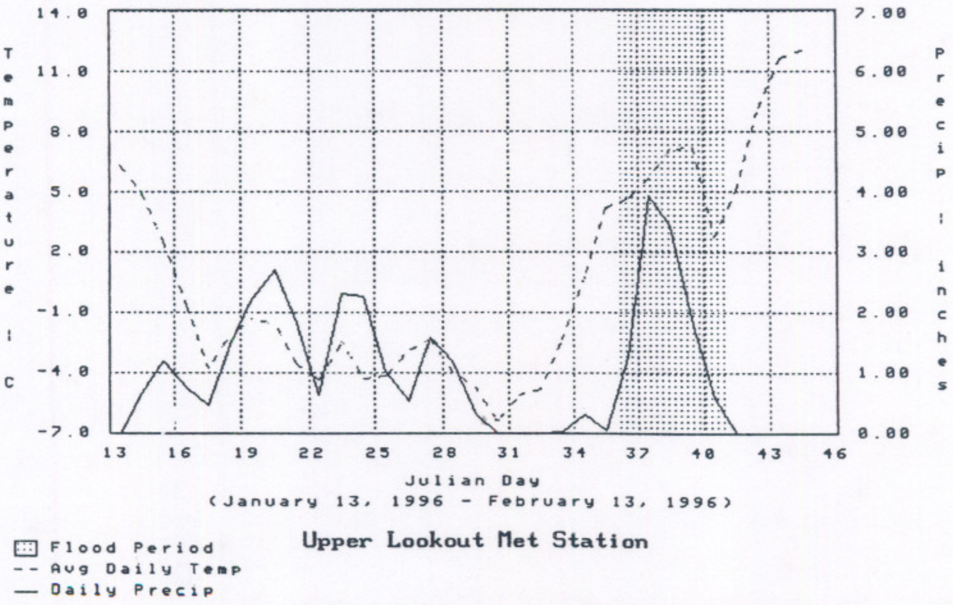


Figure 2. Daily precipitation and average air temperatures during the period of Jan. 13-Feb. 13, 1996 at Primary Weather Station elev. 1,430 ft. (436 m) in the HIA.

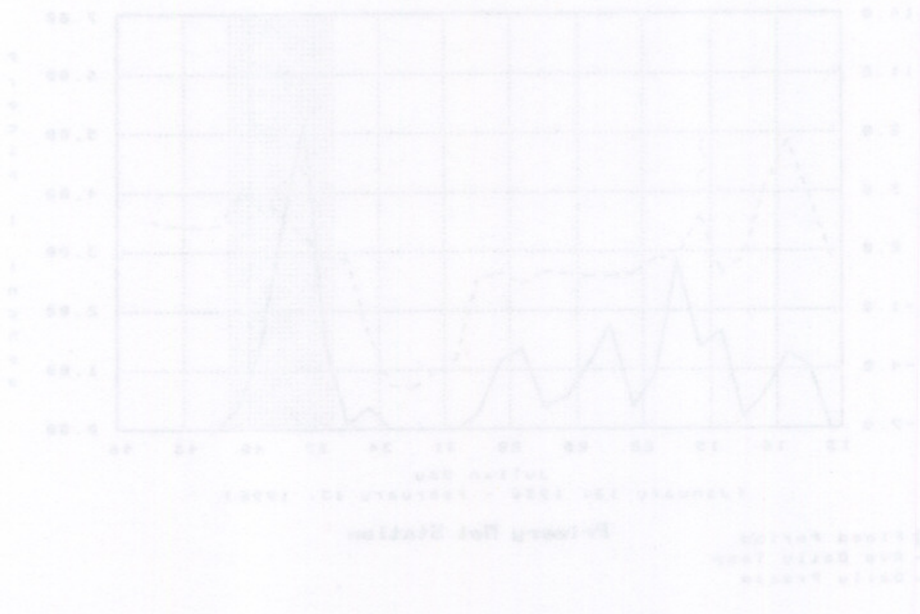


Figure 3. Daily precipitation and average air temperatures during the period of Jan. 13-Feb. 13, 1996 at Upper Lookout Weather Station elev. 4,250 ft. (1300 m) in the HIA.

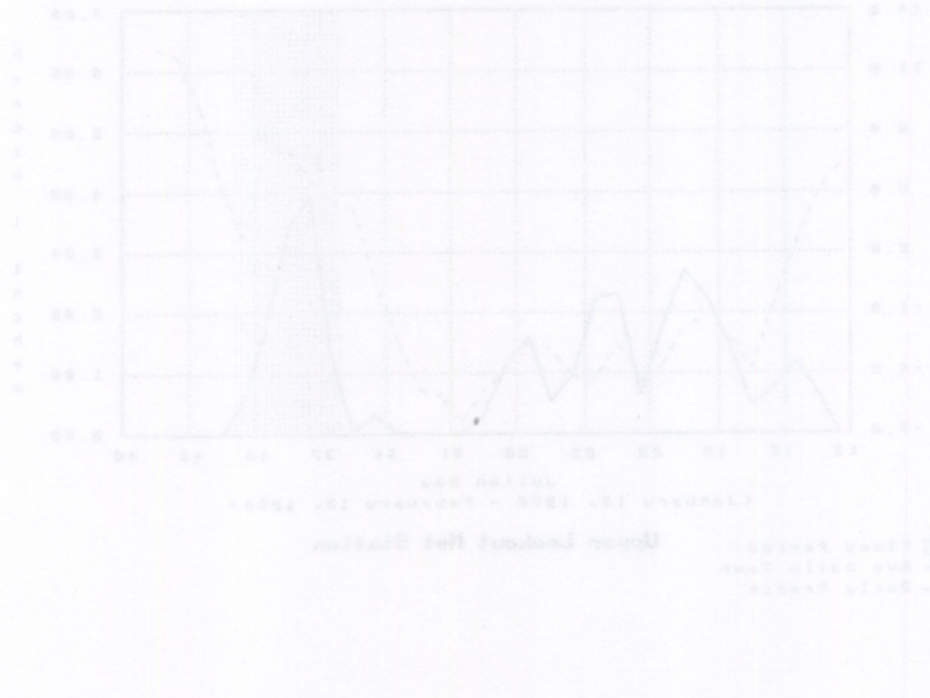


Figure 4. Flood hydrographs for control (undisturbed) watersheds with rainfall and snowmelt at 6-hour intervals for the Hi-15 Station (near WS 8). Streamflow is on an area basis (Cubic feet/second/square mile).

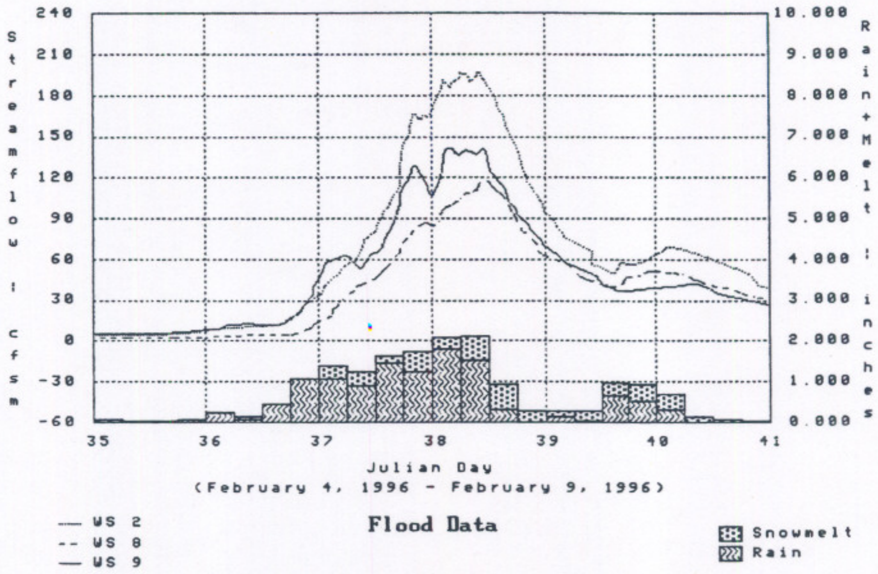


Figure 5. Flood hydrographs for clearcut logged and revegetating watersheds with rainfall and snowmelt at 6-hour intervals for the Hi-15 Station (near WS 7). Streamflow is on an area basis (cubic feet/second/square mile).

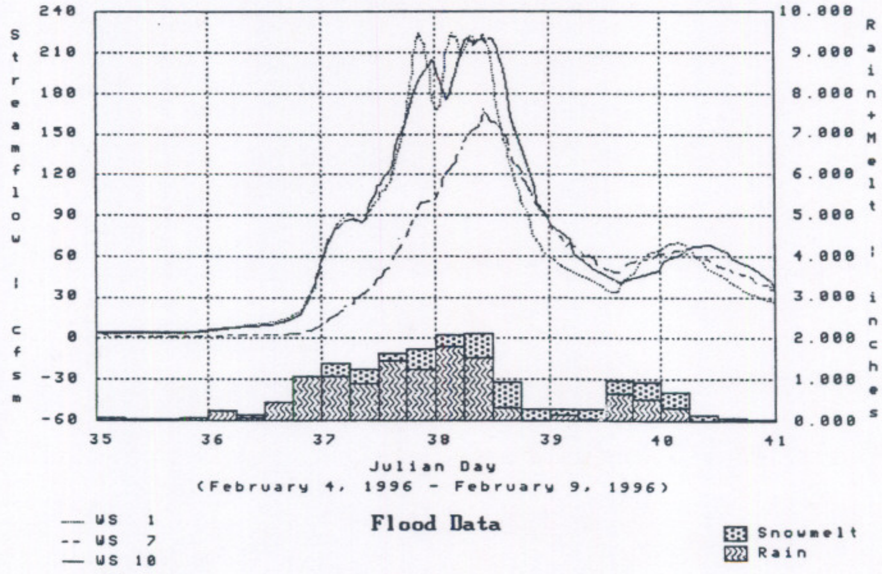


Figure 6. Summary of daily precipitation and snowmelt data from Upper Lookout, Hi-15, Vanilla Leaf, and Central meterological stations, H.J. Andrews Forest, for February 1-10, 1996. Snowmelt is calculated as the difference between lysimeter outflow and precipitation; negative snowmelt represents snowpack storage of water.

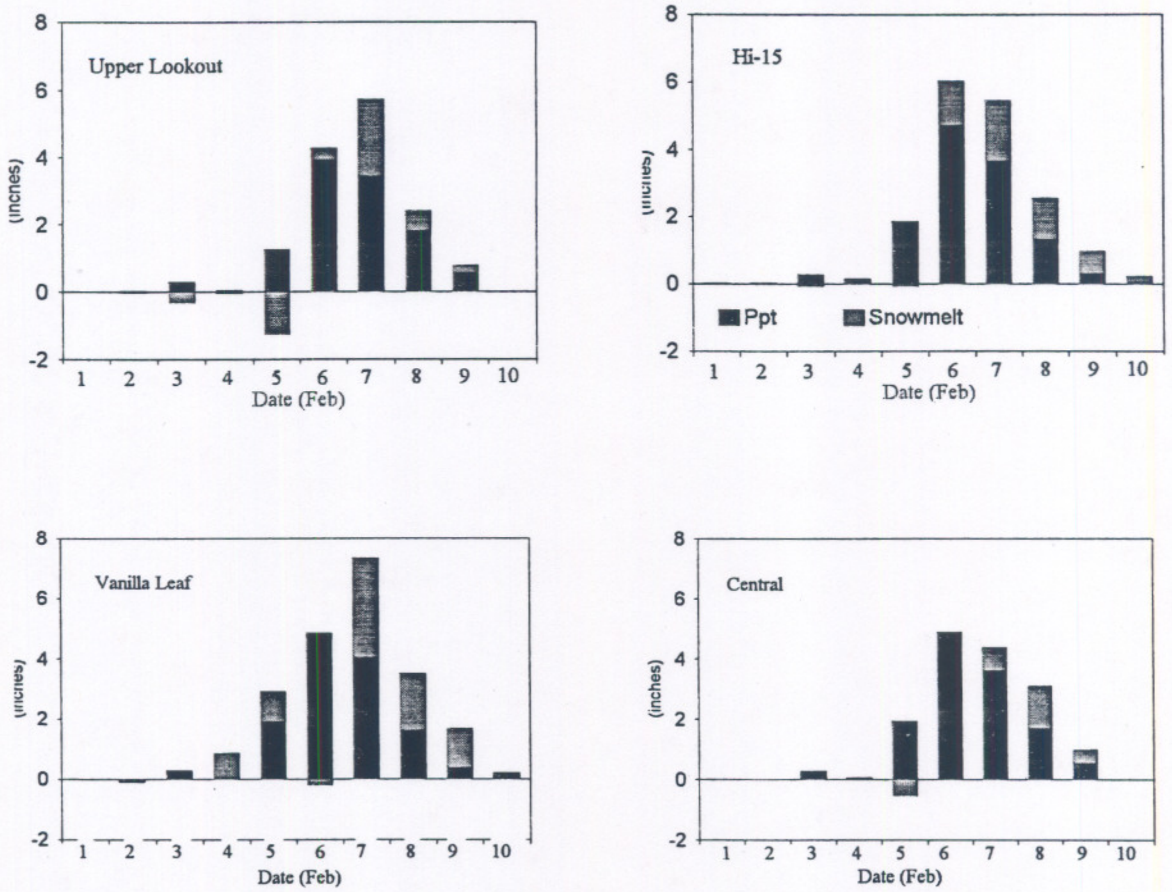


Figure 7. Comparison of Watershed 1 flood peaks of Feb. 1996 and Dec. 1964.

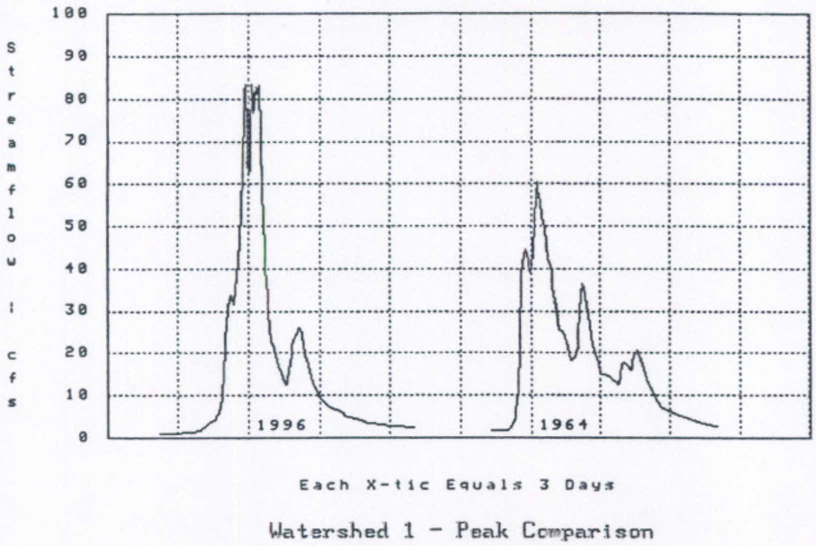


Figure 8. Comparison of Watershed 2 flood peaks of Feb. 1996 and Dec. 1964.

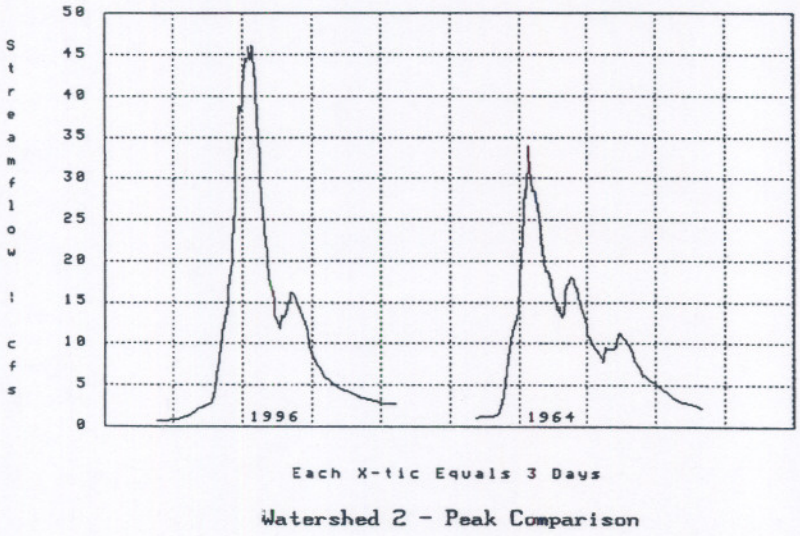
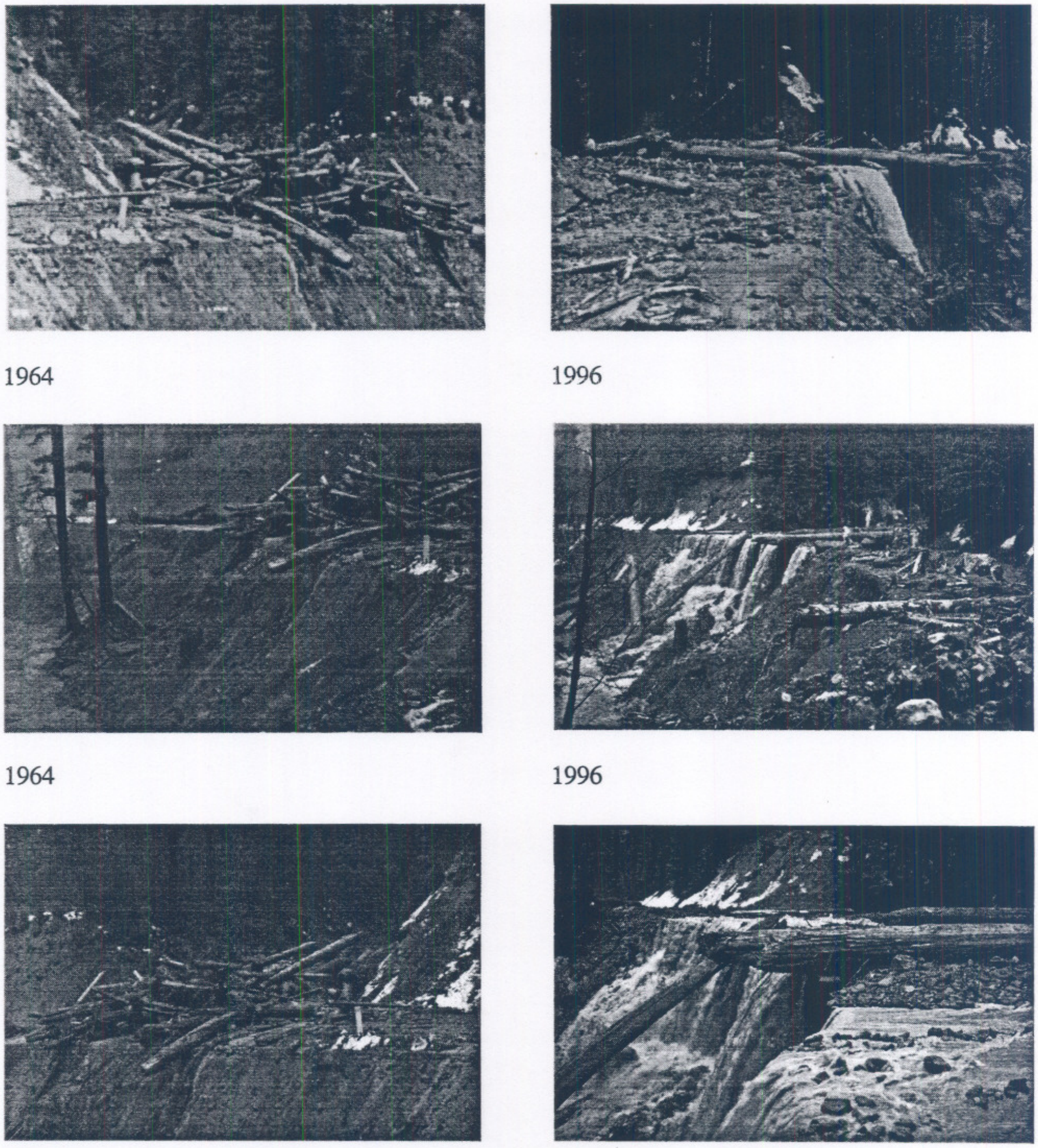


Figure 9. Comparative photos of woody debris deposition from debris flows in Watershed 3 during storms of Dec., 1964 and Feb., 1996. Both events destroyed the WS 3 gauging station.



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