

Influence of Timber Harvest on Rain-On-Snow Runoff: A Mechanism for Cumulative Watershed Effects

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ABSTRACT

Rain-on-snow dominates many geomorphological processes in the Pacific Northwest. Wind-aided transfers of heat to snow during rain-on-snow comprise the largest source of heat for snowmelt during rainfall. Recent field research in western Oregon and western Washington has shown that timber harvest and thinning can increase both snow accumulation and the wind-aided transfers of heat, resulting in higher rates of water delivery to soil during rain-on-snow conditions. Increased rates of water delivery to soil can lead to higher streamflows and to landslides on marginally stable slopes. Because of the magnitude of increase in water delivery to soils during common rain-on-snow conditions and a hydrologic recovery period that may require 40 years, rain-on-snow runoff is an important mechanism whereby forest management activities might cumulatively affect water resources.

INTRODUCTION

The cumulative effects of forest management activities on water resources have been receiving increasing attention in the Pacific Northwest. The National Environmental Protection Act of 1968 specified that the environmental effects of a proposed activity must be evaluated within the context of past activities and those planned for the foreseeable future (Council on Environmental Quality, 1978). In the State of Washington, Forest Practices Rules have been amended to reflect results of recent research on the effects of timber harvest on rain-on-snow runoff (Brunengo et al., in press). Rain-on-snow appears to be one mechanism whereby forest management can cumulatively affect water resources, because removal of forest vegetation can affect rate of water delivery to soil during cloudy-weather melt.

Rain-on-snow is the common name for cloudy periods when warm winds and rain combine to melt snow rapidly. In a broader sense, rain-on-snow has also included snow accumulation prior to snowmelt during rainfall. Rapid inputs of water to soils in steep, moun-

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tainous topography during-rain-snow have been responsible for the majority of high streamflows and flooding in the Pacific Northwest (Harr, 1981; Harr and Cundy, in press) as well as many landslides (Johnson, 1991).

The purpose of this paper is to review what is known about rain-on-snow and how it can be affected by forest management activities in the Pacific Northwest.

WHERE RAIN-ON-SNOW OCCURS

Western slopes of the Cascades and Sierras, as well as windward slopes of other mountain ranges subject to maritime weather patterns, are particularly prone to rain-on-snow events (Fitzharris et al., 1980; Harr, 1981; Berg et al., 1991). Snowpacks in these areas tend to be relatively "warm" in that their internal temperatures remain near 0° C (Smith, 1974). Thus, these snowpacks require little heat to initiate melt.

Although rain-on-snow is most common in the lower and middle elevations of the western Cascades of Washington and Oregon, it can occur from sea level to the highest elevations. Rain-on-snow is of major concern at lower and middle elevations because of the greater frequency of both snowfall and warm rainstorms that occur in that zone during fall and winter. Snowpacks at higher elevations may be deep and cold enough to absorb much of the added rainfall and heat input and yield little water outflow during rain-on-snow (Berg et al., 1991). On the other hand, snowpacks at lower elevations are commonly shallow and can yield outflow water quickly. These packs, in the elevation band known as the transient snow zone (roughly 300-900 m or 1,000-3,000 ft in the Washington Cascades), are often completely melted during rain-on-snow (Harr, 1981; Berris and Harr, 1987).

Rain-on-snow also occurs on the east side of the Cascades. Many east-side streams exhibit the spring snowmelt runoff characteristic of the more continental climate, but highest streamflows of record for most east-side streams have resulted from rain-on-snow. Rain-on-snow may also occur during fall and early winter in northern Idaho and western Montana.

RAIN-ON-SNOW RESEARCH

Soon after settlement began in the Pacific Northwest, rain-on-snow was recognized as the cause of the largest floods (Harr, 1981). In its comprehensive snow research program from 1945-1954, the U.S. Army Corps of Engineers (1956) examined cloudy-weather melt as a major source of runoff to be handled by flood-control structures. This research showed that the greatest source of heat for snowmelt during cloudy weather was the combined turbulent exchanges of sensible and latent heats followed by advected heat (heat contained in rain) and long-wave radiation. Short-wave radiation was an insignificant source of heat during rain-on-snow.

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Anderson and Hobba (1959) reported logging increased size of rain-on-snow peak flows (as well as peak flows caused by only rain and only snowmelt) in Pacific Northwest watersheds, but apparently this finding was largely ignored. Subsequent research in small, gaged watersheds in western Oregon revealed that timber harvest, by reducing evapotranspiration, resulted in wetter soils at the end of the growing season. Rothacher (1973) reported such wetter soils caused higher peak streamflows in the early fall but not in the winter. This helped establish the persistent belief that timber harvest had little effect on winter runoff after soil moisture had been recharged (Hess, 1984).

WESTERN OREGON RESEARCH

Early Observations

In 1971, when the senior author began forest hydrology research in the H. J. Andrews Experimental Forest in western Oregon, he was advised that the western Cascades below about 1060 m elevation were dominated by rain, and the small amounts of snowfall at middle elevations were inconsequential. Yet during his preliminary field work in the winter of 1971-72, he observed that shallow snowpacks were melting rapidly during warm, windy periods of rainfall whenever the highest flows occurred. Similar observations in the next few years seemed to indicate snow was much more important than was generally believed.

Though the senior author's field observations appeared to conflict with current hydrologic perceptions, he did not become formally involved in rain-on-snow research until 1976, the first year after watershed HJA-10, a 10-ha watershed in the H.J. Andrews Experimental Forest, was clearcut. In watershed HJA-10, postlogging storm hydrographs associated with snow had significantly lower peaks than exhibited by prelogging hydrographs (Harr and McCorison, 1979) (Figures 1 and 2). During rainfall, both logged HJA-10 and unlogged HJA-9 responded identically to precipitation, but when precipitation changed to snow, the logged watershed was less able to generate runoff. These lower peak flows were attributed to snow interception; snow intercepted by the forest canopy in the unlogged watershed was more exposed to the various types of heats during cloudy-weather melt, melted more quickly, and produced higher flows during storm runoff. Snow in the logged watershed accumulated on the ground, was less exposed to heat exchange, and its slower melt caused lower, delayed peak flows.

Historical Review of Rain-on-Snow

Questions about rain-on-snow that were raised during the analysis by Harr and McCorison (1979) led to a historical review of snowmelt during rainfall in western Oregon and to an analysis of the potential effects of timber harvest on rain-on-snow runoff. Using snowmelt indices derived by the U.S. Army Corps of Engineers (1956), Harr (1981) hypothesized that timber harvest could increase

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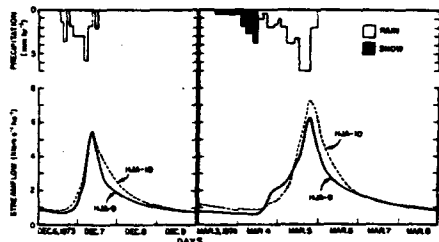


Figure 1. Typical prelogging storm hydrographs at watersheds HJA-9 and HJA-10 (after Harr and McCorison, 1979).

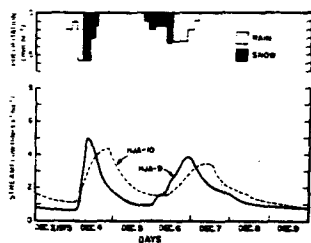


Figure 2. Initial postlogging storm hydrographs at watersheds HJA-9 and HJA-10. The forest in HJA-10 was clearcut (after Harr and McCorison, 1979).

rate of snowmelt during rainfall by 40-100% or more in certain situations (Figure 3). However, because rainfall nearly always contributes much more water than does snowmelt during rain-on-snow runoff, typical increases in total water input to soil would more likely be about 10-12% (Figure 4) (Harr, 1981). Nevertheless, an increase in total water input of only 10% at the H.J. Andrews Experimental Forest would roughly double return period of water input events caused by rain-on-snow. In other words, timber harvest could cause water input to soil of a magnitude that would occur, on the average, only every 25 yr under forest whereas the same weather conditions after harvest would result in water input to soil that would occur, on the average, every 12 yr under forest. This analysis, however, considered only increases in melt rate and did not include increases that might result from differences in snow accumulation between a clearcut area and adjacent forest.

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Energy Balance Study

A field study was begun at the 900-m elevation in the H.J. Andrews Experimental Forest in western Oregon in 1982 (Berris and Harr, 1987). This study compared snow accumulation and rate of melt during rainfall between a recent clearcut area and an adjacent forest. Data loggers and micrometeorological sensors measured air and dewpoint temperatures, wind speed, precipitation, short-wave radiation, and outflow from snow lysimeters, and time-lapse photography verified periods of snow accumulation and melt. During selected rain-on-snow events, snow depth, density, snow water equivalent, free-water content, and albedo were measured, also. Micrometeorological data were used in an energy balance model to predict snowmelt at the forested and clearcut plots.

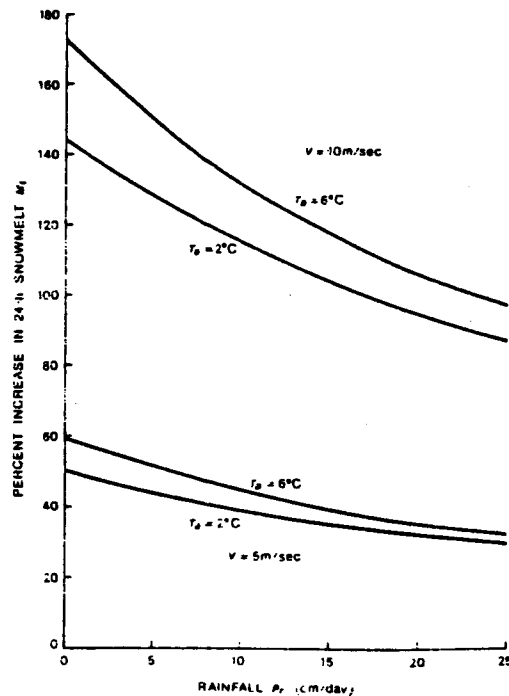


Figure 3. Percent increase in snowmelt M_t as a function of daily rainfall P_r , mean daily air temperature T_a , and wind speed V (adapted from U.S. Army Corps of Engineers, 1956).

The Oregon field study revealed the importance of snow interception in determining the amount of snow available to melt during subsequent rainfall (Berris and Harr, 1987). The clearcut

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plot commonly had 2-3 times more snow-water equivalent than the adjacent forest when snow was present in the forest (Table 1). On other occasions, snow-water equivalent in the open plot was greater than 125 mm, and no snow or only patchy snow was present in the forest. Such differences in snow accumulation can lead to large differences in rain-on-snow runoff between forest and clearcuts even in the absence of differences in melt rates.

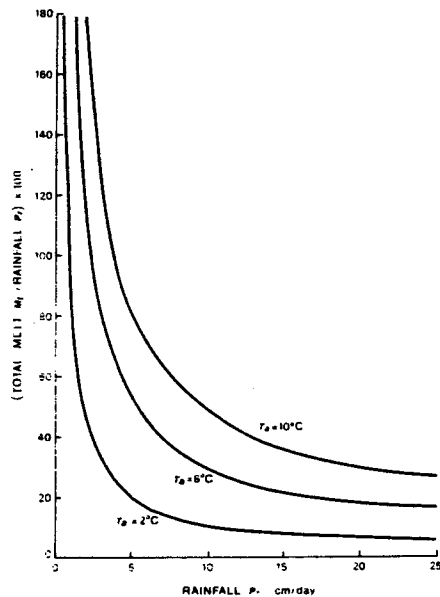


Figure 4. Percent increase in total water input to soil as a function of daily rainfall P_r and mean daily air temperature T_a at wind speed $V = 5$ m/sec (adapted from U.S. Army Corps of Engineers, 1956).

Of equal significance was the increased amount of heat available to melt snow in the clearcut. During the largest rain-on-snow event of this study (and the only one of the size for which the study was designed), the snowpack in the clearcut received twice as much heat than did the snowpack under the adjacent forest (Table 2) (Berris and Harr, 1987). Snow lysimeter outflows, corrected for rainfall and free-water content of the respective snowpacks, showed measured snowmelt agreed very well with melt predicted by the energy balance model. Snowmelt at the clearcut plot was twice that of the forest plot (Table 2).

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Table 1. Snowpack characteristics in the clearcut and forested plots, H.J. Andrews Experimental Forest, Oregon (after Berris and Harr, 1987).

Date	Clearcut Plot		Forested Plot	
	Depth (mm)	Water equiv- alent (mm)	Depth (mm)	Water equiv- alent (mm)
Nov. 30, 1982	100	* ¹	50	* ¹
Dec. 19, 1982	220	35	54	21
Dec. 22, 1982	168	32	* ³	* ²
Feb. 10, 1983	125	40	* ³	* ²
Nov. 27, 1983	135	31	* ³	* ²
Dec. 2, 1983	184	37	48	16
Dec. 7, 1983	500	116	123	42
Dec. 9, 1983	215	75	68	23
Dec. 12, 1983	200	63	43	16
Dec. 13, 1983	160	60	32	12
Dec. 27, 1983	141	39	94	30
Dec. 31, 1983	30	13	* ⁴	* ²
Feb. 11, 1984	242	36	42	16
Feb. 12, 1984	67	18	* ³	* ²
Feb. 19, 1984	64	21	* ⁴	* ²
Feb. 23, 1984	93	13	20	11
Feb. 27, 1984	253	67	90	30
Mar. 18, 1984	56	18	6	3
Apr. 11, 1984	192	* ¹	73	* ¹

¹Measurement was not taken.

²Lack of snow precluded measurement.

³Patchy snowpack.

⁴No snow.

Updating and Reanalysis of Past Research

Preliminary results of this field study led to reanalysis of results of small, gaged watersheds in order to determine if clearcut logging had increased size of winter peak flows after soil moisture had been recharged (Harr, 1986). Rothacher (1973) had reported that the slope of prelogging and postlogging regressions for peak flows at clearcut watershed HJA-1 and unlogged watershed HJA-2 in the H. J. Andrews Experimental Forest were significantly different; i.e., logging had changed peak streamflow. Most of this change appeared to have resulted from drastic increases in size of fall peak flows in clearcut HJA-1. Because the positions of the upper parts of the two regression lines were similar, Rothacher concluded that extremely high peak flows may be no greater after logging than would have been expected before logging.

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Table 2. Melt predicted by the energy balance model versus measured melt (after Berris and Harr, 1987).

Energy Source	Clearcut Plot ¹		Forested Plot ²		(mm)
	Predicted Melt	Measured Melt	Predicted Melt	Measured Melt	
	(mm)	%	(mm)	%	
Shortwave radiation	0.3	1	0.0	0	
Longwave radiation	2.9	13	2.8	25	
Sensible heat	7.8	35	2.7	24	
Latent heat	4.8	22	1.8	16	
Rain	6.4	29	3.9	35	
Total	22.2	100	25.1	100	11.9

¹From 2300 February 11, 1984 to 0300 February 13, 1984
²From 2300 February 11, 1984 to 1900 February 12, 1984

Rothacher's (1973) analysis is not useful for determining effects of harvest on rain-on-snow because all peak flows, large and small, rain-caused and snowmelt-related, were lumped together in accordance with the objectives of his study. To overcome this problem, Harr (1986) updated the postlogging tabulation of peak flows and separated peak flows by size and type. Only snowmelt-related peak flows larger than an arbitrary size of 9.8 liters sec⁻¹ ha⁻² at HJA-1 and corresponding peak flows at HJA-2 were included in the analysis. Reanalysis showed that prelogging and postlogging regressions were significantly different; i.e., flows in the 9.8-12.5 liters sec⁻¹ ha⁻² at HJA-1 were higher after clearcut logging (Figure 5). Such flows have a return period of roughly 2-8 years. Judging by the positions of the upper ends of the regressions, highest flows were not changed.

The analysis by Harr and McCorison (1979) also has a major shortcoming with respect to the effects of timber harvest on rain-on-snow runoff. Many of the postlogging snow-related storm hydrographs resulted from storm precipitation beginning as rain and changing to snow or beginning as snow and changing to rain. These precipitation sequences are only two of a number of scenarios involving snow and rain that could lead to different runoff responses between logged and unlogged watersheds. Moreover, it seems unlikely that either scenario would be of any consequence in terms of erosion processes. Of far greater importance are situations of prolonged rainfall on two snowpacks of dissimilar water equivalents, differential melting of two snowpacks with

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similar water equivalents, or differential melting of two snowpacks with dissimilar water equivalents.

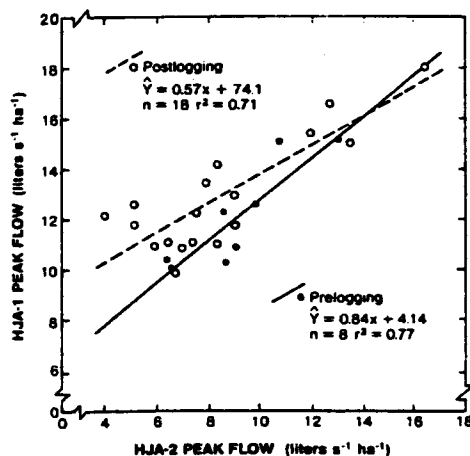


Figure 5. Prelogging and postlogging peak flows that resulted from snowmelt during rainfall at clearcut watershed HJA-1 and unlogged watershed HJA-2, H.J. Andrews Experimental Forest, Oregon, 1952-1982 (after Harr, 1986).

Updating and reanalyzing peak flow data for clearcut watershed HJA-10 and unlogged watershed HJA-9 indicate that clearcutting had a large effect on the size of peak flows associated with relatively deep (250-500 mm of snow with 100-200 mm of water equivalent). This is evident in the event of January 11-13, 1980 (Figure 6) for which there is at least qualitative information on wind speeds. According to an entry on a field crew's data sheet, the rainfall of January 12, 1980 was accompanied by a very warm, gusty wind at clearcut HJA-10. Given the normal windy conditions commonly associated with the passage of warm fronts in the Pacific Northwest, wind most likely accompanied rain during the November 1977 and February 1979 events, too (Figure 6).

WESTERN WASHINGTON RESEARCH

Following the senior author's transfer to western Washington in 1988, he continued rain-on-snow research. He initiated a study with the junior author in cooperation with the University of Washington and the Timber/Fish/Wildlife group, a coalition of native American tribes, State agencies, the forest industry, and the environmental community formed to work toward improving forest land management in Washington. This Washington field study was designed to overcome certain deficiencies of the Oregon field study described above, namely plots located at only one elevation and at only one location. A larger number of rain-on-snow events would strengthen conclusions about the effects of forest management

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activities on rain-on-snow runoff. In the Oregon study, the zone of active snowmelt frequently had been either above or below the elevation of the study plots, or storms had tracked either north or south of that study's single location. This had limited the number of suitable rain-on-snow events for analysis.

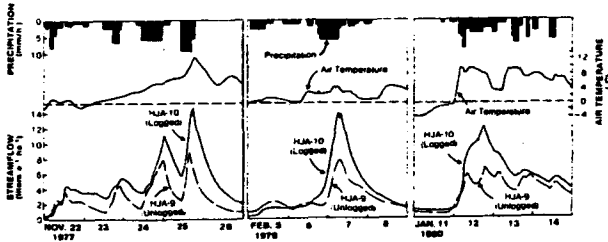


Figure 6. Streamflow, precipitation, and air temperature during with selected postlogging storm hydrographs at unlogged watershed HJA-9 and clearcut watershed HJA-10, H.J. Andrews Experimental Forest, Oregon (after Harr, 1986).

The Washington study was designed to supplement results of the Oregon study by comparing rates of water outflow from snowpacks under three different forest cover types during rainfall. In short, we were interested in increasing the number of rain-on-snow events for which differential snow meltwater outflows were available for forest and open conditions. Cover types included mature forest, a clearcut (or otherwise non-forested opening), and a forest plantation ranging in age from 18 to 40 years.

A total of 24 plots were established at three elevations (460, 610, and 760 m) and two locations in northwest Washington. At each elevation and location, plots were established in groups of three: one in a mature forest, one in an adjacent or nearby open area (in all but one case, a recent clearcut), and one in an adjacent or nearby forest plantation. Each plot consisted of a snow lysimeter with a time-of-event recorder. Each open plot was also equipped with instruments to monitor weather conditions during snow accumulation and subsequent melt during rainfall. Water outflows from snow lysimeters were compared among cover types to determine differences in rates of water delivery to soil.

Outflows from open plots ranged up to 138% greater than from corresponding forested plots during 29 plot-events over three winters (1988-90, 1989-90, and 1990-91). (A plot-event is one rain-on-snow event at one plot; five rain-on-snow events observed at each of four plots would equal 20 plot-events.) In 19 plot-events, outflows from open plots were more than 25% greater than outflows from corresponding forested plots, and of these 19, nine were more than 50% greater, and three were more than 90% greater. In only four plot-events was the increase in outflow from

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the open plots less than 15% greater than from the forested plot. In general, differences in outflow between forest and open plots were much greater than those observed by Beaudry (1984), Berris (1984), and Berris and Harr (1987).

During many events, plantations where rain-on-snow outflows were monitored in this study did not appear to be hydrologically recovered with respect to snow accumulation and subsequent melt during rainfall. Outflows from plantations were typically intermediate between those from corresponding forested and open plots. Relative changes in outflows were much more variable than those from open plots, ranging from 19% less to 96% greater than those from mature-forested plots.

We attributed part of the variability in plantation outflows to locations of snow lysimeters relative to trees. Plantations typically accumulate snow around crown margins of individual trees. Spindly, flexible branches were incapable of holding much snow and allowing it to melt in the crowns. At some plantation plots, deep accumulations of snow (often much deeper than in open plots) most likely delayed its ripening and conditioning and retarded outflow by lengthening the flow path of melt water.

Maximum differences in outflows between open and forested plots occurred during periods when air temperatures and wind speed were both relatively high. During such situations, the absence of forest vegetation in open plots greatly increased the transfer of sensible and latent heats to the snowpack. For example, Figure 7 shows the rain-on-snow event of January 2-3, 1989 when total outflow from the open plot was nearly double that from the forest plot. From 1900 on January 2 to 0500 on January 3, outflows from all three plots are roughly identical when light to moderate rainfall occurred, air temperature was 2-4° C, and wind speeds were low. But as air temperature and wind speed both increased and remained high until about 1700 on January 3, outflow from the open plot was much greater than from the forested plot. Outflow from the thinned plantation plot at this elevation remained intermediate between outflows from the open and forested plots.

The highly variable nature of rain-on-snow runoff as a result of changing weather conditions is illustrated by Figure 8. Light snowfall had occurred on January 12 and 13, and part of this snow was intercepted. Wet snow fell from 0500 to 1300 on January 15, and forest outflow surpassed outflows measured at the other lysimeters as snow melted in the forest canopy. This is the mechanism responsible for the initial differences in rain-on-snow runoff between watersheds HJA-9 and HJA-10 reported by Harr and McCorison (1979). From 1400 on January 15 to 1000 on January 16, rain heat became a more important source of heat for melt, and total outflows were nearly equal. From 1100 January 16 to 0400 January 17, air temperature averaged 4.3° C, hourly average wind speeds reached 5.3 m sec⁻¹, and rainfall averaged about 1 mm hr⁻¹. Outflow from the open plot was 156% greater than from the forest plot during this period, due partially to increased transfer of

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sensible and latent heats and partially to more snow being available for melt in the open.

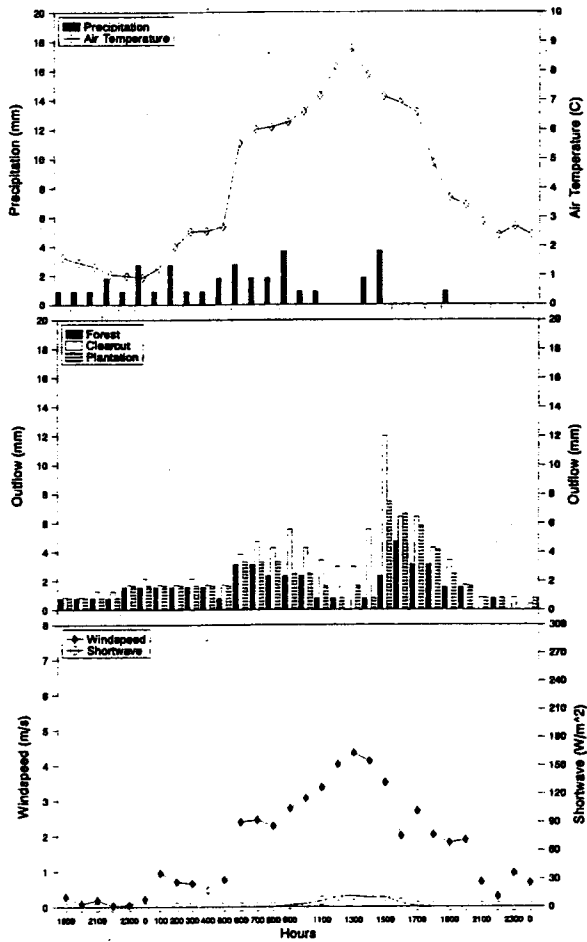


Figure 7. Rain-on-snow event, Finney Creek, 460-m elevation, 1900 January 2 - 2400 January 3, 1989: (a) air temperature and precipitation, (b) lysimeter outflow, (c) wind speed and shortwave radiation.

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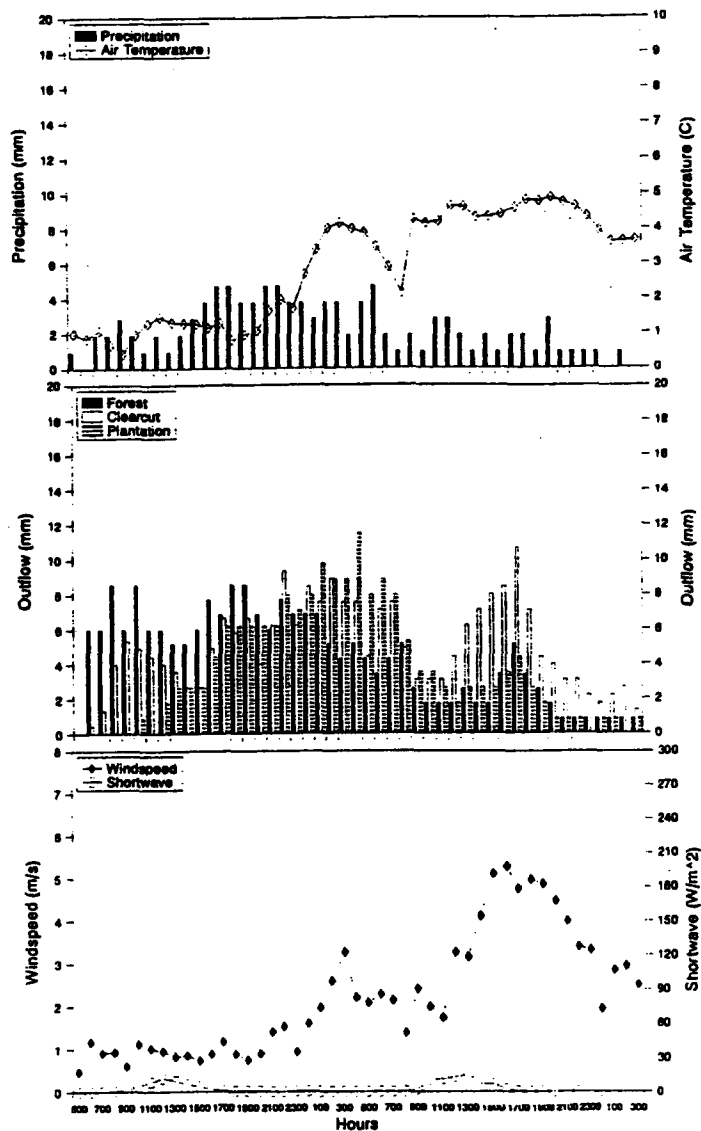


Figure 8. Rain-on-snow event, Canyon Creek, 460-m elevation, 0500 January 15 - 0300 January 17, 1989: (a) air temperature and precipitation, (b) lysimeter outflow, (c) wind speed and shortwave radiation.

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This western Washington study has shown that forest management activities such as clearcutting and thinning can increase outflow of water from snowpacks during rain-on-snow conditions by reducing snow interception and increasing heat transfer to the snow. Results from this study have supported Harr's (1981) hypothesis of greater rain-on-snow runoff following clearcutting, have complemented results of other studies (Harr and McCorison, 1979; Beaudry, 1984; Harr, 1986; and Berris and Harr, 1987).

Although hydrologic recovery is still unclear, it seems evident that one mechanism whereby forest management activities can cumulatively affect water resources is snow accumulation and its subsequent melt during rainfall. What remains now is to scale up from plots and small, gaged watersheds to large basins and incorporate information from rain-on-snow research into planning and implementing forest management activities. Scaling up has been attempted on several fronts ranging from the simple analysis of watershed scale by Connelly and Cundy (1992) to the more elaborate GIS-based methods described by Lettenmaier et al. (1991) and Brunengo et al. (in press).

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