EFFECTS OF FOREST COVER ON RATE OF WATER DELIVERY TO SOIL DURING RAIN-ON-SNOW

FINAL REPORT

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SUMMARY

Snowmelt during rainfall not only has caused most of the highest streamflows in western Washington, but the high rates of water input to the soil during rain-on-snow have also triggered landslides on steep, marginally stable slopes. State and Federal laws require analyses of the cumulative effects of forest management activities on the environment. These laws and the perception of increased flooding in western Washington have perpetuated the concern about the effcts of logging on streamflow, particularly that resulting from snowmelt during rainfall. Modelling efforts attempting to predict streamflow based on precipitation and land-use require empirical data at the plot scale that show how much water would be available for runoff from forested and nonforested sites during rain-on-snow.

This study was undertaken to: (1) determine the magnitude of increase in rate of water delivery to soil during rain-on-snow when changing from a forested condition to an open condition, and (2) compare water outflows from forest plantations with outflows from mature forest stands and open areas during rain-on-snow.

Snow lysimeters were installed under each of three cover types including a mature forest, forest plantation, and clearcut or open area. A total of 24 study plots were established at three elevations and at two locations in northwest Washington. A weather station at each non-forested plot monitored weather conditions during snowfall and snowmelt, and between rain-on-snow events. Water outflows from snow lysimeters were compared among cover types during 13 rain-on-snow events to determine differences in rates of water delivery to soil.

Open plots exhibited 1-138% greater outflows than their corresponding forested plots during 29 plot-events in 13 rain-on-snow events over three winters. (A plot-event is one rain-on-snow event at one plot; five rain-on-snow events measured at each of four plots would equal 20 plot-events.) Differences in outflows between forest and open plots were generally the greatest for rain-on-snow events exhibiting relatively high air temperatures and wind speeds and low rainfall intensities. During the parts of rain-on-snow events when air temperatures and wind speeds were relatively high and rainfall intensities were low, outflows from open plots were 25-174% greater than corresponding outflows from forest plots.

During many events, plantations monitored in this study did not appear to be hydrologically recovered with respect to snow accumulation and subsequent melt during rainfall. Outflows from 18- to 40-yr-old forest plantations were typically intermediate between those from corresponding forested and non-forested sites, but ranged from 19% less to 96% greater than from mature forest. During 30 plot-events, outflows from plantation plots were

greater than those from the forest plots in 17 cases, negative in 10, and equal in three. Reduced outflow from thinned plantation plots in some cases may reflect the extreme accumulations of snow at the margins of the crowns of several trees--the only suitable location for the snow lysimeter. Plantations typically accumulated snow around the 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 could have delayed its ripening and conditioning and retarded outflow by lengthening the routing path of snowmelt water.

Highly variable weather conditions before and during rain-on-snow events and characteristics of individual plots all contributed to the wide range of differences in outflows. However, the following conclusions can be made:

(1) **Open plots had greater outflows than corresponding forest plots.** Outflows from open plots ranged from only 1% greater than from the forest plot to more than 130% greater in two plot-events. Outflows from the open plot were 50-96% greater in seven plot-events, 25-44% greater in 10 plot-events, and 15-24% greater in five plot-events.

(2) **Differential snow accumulation and rate of melt during rain-on-snow conditions were both involved in greater outflows from open plots.** Differential snow accumulation and subsequent rate of melt during rainfall were not of equal importance in every rain-on-snow event nor at every location.

(3) **Maximum differences in outflows between open and forest plots occurred during periods when air temperatures and wind speed were both relatively high.** Even though some plot-events exhibited very small differences in total outflow between open and forest plots, there were commonly 7- to 12-hr periods during these events when outflow from the open plot exceeded that from the forest plot by 25-75%.

(4) **When snow fell at temperatures above freezing and was intercepted and allowed to melt in tree crowns during and between snow storms, outflows from forest plots exceeded those from open plots.** Such differences were of little hydrologic significance in terms of immediate water delivery to soil because they were usually of low magnitude and short duration. These differences were of much greater hydrologic significance in terms of later water delivery to soil because they often dictated how much snow water equivalent would be on the ground when a future rain-on-snow event occurred.

(5) **Outflows from plantations were sometimes greater than corresponding forest outflows and sometimes less.** This highly variable response of plantation plots was due in part to: (a) the location of snow lysimeters in relation to maximum accumulations of snow between trees, (b) differential snow accumulation across plantation stands (compared to forest stands), and (c) increased transfer of heat to the snow (compared to forest stands).

(6) **Forest managment activities (such as harvesting and thinning) that reduce snow interception and increase heat transfer can influence rate of water delivery to soil during rain-on-snow conditions.** Rates of water delivery to soil will be increased most when greater accumulation of snow in an open (logged) area is followed by moderate rainfall at relatively high air temperatures and wind speeds. These conditions combine to increase the transfer of sensible and latent heats to the snow.

(7) **Results of this study support the contention that forest management practices (primarily logging), by increasing rate of water delivery to soil during rain-on-snow, are increasing the frequency of water input events capable of causing flood flows, channel erosion, and landslides.**

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

EFFECTS OF FOREST COVER ON RATE OF WATER DELIVERY TO SOIL DURING RAIN-ON-SNOW

INTRODUCTION

In Washington State, many of the same lands valued for timber production are drained by streams that support resident and anadromous fish populations. These streams are often the source waters for domestic and industrial water supply in western Washington, as well as being focal points for many recreational activities. In addition, the low-lying floodplains from these streams have become home to many western Washington residents and industries. When questions arise as to the quantity, quality or the timing of flows in these streams, or of the values associated with them, hydrologists, fisheries biologists and other water resource planners often look upstream for answers.

The perception that timber harvest is responsible for downstream changes in water quality, fish production, and runoff regimes has grown along with the public's increased awareness of and interaction with their environment outside of urban centers. The extent to which charges against the timber harvest practices are valid is a question being pursued by those on all sides of the issue.

Past research has shown that timber harvesting can affect the rates of snow accumulation and snowmelt during rain-on-snow (Berris and Harr, 1987). The degree to which altering these factors affects water runoff or water available for runoff has yet to be shown conclusively by research. A major obstacle has been the highly variable nature of rain-on-snow, both temporally and spatially. Nevertheless, techniques for predicting the downstream propagation of these changes are being developed, and Federal and State laws require analyses of the cumulative effects of forest management activities on the environment.

Cumulative effects analyses often begin first with analysis of current conditions and the site-specific changes expected. It is important to understand the type and magnitude of these on-site changes before attempting to predict cumulative effects on a basin-scale. However, research regarding the actual size of difference in water outflow from harvested sites as compared to forested sites during rain-on-snow is lacking.

Modelling efforts are currently underway to predict downstream effects of management activities on streamflows. For these models to be useful to land managers, empirical data are needed at the plot-scale to not only describe the effect, but to quantify the expected changes following harvest. This study examined the magnitude and range of the difference in rates of water delivery to the soil between forested and non-forested plots during rain-on-snow. Results can serve as a validation of predictions made by computer simulation models of snow accumulation and melt.

BACKGROUND INFORMATION

RAIN-ON-SNOW

Rain-on-snow is the common term used to describe cloudy-weather periods when warm winds and rain combine to produce rapid snowmelt. Occurring frequently along western slopes of the Cascades, runoff from these events plays an important role in hydrologic systems of the Pacific Northwest. A majority of the landslides and large peak streamflows in western Cascade watersheds have occurred when rain-on-snow conditions prevailed over some parts of those drainages (Harr, 1981). Extensive damage to fish habitats, riparian zones, buildings, and roads has been caused by runoff resulting from rain-on-snow (Fredriksen, 1965; Rothacher and Glazebrook, 1968).

The significance of rain-on-snow runoff derives from the accelerated rates of snowmelt that often occur during cloudy, rainy periods when air temperature and wind speeds are high. It is during these events when snowmelt can dramatically increase rates of water delivery to the soil above that resulting from rain alone (Fredriksen, 1965; Harr, 1981; Berris and Harr, 1987). Under such cloudy-weather melt conditions, turbulent exchange of heat from the overlying air is the primary source of heat for snowmelt. As relatively warm air contacts the cooler snowpack, water vapor in the air condenses on the snow surface. Not only does this process contribute liquid in the form of condensate, it also releases the latent heat of vaporization to the snowpack. This latent heat is sufficient to produce 7.5 times as much meltwater from the pack as the amount of water vapor condensed on the snow surface (U.S.A.C.E., 1956).

Due to the efficiency of headwater basins in Pacific Northwest stream systems in producing runoff (Rothacher et al. 1967), the increased rates of water delivery to the soil can be translated rapidly to increased streamflow. Peak streamflows associated with rain-on-snow can be of greater magnitude than rain-only events simply because the rainfall is augmented by snowmelt. During such high flows, stream channels may be altered by bank erosion, downcutting, and redistribution of sediment and large organic debris (Harr, 1981).

In addition to increasing size of peak streamflows, the high rates of water input to the soil can generate unstable conditions on hillslopes by increasing pore water pressures (Sidle et al., 1985). As pore water pressure rises, shear strength, the soil's resistance to downslope movement, is reduced. The combination of these factors is often enough to cause slope failure in the steep, marginally stable slopes common to the Cascades (Swanston, 1974).

Where It 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 (Fitzharris et al., 1980; Harr, 1981; Moore and Owens, 1984). Snowpacks in these areas tend to be relatively "warm" in that their internal temperatures remain near 0° C (Smith, 1974). Because warm snowpacks have little "cold content," they require little hat input to initiate melt. Cold content is defined as the heat required per unit area of snow to raise its temperature to 0° C throughout (U.S.A.C.E., 1956).

Warm fronts common to the marine weather systems operating in the Pacific Northwest are often accompanied by high winds. The combination of high winds, high air temperatures and rainfall is capable of generating considerable melt from shallow snowpacks (Harr, 1981, Moore and Owens, 1984, Berris and Harr, 1987).

Though rain-on-snow occurs often in the lower and middle elevations of the Cascades, it can occur from sea-level to the highest elevations. It is of particular concern at lower and middle elevations because of the greater frequency of both snowfall and warm rainstorms occurring there during the winter months. Also, snowpacks at higher elevations may be deep and cold enough to absorb much of the added rainfall and heat input, yielding only small amounts of melt during rain events. Because snowpacks at lower elevations are commonly shallow and relatively warm, they can yield water quickly. These packs, in the elevation band known as the transient snow zone (approximately 300-900 m, or 1,000-3,000 ft in the Washington Cascades), are often completely melted during rain-on-snow (Harr, 1981).

The elevation range over which rain-on-snow occurs is more a continuum than a band with discrete upper and lower boundaries. At any given time an upper or lower elevational limit of actual snowmelt conditions can be identified. However, these limits can change during a particular storm event and can differ greatly from storm to storm. The lowest elevation at which rain-on-snow can occur is always governed by the presence or absence of snow, and this varies throughout the year as snow accumulates and melts. The highest elevation is determined by weather conditions during a particular storm.

Although rain-on-snow is most common in the transient snow zone, it does occur at elevations above and below the transient snow zone. Rain-on-snow is rare at sea level because snow is uncommon there. Likewise, rain-on-snow is rare at higher elevations because rain is rare there when snow is present.

Rain-on-snow is much more common in western Washington, but it does occur on the east side of the Cascades, too. Many streams here exhibit spring runoff that is characteristic of the more continental climate, but highest streamflows of record for most streams in eastern Washington have resulted from rain-on-snow. Also, rain-on-snow occurs during fall and early winter in northern Idaho and western Montana in many years.

SNOWMELT

A brief discussion of snowmelt processes provides a framework for discussing snowmelt during rainfall and the effects of forest cover on snowmelt. The melting of a snowpack is a process that occurs over a period of time and in response to a number of heat inputs. The time required before a snowpack releases liquid water is a function of the initial condition of the pack, the rate of heat input, and the water-holding capacity of the pack.

Ripening and Priming of the Snowpack

The initial temperature of the snowpack provides the starting point for the processes that lead up to melt. A snowpack initially deposited at temperatures below 0° C has some cold content. Before outflow can occur from the pack, this cold content must be satisfied, and the snowpack must become isothermal at 0° C, that is, the snowpack's temperature must be 0° C throughout.

Furthermore, before releasing any melt water, the pack must have its "liquid-water-holding capacity" satisfied. The liquid-water-holding capacity is simply the amount of liquid water that can be held in the snowpack against the force of gravity. Liquid-water-holding capacities are a function of snowpack conditions (grain size and porosity), but generally fall within a range of 2-5% of the total water equivalent of the snowpack (U.S.A.C.E., 1956). Some researchers have measured values as high as 25% (de Quervain, 1948; Berris and Harr, 1987), though these values may have included water in transit through the snowpack.

The process by which a snowpack reaches isothermality at 0° C and has its liquid-water-holding capacity filled is called "conditioning" or "ripening" of the pack. This occurs when heat or water is added to the snow. During this process, the density of the snowpack increases as individual ice crystals melt and refreeze.

Because heat exchange with the underlying soil is generally of secondary importance to heat inputs at the upper snow surface (Gray and Male, 1981), the melting of the individual crystals occurs primarily in the upper layers. As the melt water from these crystals begins moving down through the pack, it comes into contact with snow or ice at temperatures below 0° C and refreezes, releasing the latent heat of fusion to the snowpack.

The melting and refreezing of the snow particles has two effects on the snowpack. First it allows heat inputs at the snow surface to be distributed down through the pack by the percolating and refreezing of the melted crystals. In this way, the pack is gradually warmed from the top down. Second, the individual snow crystals in the pack increase in density, becoming coarse and granular.

Once the snowpack has become isothermal at 0° C, heating of the pack no longer occurs, and additional heat inputs are used to melt the snow. However, the snowpack will still not produce meltwater outflow until its water-holding capacity has been satisfied. Once this has occurred, additional heat or water added to the pack will result in water outflow from the pack. At this stage, the pack is considered "primed" to produce liquid runoff (U.S.A.C.E., 1956).

In the Sierra Nevada, the Rocky Mountains, and at high elevations in the Cascade Range, ripening and priming require a period of many months, but at lower and middle elevations in western Washington where shallow snowpacks are common, ripening can occur in a matter of hours.

Sources of Heat

Snowmelt occurs in response to the transfer of heat from a number of sources, including net solar radiation, net longwave radiation, turbulent transfer of sensible and latent heats from the air, conduction of heat from the underlying ground, and the heat contained in rainwater (U.S.A.C.E., 1956). The relative importance of any one of these sources in causing melt depends on location, season, and ambient conditions during snowmelt.

Solar or shortwave radiation is sunlight or energy emitted by the sun. Since this radiation is the primary source of energy at the earth's surface, it can be of great importance to snowmelt. However, the amount of shortwave radiation reaching the earth's surface can vary considerably over space and time. Moreover, the amount of heat actually transferred to a snowpack from shortwave radiation is dependent on a number of variables including latitude, season, time of day, vegetation, cloud cover and reflectivity of the snow (Gray and Male, 1981).

Although shortwave radiation is the dominant factor in causing snowmelt in many areas (U.S.A.C.E., 1956; Hendrie and Price, 1978; Male and Granger, 1981), it is of less direct importance to much of the winter melt in forested watersheds of the Pacific Northwest. Here, cloud cover is common throughout most of the winter, and most snowmelt occurs as maritime frontal systems transit the area. During these periods, cloud cover can reduce incoming shortwave radiation by over 90% (Berris, 1984).

Shortwave radiation is still important to snow maturation and melt in this region, but only in an indirect way. The temperature of forest vegetation increases as it absorbs shortwave radiation. As the temperature of the vegetation increases, the surrounding air is heated, and longwave radiation from the vegetation increases. Longwave or terrestrial radiation is that radiation continuously emitted by the earth's atmosphere and all matter at the earth's surface having a temperature above -273° C (Lee, 1978).

The rate of longwave emission is a function of the temperature of the body emitting the radiation. Although a snowpack emits longwave radiation in the same way as forest vegetation, the rate of emission from the snowpack is limited by the pack's maximum temperature of 0° C. Forest vegetation, on the other hand, can reach temperatures well above freezing, and thus will have higher rates of longwave emission. Net longwave radiation to the snowpack is the difference between the incoming longwave radiation absorbed by the snow and that emitted by the snow.

A snowpack receives longwave radiation from a number of sources, including forest vegetation, clouds, and other topographic features. Under a forest canopy or during the cloudy periods associated with rain-on-snow, the net longwave component is nearly always positive to the snowpack. However, during clear weather, a snowpack in the open can actually emit more longwave radiation than it receives, and thus have a net loss of longwave radiation (U.S.A.C.E., 1956).

During rain-on-snow conditions, air temperature can be used to index the longwave radiation inputs to the snowpack. As air temperature increases, the relative importance of the longwave component in causing snowmelt increases. Using melt indices developed by the U.S. Army Corps of Engineers (1956), Harr (1981) calculated that longwave radiation would account for up to 35% of the melt during a hypothetical rain-on-snow event when air temperature was 10° C.

Latent and sensible heat exchanges occur when turbulent or convective eddies bring warm air into contact with the snow. Sensible heat is the heat that feels warm to the touch. During this type of heat exchange, sensible heat is transferred directly from the air to the snow, and latent heat is given to the snowpack as water vapor in the air condenses onto the snowpack. For these types of heat transfer to occur, there must be a temperature gradient in the direction of the snow. That is, for the snowpack to experience sensible heat gains by this process, the air moving over the pack must be warmer than the pack. Similarly, the vapor pressure of the air moving over the pack must be greater than that of the snowpack for condensation to occur. Whenever the overlying air is warmer than 0° C, the vapor pressure gradient is toward the snow.

The principal variables affecting convective heat exchange are the temperature gradient of the air above the snow and the wind speed. Similarly, the vapor pressure gradient and wind speed are the primary variables affecting condensation. Without directly measuring or calculating the turbulent fluxes of sensible and latent heat, measurements of wind speed, and air temperature, can be used to index these exchanges reasonably well (U.S.A.C.E., 1956).

During cloudy weather melt, heat exchange by turbulent transfer is the dominant factor in causing snowmelt. Harr (1981), using melt indices developed by the U.S. Army Corps of Engineers (1956), estimated turbulent heat exchange would be responsible for up to 50% of the total melt in a hypothetical rain-on-snow event during which air temperature is 10° C and 24-hr rainfall is 50 mm. Prowse and Owens (1982) calculated that sensible and latent heat exchange accounted for 70% of the total heat supplied to a snowpack during selected days of spring melt. Similarly, Moore and Owens (1984) reported that combined inputs of latent and sensible heats accounted for 82% of the energy used in melting snow during a period of spring melt. During a February rain-on-snow event, Berris and Harr (1987) attributed over 50% of the snowmelt to latent and sensible heat exchange.

Although longwave radiation and turbulent exchange are the two dominant heat fluxes influencing snowmelt, heat conducted from the ground is also capable of melting snow. This heat is often negligible in daily melt computations, but can be significant when the entire melt season is considered (U.S.A.C.E., 1956). Gray and Male (1981) point out that while snowmelt may occur at the bottom of the pack when snow temperatures remain near 0° C, the amount of melt is relatively small and negligible when considered over hours to several days.

The contribution of heat from rain falling on a snowpack is a function of the air temperature and rate of precipitation (U.S.A.C.E., 1956). As a raindrop enters the snowpack, it conducts heat directly to the pack as the raindrop cools to the temperature of the snow. If the pack is isothermal at 0° C, the raindrop does not freeze, and the heat delivered to the pack causes snowmelt. However, if the temperature of the snow is less than 0° C, the raindrop freezes in the pack, releasing the latent heat of fusion and further heating the pack.

Because the latent heat of fusion is relatively large and the specific heat of snow is small, the freezing raindrops can do much to raise the temperature of the snowpack when it is below 0° C. For this reason, snowpacks at temperatures below freezing are quickly brought to 0° C during rainfall. However, once the pack is isothermal at 0° C, rainfall is relatively less effective in actually melting the snow (U.S.A.C.E., 1956).

During rain-on-snow, the importance of rainfall itself in causing snowmelt increases as rainfall intensity increases. Some studies have shown heat inputs from precipitation contributing less than 10% of the total heat delivered to the snowpack during rain-on-snow (Prowse and Owens, 1982; Braun and Zuidema, 1982; Moore and Owens, 1984). However, when precipitation rates are high, heat from the rain can be as large as 20 to 35% of the total heat flow to the snowpack (Fitzharris et al., 1980; Harr, 1981). Using the U.S. Army Corps of Engineers snowmelt indices (1956), Harr (1981) showed that at air temperature of 2° C and precipitation rate of 100 mm/day, heat transfer from rain would account for just over 20% of the total snowmelt--less than the heat exchanges from either longwave radiation or convection-condensation. Once precipitation exceeded about 170 mm/day however, it became the dominant heat source for snowmelt, accounting for more than 30% of the total melt.

Influences of Forest Cover

The presence or absence of forest cover at a site can affect a number of snowmelt processes and the relative importance of the various heat sources. Initially, the forest canopy plays an important role in altering both the amount and distribution of snow over the landscape. Because the microclimate within a forest differs from that in an open area, the rate at which a snowpack ripens can also differ between the two. Likewise, rates of melt can vary substantially between open and forested sites.

The large surface area of a coniferous forest canopy is capable of intercepting and storing large quantities of snow. Interception reported from a number of studies has generally fallen between 10 and 35% of total snowfall measured in the open (Dunford and Niederhof, 1944; Wilm and Dunford, 1948; Rowe and Hendrix, 1951; Kittredge, 1953; Satterlund and Haupt, 1970).

However, Ingebo (1955) measured interception ranging from 5% to 45% over a number of different plots with differing canopy densities. Connaughton (1935) found that while a virgin stand of timber intercepted an average of 24% of the snowfall, a young reproduction stand intercepted an average of only 5%. Connaughton did not report the age of the reproduction stand, nor did he speculate as to why the stand intercepted so little snow. However, his results support observations by Haupt (1972) and Berris and Harr (1987), that limbs of younger trees are often incapable of supporting a snowload. Limber branches were observed to flex downward in response to snowloading, and as the angle of the branches became steep, snow masses would fall to the ground.

The amount of snow retained in a canopy is a function of the air temperature during snowfall and the interception storage capacity of the canopy. At lower temperatures, less snow has been found to remain in the forest canopy because it does not adhere to the branches as well and is more easily blown off (Miller, 1964; Satterlund and Haupt, 1967). Interception storage capacity for a canopy is a function primarily of canopy density, but also of such factors as branch angle, type of needle or leaf, and the age, height and type of the vegetation, as these influence stiffness of branches (U.S.A.C.E., 1956).

Snow that is held in the canopy can be melted and released to the forest floor as drip, evaporated, or unloaded in clumps before completely melting (Miller, 1966; Berris, 1984). When snow is retained in the canopy, it may be subject to increased melt rates as compared to snow accumulated on the ground, because of the larger surface area per unit volume exposed, and the higher temperatures often found in the canopy (Miller, 1966). Berris (1984) and Beaudry (1984) both measured snowmelt from forest canopies occurring sooner than from snow accumulations on the ground, and Harr and McCorison (1979) suspected that this was the cause of higher peak flows from a forested watershed when compared with a clearcut watershed.

While limiting the timing and amount of snow reaching the forest floor, the canopy also affects the quality of the snowpack and the rate of melt in the forest. As snowmelt occurs in the forest canopy, it contributes drip water to the snowpack below. The drip water increases the water content of the snowpack, but can also contribute the latent heat of fusion to the pack. As the snow underneath the dripping canopy ripens, subsequent canopy drip may exceed the liquid water-holding capacity of the snowpack, and water may flow directly into the soil (Smith, 1974). In this way, a forested site can begin routing water offsite before a site in the open does (Berris and Harr, 1987). If a forest's water has been routed offsite in this manner prior to a rain-on-snow event, then the forest has less snow to melt and less water available for runoff during rain-on-snow.

Short and longwave radiation exchanges with the snow are different in the forest as well. Because over 90% of the incoming shortwave radiation can be absorbed by a coniferous forest canopy, direct shortwave radiation plays a very minor role in melting snow under the forest canopy even on sunny days (U.S.A.C.E., 1956). Longwave radiation in the forest is increased by the transformation of the absorbed shortwave in the forest canopy. However, during rain-on-snow conditions, Berris and Harr (1987) found consistently higher air temperatures and net longwave radiation in the open than in the forest.

Heat exchange by the turbulent transfer of latent and sensible heats can also be dramatically altered in the forest environment. Because forest vegetation influences wind penetration and air movement through the forest, wind speeds in an open area can be much greater than those in a forest. Holbo (1984) measured wind speeds in forested and open sites, and found wind speeds in the open were up to four times greater than those in the forest. If wind speeds are used as an indicator of the potential for turbulent heat exchange, this difference could cause large differences in snowmelt between the forested and open sites when turbulent melt is dominant (Harr, 1981).

Effects of Forest Management

The debate over the effects of timber harvest on size of peak flows caused by rain-on-snow has been ongoing since Kittredge (1953) noted that the presence of forest cover could reduce flood peaks by reducing the rates of snowmelt in the forest. Anderson and Hobba (1959) also found that size of peak flows associated with rain-on-snow conditions were increased after clearcut timber harvesting. However, subsequent studies (Rothacher, 1973; Harr and McCorison, 1979) indicated no increase or reduced peak flows following timber harvest.

Harr (1981) used snowmelt indices developed by the U.S. Army Corps of Engineers (1956) to illustrate that snowmelt rates could be dramatically increased after clearcut harvesting. The increases he described were in response to higher wind speeds in the clearcuts, allowing increased rates of turbulent heat transfers. Christner and Harr (1982), analyzing streamflow records for six large watersheds in Oregon, found that increased size of peak flows over time appeared to be linked to rates of timber harvest in those drainages. They speculated that the cause of the increase in size of peak flows was most likely due to higher rates of snowmelt in clearcut areas during rain-on-snow.

In response to the apparent contradictory results of some of these studies, Harr (1986) reanalyzed data from the Rothacher (1973) and Harr and McCorison (1979) studies, putting them in the context of the rain-on-snow question. When focusing only on the streamflow records associated with rain-on-snow conditions, Rothacher's (1973) data showed a significant increase in size of peak flows following timber harvest. Although this difference was particularly evident in the moderate-sized peak flow events, Harr pointed out that even these events can be important in terms of altering in-channel fish habitat. His reanalysis of the Harr and McCorison (1979) study was based on very few events when rainfall actually occurred on a snowpack. However, in three of five post-logging rain-on-snow events, sizes of peak flows in the clearcut watershed were nearly double those in the uncut drainage. These peak flows occurred when air temperatures and wind speeds were high, conditions when turbulent heat transfers would be expected to dominate snowmelt.

In the early 1980's, two plot-scale studies were conducted in the Oregon Cascades and British Columbia (Berris, 1984; Beaudry, 1984; Berris and Harr, 1987). These studies sought to either corroborate or refute results of the earlier watershed studies by focusing on differences in energy balances between forested and clearcut plots, and differences in water outflow during rain-on-snow.

Beaudry (1984), working in British Columbia, compared rates of water outflow from a forested site with those from an adjacent clearcut during rain-on-snow. He found higher peak outflows from the clearcut plot in all cases. However, when large quantities of snow were present in the forest canopy, peak outflows from the clearcut were only slightly greater than those from the forest, and total outflow was greater from the forest plot. When there was no snow in the canopy, outflow totals were greater from the clearcut.

Berris and Harr (1987), working in the Oregon Cascades, compared rates of snow accumulation and melt between a forested and clearcut plot during rain-on-snow. They found two to three times more snow accumulated in the clearcut as compared to the adjacent forest site. They also measured higher wind speeds in the clearcut, and calculated turbulent heat fluxes in the clearcut of nearly three times those in the forest. During the largest rain-on-snow event monitored, estimated to have a return period of only two years, outflow from their clearcut plot was 21% greater than that from the forest plot. They attributed this outflow difference to the increased snow accumulation in the clearcut and greater heat transfers there.

Although Berris and Harr's (1987) results showed an increase in snowmelt from the clearcut site during rain-on-snow, the strength of their conclusions was somewhat limited by the paucity of suitable rain-on-snow events. Beaudry (1984) concluded in his study that rain-on-snow runoff from clearcut plots was not necessarily greater than that from the forest. This was based on his observing large snowmelt peaks occurring from the forest site during a relatively short period of canopy melt. However, at times when wind speeds and air temperatures were high, outflow from the clearcut plots was greater than that from the forest in both of these studies. In this light, both studies supported the argument for higher rates of snowmelt in clearcut sites when snowmelt is dominated by turbulent transfers of heat.

OBJECTIVES AND SCOPE

The primary objective of this study was to determine the effect of forest cover on the rate of water delivery to soil during rain-on-snow over a number of rain-on-snow events. A second objective was to compare water outflows from forest plantations with outflows from mature forest sites during rain-on-snow to determine if these plantations had hydrologically "recovered" in terms of their response to rain-on-snow.

The study was designed to find the magnitude of difference in water output from snowpacks in mature forest plots, non-forested plots, and forest plantations during rain-on-snow. New efforts at modelling runoff regimes before and after timber harvest will require estimates of the size of rain-on-snow runoff increases following timber harvest. This study was designed to begin establishing a range of expected increases in water delivery to the soil from open plots during various rain-on-snow events.

Two primary factors affecting water outflow during rain-on-snow are snow accumulation and rate of melt. As a plantation grows from individual seedlings to mature trees, the individual tree canopies enlarge and coalesce, forming a more complete and often very dense canopy layer. Throughout this process, the increasing density of vegetation and branch strength alters interception and accumulation rates within the stand as well as the penetration of wind into the stand.

A young plantation offers little surface area to intercept snow and little strength to support the intercepted snow. However, the deep canopy of a mature forest provides a great deal of surface area for interception, and the stronger branches can often support large amounts of snow. Connaughton (1935) showed that snow accumulation beneath mature forests and younger forest plantations can differ widely.

Because a mature forest differs in stand structure from a young forest plantation, air flow through the two can also differ. Holbo (1984) reported that trees with smaller diameters have less effect on moderating air movement through a forest than do larger trees. Snowmelt rates in forest plantations can be affected by the degree to which air flow is limited through the stand when turbulent heat transfers are the dominant source of heat for snowmelt. As a stand develops, it can be expected to resemble the mature forest more closely in its ability to limit wind penetration and movement.

This study was not designed to measure differences in snow accumulation or wind speed between the mature forest and plantation stands, but looked for these differences to be manifested in outflow comparisons between the two cover types. In the third winter of data collection, however, measurements of snow depth and snow water equivalent were made at each plot during each field visit as part of a study being conducted by the U.S. Geological Survey, Tacoma, Washington.

For logistics reasons, this case study was limited to the transient snow zone of the Cascade Range in northwest Washington. Results from the study, however should be applicable to other areas having similar vegetation that experience similar climate and rain-on-snow conditions.

This report reflects data analyses completed at the time of writing. Additional analyses may slightly change some conclusions.

METHODS AND MATERIALS

EXPERIMENTAL DESIGN

The study was designed to compare rates of water outflow from snowpacks under three different forest cover-types during rainfall. The three cover-types include a mature forest, a clearcut or otherwise non-forested opening (hereafter referred to as an opening), and a forest plantation ranging in age from 18 to 40 years. Since microclimate and snow accumulation differ among each of these environments, snowpacks in each may yield a different rate and quantity of water during rain-on-snow.

Twenty-four plots were established at three elevations and at two locations (Table 1). At each elevation and each location, plots were installed in groups of three: one in a mature forest, one in an adjacent or nearby open area (most often a recent clearcut), and one in an adjacent or nearby forest plantation. Water outflows from the three plots were then compared during rain-on-snow. In some cases, more than one plot was established in the same mature forest stand or plantation to get some idea of variability in outflows under the same stand.

STUDY LOCATION

Study plots were established at two locations. The northern study plots were located in the Finney Creek and Deer Creek drainages, tributaries of the Skagit and North Fork Stillaguamish Rivers, respectively (Figure 1). These study plots will hereafter be referred to as the Finney Creek plots. About 24 km

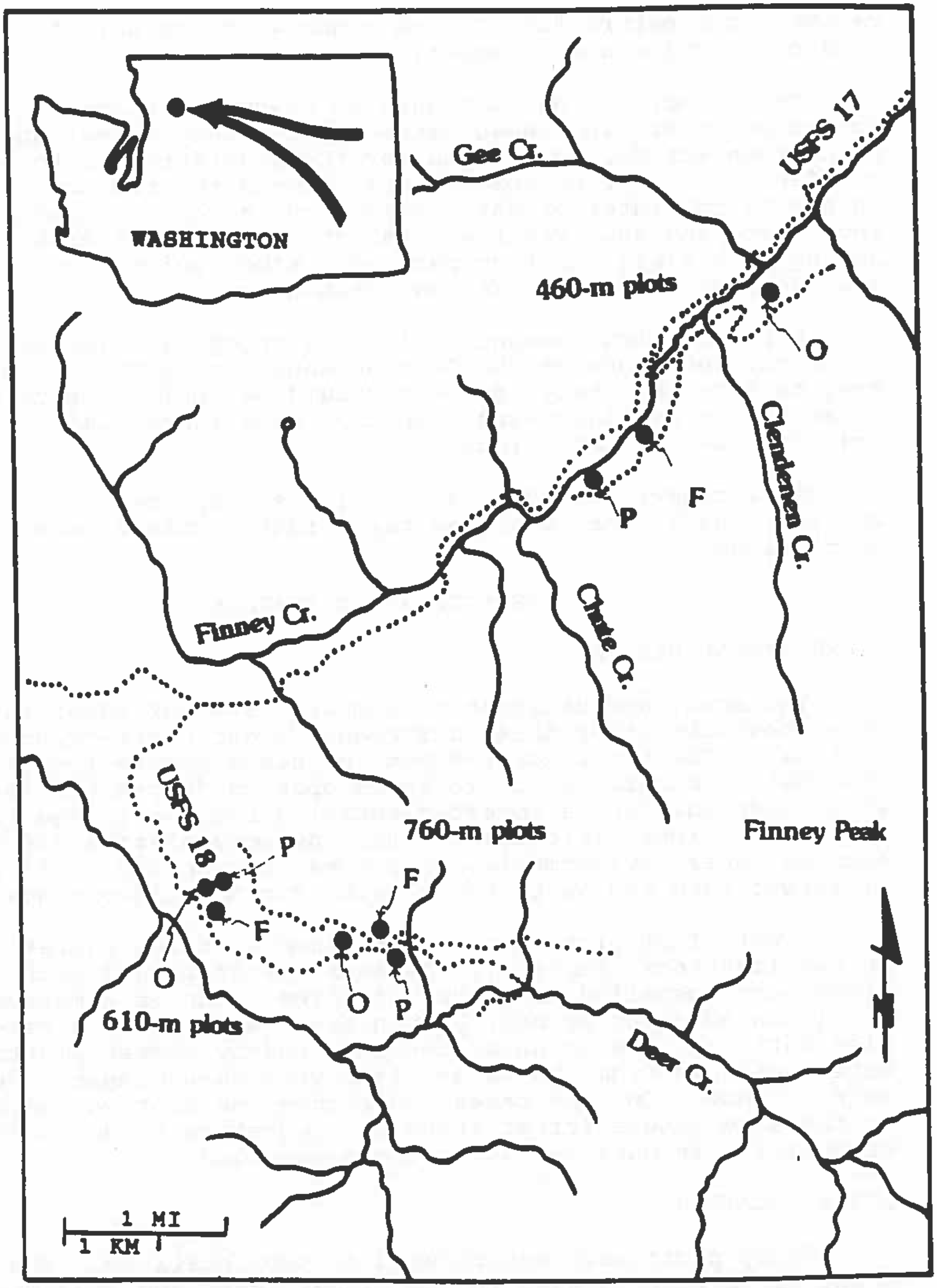

Figure 1. Location map of Finney Creek plots.
(F = Forest, P = Plantation, O = Open.)

south of this location are the second set of study plots. Plots at this location are referred to as the Canyon Creek plots, and are located in the South Fork Canyon Creek drainage, a tributary of the South Fork Stillaguamish River (Figure 2).

Table 1. Number of plots by elevation, forest cover and location.

	Elevation		
Canyon Creek:	460-m	610-m	760-m
Mature Forest Plots	1	3	1
Open Plots	1	1	1
Forest Plantation Plots	1	2	1
	Elevation		
Finney Creek:	460-m	610-m	760-m
Mature Forest Plots	3	1	1
Open Plots	1	1	1
Forest Plantation Plots	2	1	1

The elevational distribution of the study plots was used to address the storm-by-storm fluctuation in the zone of active melt. This zone is the elevation band stretching from the lowest elevation having snow to the highest elevation experiencing melt during any given event. As such, it can be very wide during some storms, and very small or nonexistent in others. It differs from the transient snow zone because the transient snow zone is a fixed elevation band wherein the probability of rain-on-snow is highest. The zone where snow is actually melting during any given event may be above, below or within the transient snow zone.

Study plots were established at elevations of 460 m, 610 m, and 760 m at both the Canyon Creek (Figure 3) and Finney Creek locations. All plots were located on land administered by the Mt. Baker-Snoqualmie National Forest.

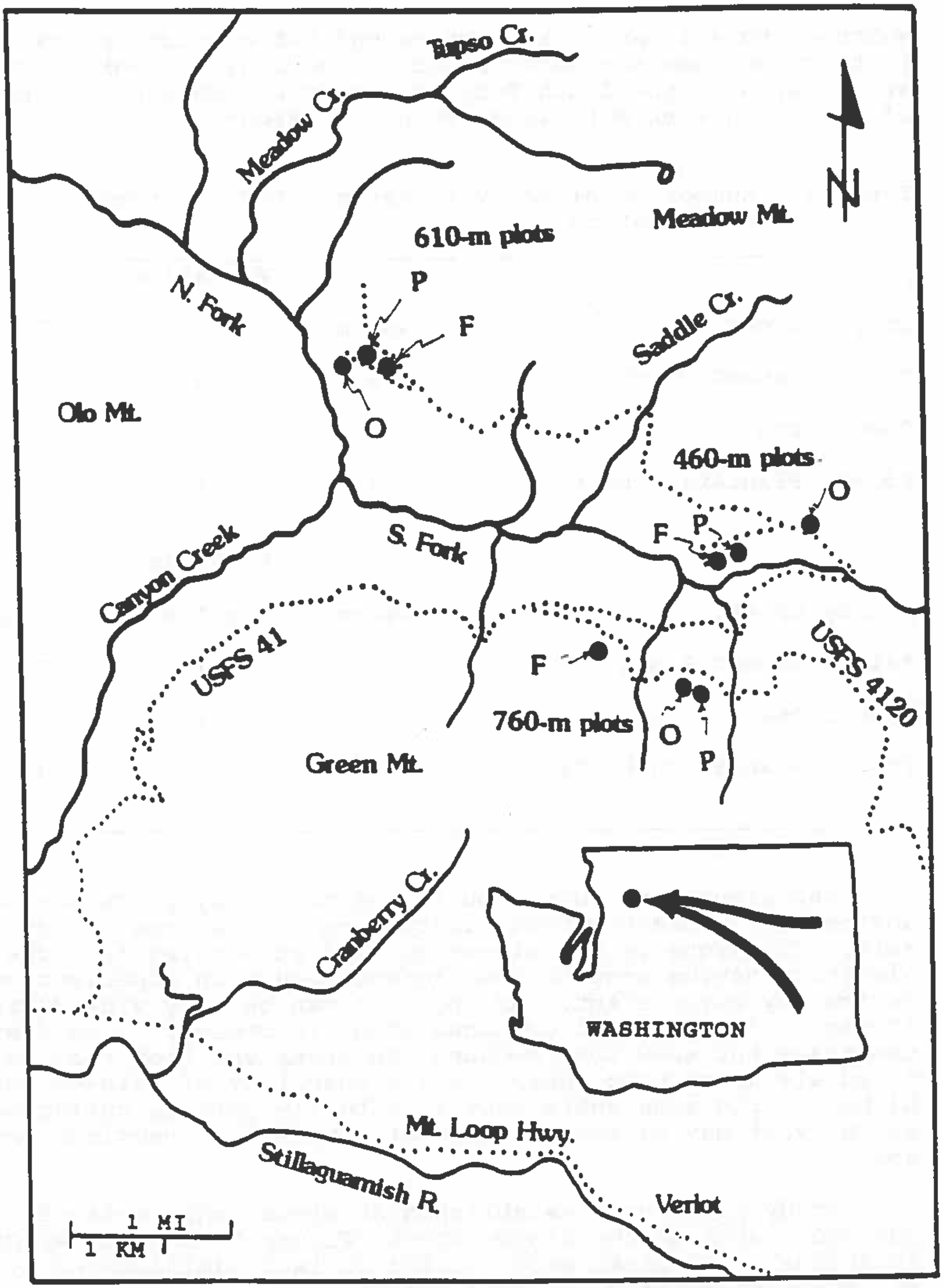

Figure 2. Location map of Canyon Creek plots.
(F = Forest, P = Plantation, O = Open.)

SITE SELECTION

A number of constraints and considerations were important in selecting plots for the study. These were governed primarily by environmental and logistical factors. The first consideration was to find sites with a high probability of experiencing rain-on-snow. Since by definition, the highest probability of rain-on-snow would be in the transient snow zone, this was the target elevation band. The transient snow zone is presumed to lie roughly between the 300-m and 900-m elevations in the Washington Cascades.

Within this elevation band, each set of study plots required a mature forest, an open site and a 20- to 25-year old forest plantation in close proximity to one another. In some cases, harvest history was such that a 20- to 25-year old plantation was not available, so an older or younger stand was used. Further, an attempt was made to ensure that the three cover types had nearly identical elevations, aspects, and exposures to winds.

Age and character of the forest and plantation stands was also important since they were to be representative of other forests and forest plantations. In addition, the specific location within the forest or plantation had to be generally representative of the stand in terms of canopy cover, surrounding vegetation and exposure to winds. Actual siting of individual plots was done subjectively, taking into account the factors noted above and physical requirements for installing instruments.

Patterns of drip, snow interception, and snow unloading within forested environments and particularly in forest plantations can be highly variable. Since outflow from the lysimeters was used to represent the surrounding stand, measuring large deviations from the "average" conditions in a stand could bias the study's results substantially.

In an attempt to improve the assessment of the range of outflows expected from forested plots, six additional lysimeters were installed in some forest and plantation plots prior to the second year of data collection. These additional lysimeters were located near the other lysimeters in the stands and were used to compare outflows from within an individual forest or plantation stand.

In addition to the environmental constraints, logistics played an important role in the site selection process. Terrain between the access roads and study plots was important because materials had to be packed in, and winter servicing would require access during adverse weather and on deep snowpacks. Time in travel, mode of travel, and safety were all important factors taken into consideration. During an early field reconnaissance trip, potential for vandalism was noted by the damage done by

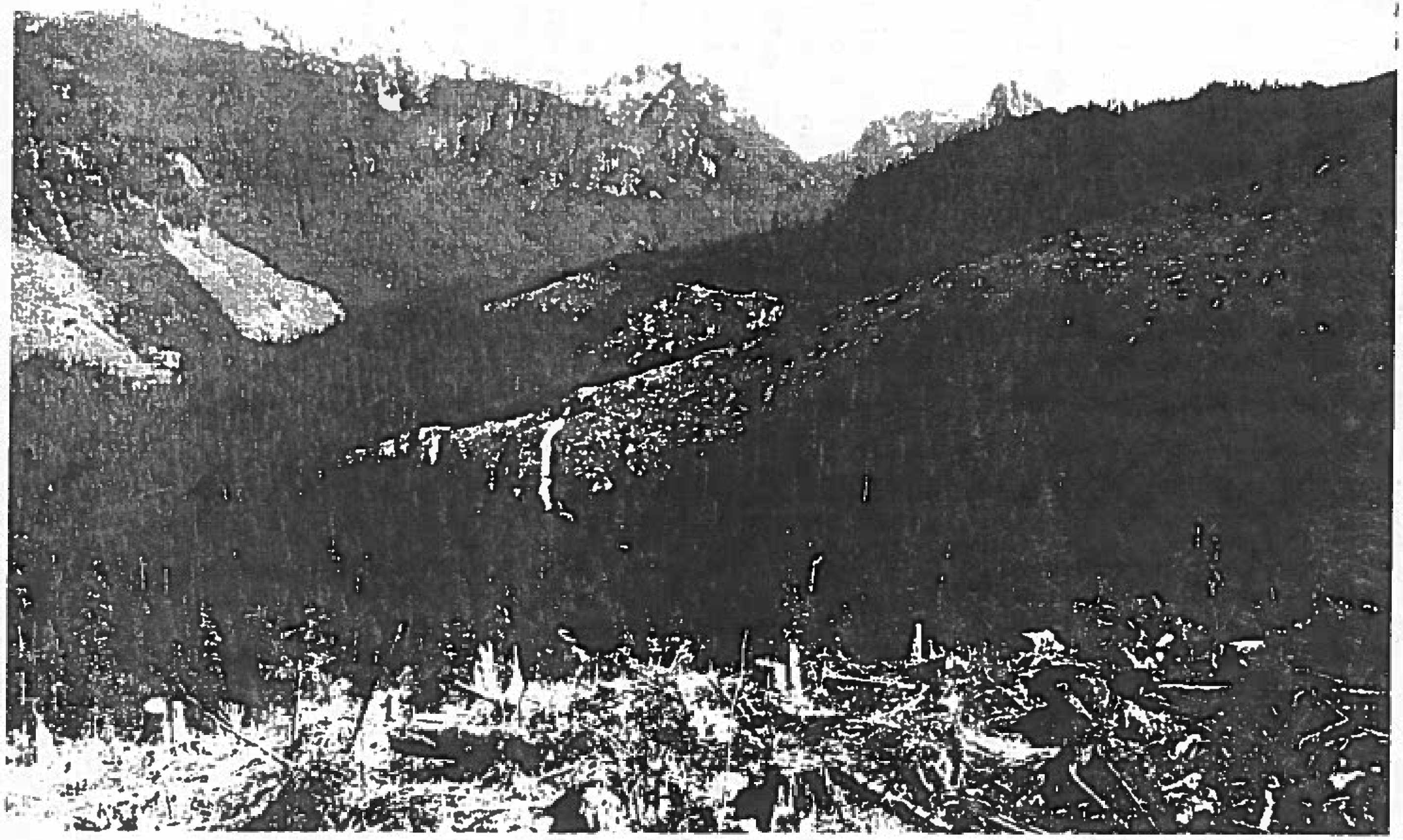

Figure 3. View looking northeast across South Fork Canyon Creek drainage from "760-m plots" label in Figure 2. The 760-m open plot is located in the clearcut above the road in the middle of the photo. The 460-m open plot is located in the clearcut along the left edge of the photo.

bullets to road signs, trail markers and other objects. Many potential sites were not selected because they were too visible from the access roads and deemed likely to be vandalized.

INSTRUMENTATION

Each study plot consisted of a snow collection box, or snow lysimeter, a large tipping bucket, and a time-of-event recorder. Snow lysimeters were constructed of pressure-treated plywood and lumber (Figure 4). The inside dimensions of the lysimeters were 1.14 m by 2.06 m, and they had 0.29-m high walls. Each lysimeter was lined with Hypalon[1], a watertight and weatherproof rubber-like material that is resistant to punctures and tears. (Despite the Hypalon's strength, curious coyotes and bears did puncture several of the liners.) The lysimeters were placed to allow water to drain to one corner where a metal bathtub drain was located. Outflow from the lysimeter was routed through the drain and a length of ABS plastic pipe to a large stainless steel tipping bucket located just downslope from the lysimeter.

The tipping bucket was housed in an A-frame structure to protect it from damage and incident precipitation (Figure 5). Magnetic switches of the kind used on doors and windows in household burglar alarm systems were mounted on each tipping bucket and on the tipping bucket supports. Each tip of the bucket sent an electrical pulse from the switch to an Omnidata Model DP101 One Channel Time-of-Event Recorder (Datapod) which recorded the time of each tip. Tipping buckets were calibrated to tip at a volume of one liter which represents a 0.425-mm depth of water over the area of the snow lysimeter.

In addition to the snow lysimeter and tipping bucket arrangement, each open site was instrumented with a small weather station (Figures 6 and 7). The weather station included an R.M. Young Model ES-050 Wind Speed and Direction Sensor, a Vaisala HMP 113Y Humidity and Temperature Probe for measuring air temperature and relative humidity, a Skye Model ES-250 pyranometer for measuring incident shortwave radiation, and a tipping bucket precipitation gage charged with antifreeze. These instruments were controlled by an Omnidata Easy Logger, Model EL-824GP (Figure 7). During the first year of data collection, the Easy Loggers were powered by two 7.5-volt carbon-zinc batteries linked in series. The following season, the systems were powered by sealed, lead-acid, 12-volt, 9.5 amp-hr batteries that were recharged after each use. The Easy Loggers and Datapods at each site were kept in watertight ammunition boxes that were bolted to stumps, trees or the A-frame tipping bucket shelters.

Each precipitation gage consisted of a 1.22-m section of 305-mm diameter PVC sewer pipe cemented to a PVC base. The top

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[1] Trade, brand, and corporate names are used for the benefit of the reader. Their use does not constitute endorsement by the USDA Forest Service or the University of Washington to the exclusion of other products that may be suitable.

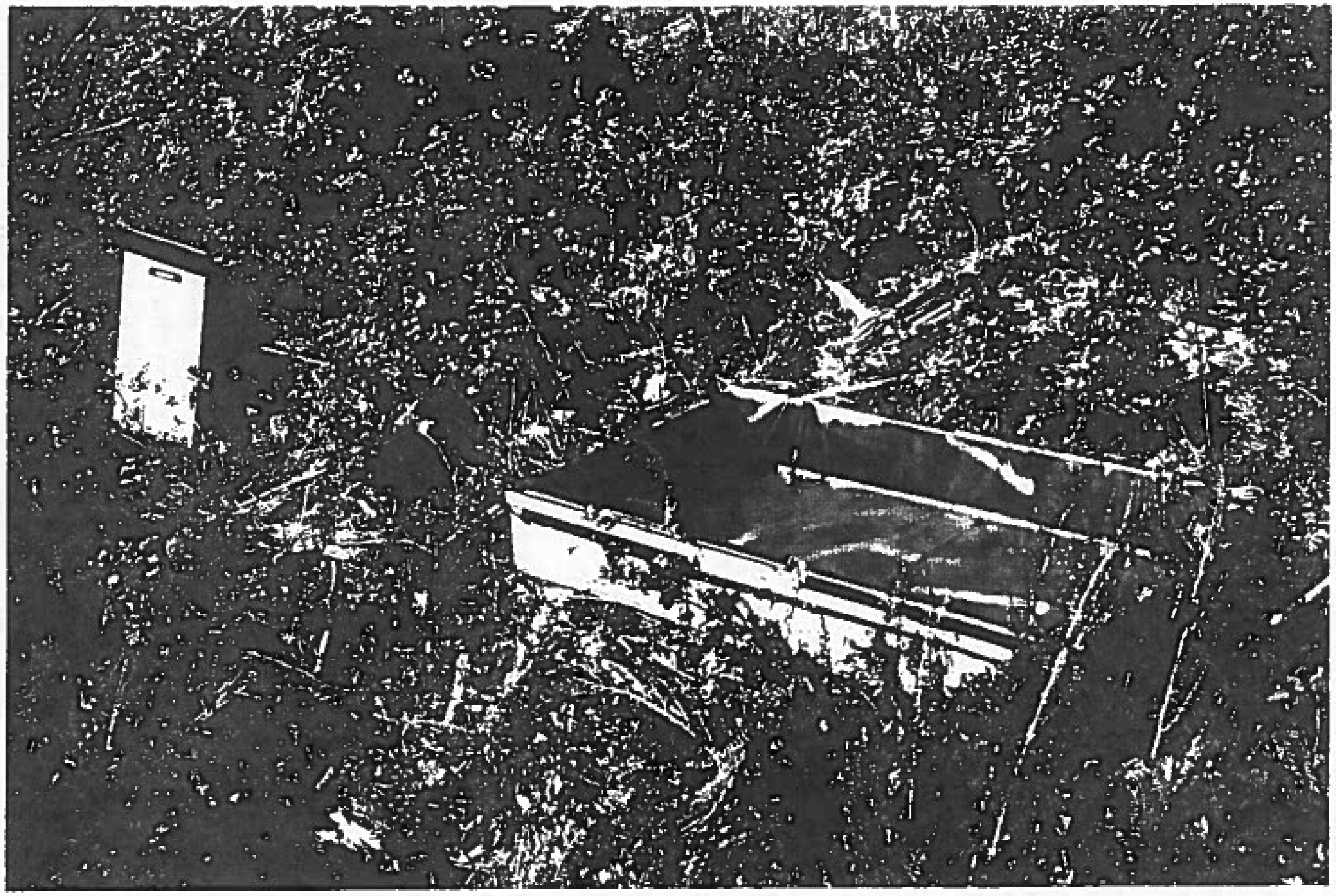

Figure 4. Snow lysimeter and tipping bucket shelter, open plot at Canyon Creek, 610-m elevation

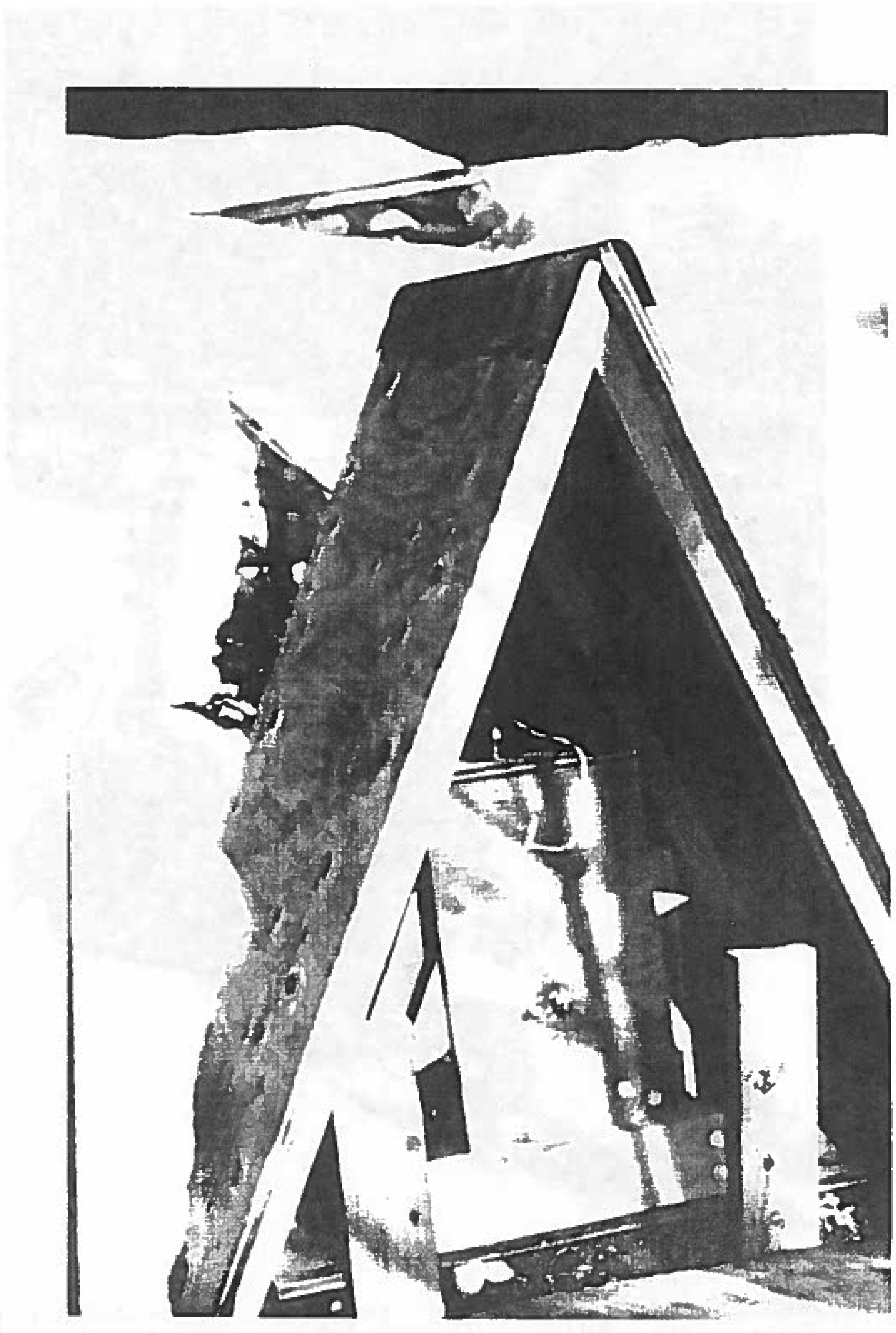

Figure 5. Tipping bucket and support inside A-frame shelter.

Figure 6. Weather station, Finney Creek 760-m elevation open plot. The small tower supports a wind monitor (top), a pyranometer (mounted on the arm), and an air temperature-relative humidity sensor (under the hemispherical shield). A raingage camouflaged to avoid vandalism is visible on the left.

Figure 7. Programming the data logger, open plot, Canyon Creek, 460-m elevation. Located on the tower is a wind monitor (top), a pyranometer (mounted on the side arm), and a temerature-relative humidity probe (under the hemispherical shield.)

end of the pipe was beveled outward to minimize snow accumulation around the orifice. The gage was a reservoir charged with 22.7 l of anti-freeze consisting of a mixture of propylene glycol and ethanol with a density of 0.95 g/cm^3. A given amount of incoming precipitation mixed with the antifreeze and displaced a like amount of anti-freeze from the reservoir. This liquid was routed to a small Sierra-Misco Model 5050 tipping bucket, calibrated to tip with each millimeter of rain and snow water equivalent (SWE).

In some cases, when heavy precipitation was followed by cold temperatures or when the gages were left unserviced for long periods of time due to access problems, the antifreeze solution was over-diluted or unable to maintain a fully liquid state. During these times, the gage reservoirs froze solid, or liquid from the gages froze in the outflow tube blocking further outflows.

The gages were wrapped in red-cedar bark to camouflage them in order to minimize vandalism (Figure 6). Unfortunately, the bark enabled mice to climb up the side of the raingage, fall inside, and drown. In November and early December of each year, dead mice had to be removed to prevent them from plugging the raingage's outflow tube.

Wind screens were installed around most gages before the second year of data collection to decrease the expected gage catch deficiency. However, even with the windscreens, large gage catch deficiencies were possible during windy periods of snowfall because of the location of the gages in large exposed areas. The U.S. Army Corps of Engineers (1956) notes that even shielded gages, if located in unprotected areas, can experience gage catch deficiencies as large as 50% of actual snowfall during windy periods.

The 460-m Canyon Creek site was not fitted with a windscreen because of that site's proximity to a well travelled road and a common campsite for hunters. A windscreen at this location would have served only to increase the probability of vandalism at the site. Even without the windscreen to attract attention to the site, the wind monitor and rain gage here were damaged during the first year of data collection by bullet holes in the propeller and housing and in the raingage orifice. No windscreen was installed around the gage at the 760-m elevation at Finney Creek because it had wind protection from surrounding vegetation.

SITE DESCRIPTIONS

Table 2 describes general characteristics of the individual plots. Data was acquired using both field measurements and data from the Total Resource Inventory records at the Mt. Baker and Darrington Ranger Districts of the USDA Forest Service, Mt. Baker-Snoqualmie National Forest.

Table 2. Descriptions of individual study plots.

Study Plot	Tree Age (yr)	Remarks
460-m Canyon Creek:		
Forest	>80	Western hemlock dominated stand. South aspect, slope < 10%. Lysimeter sits on bench just above a break in slope.
Open	<5	15-ha clearcut, harvested 1987. South aspect, slope 30-40%. Lysimeter sits on bench just above road.
Plantation	22	Very dense stand of unthinned western hemlock. Avg. diameter[1] of planted trees, 0.21 m. Many volunteer hemlock underneath the planted stand ranging from 20-150 mm in diameter. South aspect, slope 25-35%.
610-m Canyon Creek:		
Forest	>80	Western hemlock, Douglas-fir. Southwest aspect, slope < 10%. Stand subject to blowdown, three lysimeters located 50 m apart.
Open	<5	14-ha clearcut, harvested 1987. Southwest aspect, slope 5-15%. Slope increases rapidly below lysimeter. Lysimeter located at upper end of clearcut, exposed to winds coming up Canyon Creek.
Plantation	29	Western hemlock stand, avg. diameter, 0.21 m. Southwest aspect, slope <10%. Two lysimeters located 18 m apart.
760-m Canyon Creek:		
Forest	>75	Douglas-fir, true fir, western hemlock. North aspect, slope 25-35%.

[1] Average diameters were calculated by measuring all trees within a distance of 15 m of each lysimeter.

Table 2. (cont.) Descriptions of individual study plots.

Study Plot	Tree Age (yr)	Remarks
Open	<5	17-ha clearcut, harvested 1986. Lysimeter sits in the middle of the unit.
Plantation	25-40	Western hemlock, true fir; avg. diameter, 0.19 m. Stand includes both 25 yr and 40-42 yr old trees. North aspect, slope 25-35%.
460-m Finney Creek:		
Forest	>75	Western hemlock, true fir, redcedar. Northwest aspect, slope < 5%. Lysimeter sits just above break in slope that leads down to Finney Creek. Three lysimeters located along slope break, 5-50 m apart.
Open	<5	14-ha clearcut, harvested 1987. Northwest aspect, slope 35-45%. Lysimeter sits along slope near upper end of clearcut. Subject to direct winds down Gee Creek and Finney Creek valleys.
Plantation	18	Douglas-fir, avg. diameter, 0.21 m. Northwest aspect, slope <10%. Two lysimeters located 10 m apart on old terrace above Finney Creek.
610-m Finney Creek		
Forest	>80	Western hemlock, true fir. Southwest aspect, slope 5-15%
Open		Lysimeter sits at top of large, open cut-bank, just below 28-yr old plantation. Southwest aspect, slope 35-45%
Plantation	28	Douglas-fir, avg. diameter, 0.33 m. Southwest aspect, slope 25-35%

Table 2. (cont.) Descriptions of individual study plots.

Study Plot	Tree Age (yr)	Remarks
760-m Finney Creek:		
Forest	>80	Western hemlock, redcedar, true fir. South aspect, slope 20-30%. Stand has a dense understory of very small trees.
Open	<10	50-ha clearcut, harvested 1984. South aspect, slope 5-15%. Lysimeter sits at lower end of unit, trees surrounding plot are up to 3 m high.
Plantation	25	Western hemlock, true fir; avg. diameter, 0.18 m. Stand includes a few 35-38 yr old trees. South aspect, slope 5-15%. Canopy relatively open above lysimeter.

DATA COLLECTION

Data were collected hourly at all the open study plots. Sensors were scanned at 5-min intervals, and data were summarized into hourly reports by the Easy Loggers. Hourly reports included mean and standard deviation of 12 measurements of air temperature; mean and standard deviation of 12 measurements of wind speed, mean shortwave radiation, relative humidity, and wind direction; and total volumes recorded by the rain gage and snowmelt tipping bucket for the hour. Datapods at the forest and plantation plots recorded the time of each tip of the tipping bucket. During field visits, data storage modules were removed from the Datapods and Easy Loggers in the field, brought to the office, and read into spreadsheet format on a microcomputer.

Study plots were established in September, 1988 and serviced thereafter on a monthly or bimonthly schedule throughout the fall-spring period. During the first year of data collection, field visits were made on average once every six weeks to replace dry-cell batteries and data storage modules, recharge precipitation gages and maintain other instruments as required. Because of difficulties with battery life and dilution of the antifreeze solution in the precipitation gages, dry-cell batteries were replaced with sealed, lead-acid batteries, and field visits were scheduled monthly in the second and third years.

In the early part of the season, access to the plots was possible with a four-wheel drive vehicle. But as snow accumulated, it became necessary to use a tracked over-snow vehicle.

Landslides and debris flows made regular field visits difficult, particulary during the third year of data collection. In February 1990, a landslide in Finney Creek delayed one field visit by several weeks. A debris flow that closed the Finney Creek road (USFS 17) in early November 1990 forced the November Finney trip to be made over Cumberland Pass (west of the area shown in Figure 1). Heavy rainfall and snowmelt later in November 1990 caused debris flows that closed that alternate route, and a large section of USFS 17 below Gee Creek (Figure 1) slid into Finney Creek. The December trip into Finney was made over Segelesen Pass, located southeast of the area shown in Figure 1, but in January 1991, snow avalanches closed this alternate route and prevented access to the Finney plots. In February, the Cumberland Pass route was used with difficulty after clearing of landslide debris.

In general, access to the Canyon Creek plots was not hindered by landslides to the degree that the Finney Creek plots were. Nonetheless, in November 1990, a landslide did block the Canyon Creek road (USFS 41) south of Saddle Creek (Figure 2). Subsequent access to the 610-m plots at Canyon Creek was by snowshoe from the landslide site, a distance of 4.8 km.

DATA INTERPRETATION

With very limited time in the field during the snow season, events and on-site conditions were interpreted from the numerical data. General observations recorded during field visits provided reference points for estimating snow accumulation, and as checks for operation of the instruments. In the third year, a snow surveyor from the Tacoma office of the U.S. Geological Survey measured snow depth and snow water equivalent as part of another study funded in part by the Timber/Fish/Wildlife Agreement. When appropriate, these data were used to check estimates of snow accumulation and of snow remaining in lysimeters.

Two of the more difficult tasks of interpretation involved differentiating rain from snow and estimating the amount of snow on the ground. Differentiating rain from snow could be done by comparing outflow from the precipitation gage with that from the lysimeter in the open when no snow was on the ground. During rainfall, outflows came from both the gage and the open lysimeter at approximately the same rate. When snow fell, outflow would occur only from the precipitation gage, and snow landing in the lysimeter would accumulate, showing up as outflow only later as it melted.

Differentiation became less straightforward when there was already snow in the lysimeter. Depending on the depth and condition of the snowpack, any rain falling onto the snow could be absorbed and held in the pack, thus producing no immediate outflow. During these instances, comparing the gage and lysimeter outflows would suggest snow accumulation. However, if snowfall were assumed in all of these cases, total snow accumulation could be substantially over-estimated. Moreover, the quality of the snowpack could be dramatically different depending on whether the precipitation fell as rain or snow.

When the form of the precipitation could not be determined by comparing outflows, air temperature was used as the basis for differentiation. The U.S. Army Corps of Engineers (1956), used an air temperature of 1.7° C as a breakpoint in estimating the form of precipitation. When air temperature is 1.7° C, there is a 50/50 chance of the precipitation being snow. By the same token, the further the air temperature is below 1.7° C, the greater the probability that precipitation is snow. For example, at an air temperature of 1.1° C, the probability that precipitation fell as snow is roughly 70%. The 1.7° C value was used as the break point for differentiating rain from snow when other methods were unavailable.

The air temperature method for differentiating rain from snow was less useful in the forest and plantations. At air temperatures near freezing, snow was commonly found to accumulate in the open lysimeter, while snow intercepted by the forest or plantation canopy was quickly melted and appeared almost immediately as outflow from the lysimeter. This "rain response" from the forested sites, while snow was accumulating in the open, has been documented by other researchers as well (Haupt, 1972; Harr and McCorison, 1979; Harr and Berris, 1987, Beaudry, 1984).

Estimating the amount of snow accumulating in the open plots was problematic because of the difficulties in differentiating rain from snow, but also because of gage catch losses (U.S.A.C.E., 1956). The highest losses occurred when wind speeds were high. Because gages in this study were located in large open areas, they were exposed to high winds, and likely experienced catch losses during some snowstorms. This became apparent when comparing accumulation estimates based on recorded gage data with observations of snow depth made during field visits. Fortunately, many snowstorms were accompanied by very light winds.

Estimating snow accumulation in the forests and plantations was made more difficult by the added factor of interception. One method considered was to develop a catch relationship between lysimeters in the forest and those in the open during rainfall, and then to apply that relationship during periods of snowfall. However, as pointed out by Rothacher (1963), the interception relationship at any point under the canopy changes based on the storm size and conditions between storms. Furthermore, the proportion of rainfall intercepted by a forest canopy decreases with increasing storm size, but interception rates for snow increase up to a point as more snow accumulates on needles and branches (Rothacher, 1963; Satterlund and Haupt, 1970).

In addition, the patterns of throughfall or drip from the canopy can differ considerably between rain and snow. As snow loads a canopy and weights down the individual branches, drip water and unloading snow is deposited preferentially around the canopy margin, causing large spatial variability in the snowpack depth and water equivalent on the ground (Smith, 1974). As the branches flex downward with increasing snow load, they also flex inward so that the drip zone contracts and expands as snow load increases and decreases. This phenomena is particularly evident in younger forest plantations, as noted by Berris (1984), and is less important for trees with stiffer branches which are better able to maintain their positions under snow loads (Smith, 1974). Figures 33 and 34 in the Appendix shows an example of the large variability in snow accumulation often found in plantations.

Because of these difficulties, a combination of field notes and outflow data surrounding the rain-on-snow events was used to assess the presence or absence of snow and, to some degree, the quantity of snow on the plots at any given time. For example, outflow records from the lysimeters could be checked during periods when air temperatures were relatively high. If snow was present, a trickle from the lysimeter would often be evident. When no snow was present, no outflow would occur from forest or plantation lysimeters until it appeared from the precipitation gage. In addition, when there was no snow in the lysimeter, outflow from the lysimeter would drop quickly following rainfall, even when hourly average air temperatures remained high. With snow in the lysimeter, outflow would continue to trickle out and generally take longer to stop completely. As stated above, this interpretive information was supplemented where possible during the third field seasons by measurements of snow depth and SWE made by the U.S. Geological Survey's snow surveyor.

Throughout the data are a number of periods when outflows occurred from some lysimeters, but not from others. Sometimes this was presumably due to differences in air temperature and/or precipitation between sites, or just availability of snow in the different lysimeters. However, in some cases, these apparent discrepancies in outflow occurred between lysimeters that were very near one another when air temperature, precipitation and the presence of snow were most likely very similar between the two locations. Similarly, there were times when air temperatures were well above freezing, and outflow occurred from the precipitation gage but not from the lysimeters. Following these periods, outflows often began suddenly from the lysimeters that had been showing no outflow.

The lag in outflow followed by a sudden release of water from some lysimeters during some events can reflect actual differences in snowmelt and water routing between the plots, or may be attributable to problems with the instrumentation. Other researchers have noted snowpacks absorbing rain water until they can no longer hold the water against the pull of gravity. The sudden beginning of outflow from these packs occurs as they "let go" of the transient water (Beaudry, 1984; Gray and Male, 1981). This phenomena may be occurring in some cases, but is less likely when snowpacks are shallow and already near their liquid-water-holding capacity.

Following very cold periods, the "lag and release" of outflow from some lysimeters could have been a result of ice blockages forming and later melting in the lysimeter drains, or ice blocks forming in the tipping buckets. Ice formation in the lysimeter drain was generally associated with an accumulation of needles and debris around the drain. The debris slowed water movement from the lysimeter into the drain, allowing the water to freeze and block the outlet. This problem occurred more commonly during the first year of data collection when a fine screen was put over the drains to keep needles out. During the second year, the fine screens were replaced with coarser mesh screening, and fewer problems occurred.

When ice formed in the drain, rainfall and melt outflow were retained in the lysimeter until the ice blockage melted. A large pulse in the outflow data would indicate the time the blockage was removed and when free drainage from the lysimeter resumed. It was assumed that during these cases, all outflow water was accounted for in the data. That is, no meltwater was lost or released without going through the tipping bucket and being "counted." When this happened, the total volume of outflow was assumed to be accurate though the timing of the outflow was delayed.

On the contrary, when ice blocks formed in the tipping buckets, outflow from the lysimeter was not always recorded. The added weight of a block of ice in one side of the tipping bucket would prevent the bucket from tipping when the other side filled with water. As a result, the bucket remained tipped in one direction until the ice block melted or slid out of the bucket. While the bucket was held stationary, water outflow from the lysimeter flowed out over the tipping bucket and was unaccounted for in the data. Where this was suspected, the rain-on-snow event was withdrawn from data analyses.

Differentiating between periods when rain water was being absorbed by the snowpack, and those times when the lysimeter drains or tipping buckets were frozen, was not always possible. When snowpacks were shallow, it was assumed that they could hold only little rainfall without yielding outflow. Furthermore, routing of water through these packs would have been relatively rapid because of the short travel distance. During these times, substantial outflow "lag" periods were thought to be related to ice formation in the drain or bucket. However, when snowpacks were deeper, the lag in water outflow could have been caused by either ice problems or rainwater absorption and routing within the pack.

RESULTS AND DISCUSSION

OVERVIEW OF WEATHER DURING THE STUDY

During the three winter field seasons of data collection, exceptionally low temperatures, snow-free periods, and heavy snowloads at times hampered data collection and created difficulties for instrumentation. A general overview of weather conditions experienced over the three winters is provided here for for general background information.

In 1988-89, the first winter field season, precipitation and snow accumulation in western Washington were considered slightly below normal through the fall and early winter. By the end of January, a number of accumulation-melt sequences had occurred at lower elevations in the Cascades.

During the first three days of February, temperatures dropped to record lows as an Arctic front moved into the western part of the state, and temperatures fell below -18° C at the 760-m elevation plots at both Canyon and Finney Creek. Since the study plots were designed for "average" winter weather conditions, this 15-20-yr cold snap caused a number of problems with data collection. In fact, data collected after this time were largely inconsistent and unreliable due to a combination of freezing lysimeter drains and extensive formation of ice lenses within the snowpacks.

The 1989-90 winter began with very little snow accumulation at lower and middle elevations in the Cascades, and so little at higher elevations that many ski resorts remained closed until after January 1, 1990. The first significant snow accumulations at the study plots occurred early in January, setting the stage for the rain-on-snow events of January 5-8, 1990. Following this week of rain, all study plots were again free of snow.

During the latter part of January and into early February, heavier than normal asccumulations of snow occurred throughout the Cascades. Ski resorts were again closed along with mountain passes, this time due to extreme avalanche danger posed by the heavy snowpacks and wet conditions. By February 3, over 1.5 m of snow had accumulated at the 760-m elevation plots at both Canyon Creek and Finney Creek. This heavy accumulation damaged some field equipment and exceeded the design capacity of the snow lysimeters and precipitation gages. Anti-freeze solutions in the precipitation gages were, in many cases, over-diluted by the high volumes of precipitation. When the anti-freeze solution became slushy, many of the gages filled with snow, and liquid in gage outlets froze. Wiring between tipping buckets and the data loggers was also damaged from the weight of the snow, and in one case, a precipitation gage was actually pushed off of its base by the snowpack creeping downhill, despite its being braced to resist snow creep. Since the lysimeters were constructed to handle shallow (<0.30 m) snowpacks, meltwater from these deep packs could have been routed horizontally out of the snow directly above the lysimeter (or into the lysimeter from snow not directly above the lysimeter) by ice lenses and layers formed within the pack. Data collected after February 3 were highly variable (and suspect) among study plot locations.

After rainfall on February 9, mostly clear weather occurred for the next month, with temperatures falling at times to below -10° C at night and to above 15° and 20° C on some days. The remaining snowpack melted primarily during these sunny periods.

The 1990-91 data collection season began with extreme rainfall November 8-10 which caused a landslide that closed the Finney Creek road. This rainfall, augmented by rapid snowmelt at higher elevations in the Cascades, caused severe flooding in the major river valleys of northwest Washington. Two weeks later, western Washington was hit again with extreme rainfall that sent rivers back to flood stage. This time, there was considerable snowmelt above the 610-m elevation. The increased snowmelt, combined with higher streamflows and soil water contents following the storm of November 8-10 caused the flooding to be more widespread and severe than the earlier flood.

Snowfall began on November 29 followed by rain-on-snow on December 3-4 and again on December 8-10. After intermittent snowfall through December 18, temperatures plunged on December 19 with the arrival of an Arctic air mass, the second one in three winters. Weather remained cold through December with temperatures reaching -20° C at the 760-m sites and -18° C at the 460-m sites. Snowfall continued through January 1, and temperatures remained below freezing through January 6. Several rain-on-snow events occurred during January, but the deep snowpacks released little water and some intruments were not functioning; consequently, only one of those events is included in the analysis. Sunny weather through the remainder of January melted some snow, and the remainder melted the first week in February. A snowpack accumulated again in March, followed by sunny weather with warm temperatures throughout most of March that melted considerable snow. Thus, at the time of a moderate rain in early April, little snow remained.

This chronicle of weather during three years of data collection illustrates part of the difficulty of studying rain-on-snow. Despite the range of elevations in this study, melt often occurred at elevations above those used in this study or at other locations in western Washington either north or south of this study's locations. At other times, favorable melt conditions were present at the location of the study plots, but snow was limited or some instruments were malfunctioning because of extreme weather conditions prior to the rain-on-snow event. With few exceptions, events reported in this study do not exhibit the exceptionally large amounts of snowmelt that have occurred at times in western Washington over the last 40 years.

The severely cold weather in two of the three winters hampered data collection considerably and reduced the number of usable rain-on-snow events. Temperatures of -20° C have been rare in western Washington, having occurred roughly only every 10-15 years, yet such temperatures occurred twice in the three winters of this study. Although it did provide two of the largest rain-on-snow events of the study, the extreme weather of November 1990 also severely damaged forest roads required for winter access. Less frequent access meant equipment malfunctions could not be detected or corrected, and data analysis was delayed.

RANGE OF RESPONSES DURING RAIN-ON-SNOW

Although nearly three dozen melt sequences of various sizes were recorded over the three-year period, only 13 rain-on-snow events were found suitable for analysis in this study. In all of these cases, greater total outflows were measured at open plots than at forest plots. In some cases, outflow from the open plot was more than 100% greater than that from the corresponding forest plot, but in other cases, open site outflow exceeded the forest outflow by as little as 1%. Outflows from the plantation plots were often intermediate between the forest and open site outflows, but at times were less than corresponding outflows measured from the forest plots.

These 13 rain-on-snow events are described in detail in narrative form because such descriptions help explain how a particular plot responded to snowfall and snowmelt. These naratives show not only how a particular rain-on-snow event as a whole was affected by relative amounts of forest cover but also how the various processes of snow accumulation and melt can vary drastically within a single rain-on-snow event. They also illustrate some of the difficulties encountered in this type of field study.

Description of Events

Event 1: December 29-30, 1988

This event, which followed over 10 days of mostly sub-freezing temperatures, was recorded at the 460-m and 610-m elevation plots at Finney Creek and the 460-m plots at Canyon Creek. No data were available from the forest lysimeter at the 610-m elevation of Canyon Creek because prior to the event a large tree fell on the tipping bucket shelter and crushed it. That site remained out of commission for the remainder of the year. Outflow data were also missing from most of the lysimeters at the 760-m elevation plots during this event, although rain-on-snow undoubtedly was occurring there, too. This was probably due to frozen lysimeter drains at those higher and colder locations, but might reflect the deeper snowpacks there absorbing the rain and snowmelt water.

From December 20-23, about 20 mm of snow water equivalent (SWE) accumulated at the 460-m open site at Canyon Creek. Little precipitation fell after that until late December 28 when a light snowfall began. The majority of rainfall in this event occurred in a 7-hr period from 1500 hr to 2100 hr on December 29 during which time outflow from the forest plot exceeded that from the open plot (Figure 8). Outflow from the plantation plot did not begin until 2000 hr December 29. The nature of outflow from all three plots, i.e., the lack of a slow trickle of outflow exhibited by other lysimeters the afternoon of December 29, suggests that the outlets of all lysimeters were frozen prior to this rain-on-snow event.

As hourly average air temperatures began climbing at 2200 hrs on December 29 and steadily increased to a peak of 7.0° C at midnight December 29, windspeed also increased markedly. By 0800, on December 30, all outflows had reduced to a trickle.

During the 24-hr period beginning at 1100 hr on December 29, 103 mm of outflow was recorded from the forest lysimeter at the Canyon Creek 460-m elevation, while 131 mm and 86 mm were recorded from the open and plantation plots, respectively (Table 3). During the same period, outflow from the 460-m forest site at Finney Creek was 45 mm, while the associated open site and plantation plots both registered 88 mm. At the 610-m elevation plots at Finney Creek, 11 mm of outflow were measured from the forest lysimeter, while the open and plantation outflows were 19 and 15 mm.

Although the actual timing of snowmelt from the lysimeters with frozen drains cannot be determined, the total volume of outflow is most likely accurate. That is, the lysimeters are watertight and any melt or outflow that would have occurred from them is retained in the lysimeter while the drain is blocked.

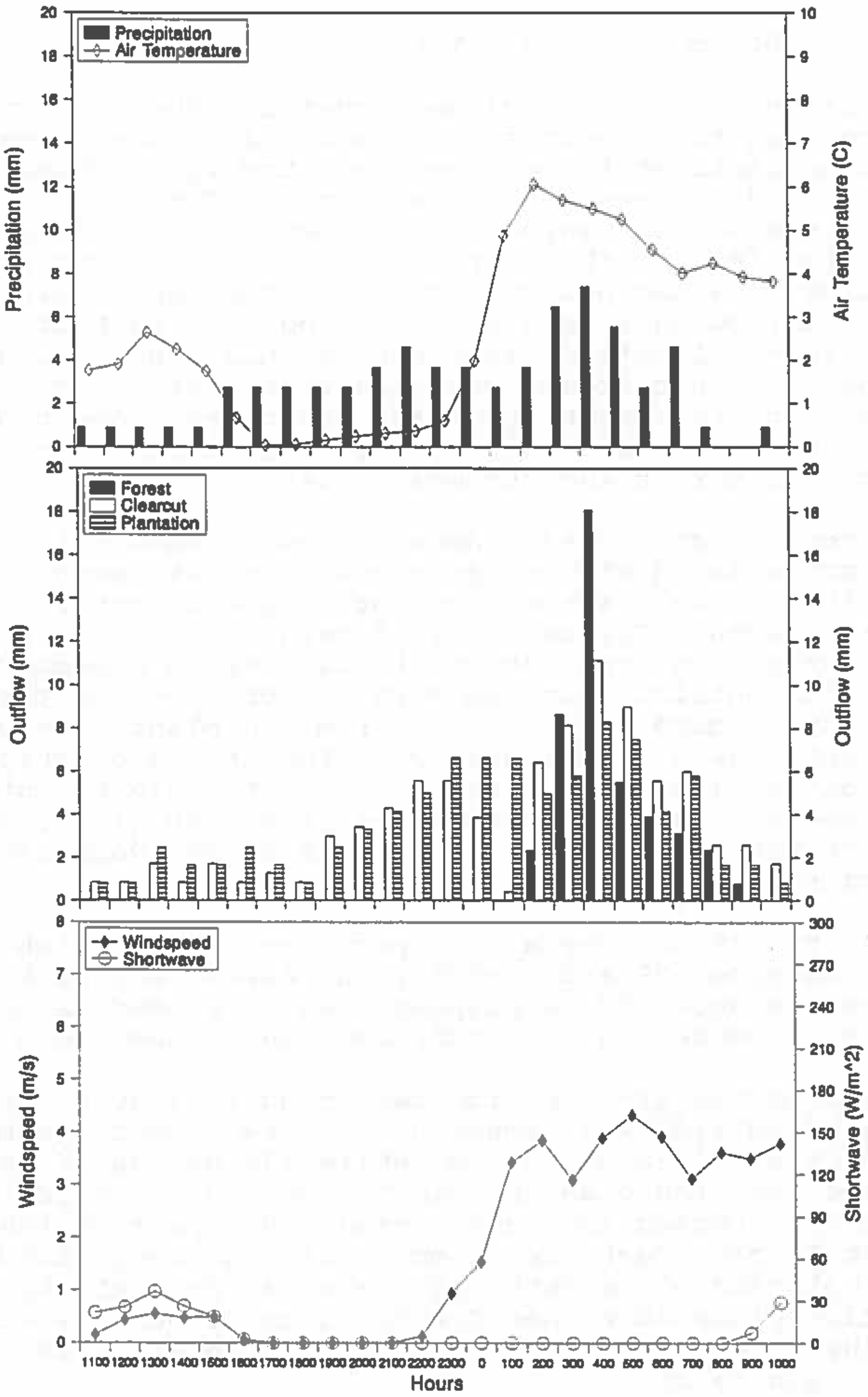

Figure 8. Rain-on-snow event, Canyon Creek 460-m elevation, 1100 December 29 -1000 December 30, 1988:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

Thus, the total volume is released and measured when the plug melts completely or is removed during a field visit. This appears to have been what happened during this event.

Table 3. Comparison of lysimeter outflows during December 29-30, 1988 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			24-hr totals
Forest	103		
Open	131	+27	
Plantation	86	-16	
460-m Finney Creek			24-hr totals
Forest	45		
Open	88	+96	
Plantation	88	+96	
610-m Finney Creek			24-hr totals
Forest	11		
Open	19	+73	
Plantation	15	+36	
610-m Canyon Creek			Instrument damaged
760-m Finney Creek			Outflow data missing
760-m Canyon Creek			Outflow data missing

Outflow from the forest lysimeter at the Finney Creek 460-m elevation during the event was just 65% of the precipitation measured in the open. It is possible that because of interception and re-routing of the rain, less rain was caught in the forest lysimeter than in the gage in the open. However, analysis of nine rain-only events revealed that the forest lysimeter catch at this site averaged 88% of the rain gage catch. And in only one of the nine rain-only periods analyzed did the forest catch show less than 75% of the rain gage catch. Nevertheless, even if a 60% catch differential is assumed (smaller than any differential measured during rain-only), this would allow for just 3 mm of SWE to have melted from the forest site. This is possible, but such a large melt differential seems out of line with data from other plots during this event, and with other data from this plot at other times.

The "missing" outflow most likely resulted from a loose connection at the magnetic contact switch that counts tips of the tipping bucket. The loose connection was discovered and repaired during the following field visit. The problem may have been linked to the cold weather preceding this event, since outflow data from this site appears reasonable at all other times.

That outflow from the plantation lysimeter at the 460-m elevation of Canyon Creek was 16% less than that from the forest during this event appeared suspect at first glance. At most plots during many events, plantation outflows were intermediate between forest and open site outflows. However, at this location, lower-than-expected plantation outflows were common throughout the study. A number of conditions specific to this plot may account for this.

This plantation is an extremely dense, unthinned stand of western hemlock, consisting of 22-year old planted trees interspersed with numerous smaller (20-100 mm in diameter) "volunteer" hemlocks (Table 2). This has created a complete canopy cover and very high stem densities. Because the trees are very young and spindly, however, they cannot support much snow in the canopy. This results in large differences in snow accumulation throughout the stand.

One of the large piles of snow that accumulates beneath the convergence of several canopy margins, lies directly on the snow lysimeter in this stand. This pile offers more liquid-water-holding capacity than the shallower packs generally found in other forest and plantation stands. Incident rainfall or drip water can be absorbed and held in this pack when it would be routed more quickly through a shallower pack. During rain-on-snow, this could slightly reduce the amount of water reaching the drain, and delay outflow by offering a longer route through the pack.

Moreover, melt rates within this plantation may have been greatly reduced because the density of the stand limits wind penetration and air movement within the stand. The lack of wind in the stand not only reduces the potential for exchange of sensible and latent heats, but may also affect temperature change within the stand. As large, warm air masses move into the Canyon Creek drainage, increases in air temperature are felt immediately at the open plots. However, air temperatures within this plantation may take longer to respond than in the open site or the more open forest site as noted in Oregon by Berris and Harr (1987).

Event 2: January 2-3, 1989

Prior to this event, the snowpack had been primed by the rain-on-snow event of December 29-30. However, air temperatures during the intervening days remained fairly low, so ice problems occurring at the upper elevation plots during the last event continued to prevent collection of outflow data at most of those plots. Analysis of this event was thus limited to the 460-m elevation plots at Canyon Creek and the 460- and 610-m elevation Finney Creek plots.

From 0100 hr January 1 through 0700 hr January 2, a net accumulation of 12 mm SWE was added to the snowpack at the Finney Creek 460-m open site. Hourly average air temperatures during this time fluctuated between -1° and +1° C. While most of the heavy, wet snow was accumulating at the open site, much of that falling on the forest and plantation was intercepted by the canopies, where it melted quickly and produced outflow from each of these lysimeters.

As air temperature began climbing through the morning and afternoon of January 2, precipitation became light and sporadic. Maximum temperatures for the day were reached by 1400 hr, peaking at 4.9° C. Incoming shortwave radiation reached only 36 W/m^2 while hourly average wind speeds in the open remained below 1.0 m/s throughout the day. These conditions, without significant rainfall, were capable of producing only small amounts of snowmelt outflow from the three lysimeters. During the late afternoon and evening, hourly average air temperatures again dropped to near freezing levels, and precipitation increased.

Mixed rain and snow during the late hours of January 2 became rainfall by 0200 hr January 3, and continued into the afternoon. By 1300 hr January 3, hourly average air temperature had climbed to 8.8° C, and hourly average wind speeds had increased to 4.4 m/s (Figure 9). Lysimeter outflows showed two peaks during this period, the first and smaller peak at 0900 hr and the larger peak at 1500 hr.

Although precipitation had decreased by 1500 hr, the size of this second peak from the open lysimeter was more than double that of the first. Increased outflows during this second peak were largely the result of higher air temperatures and wind speeds occurring at that time. Differences in outflow between the open and forest lysimeters were maximized during the time between these peaks when wind speed and air temperatures were at a maximum. During the 12-hr period of highest air temperature, outflow from the lysimeter in the open exceeded that from the

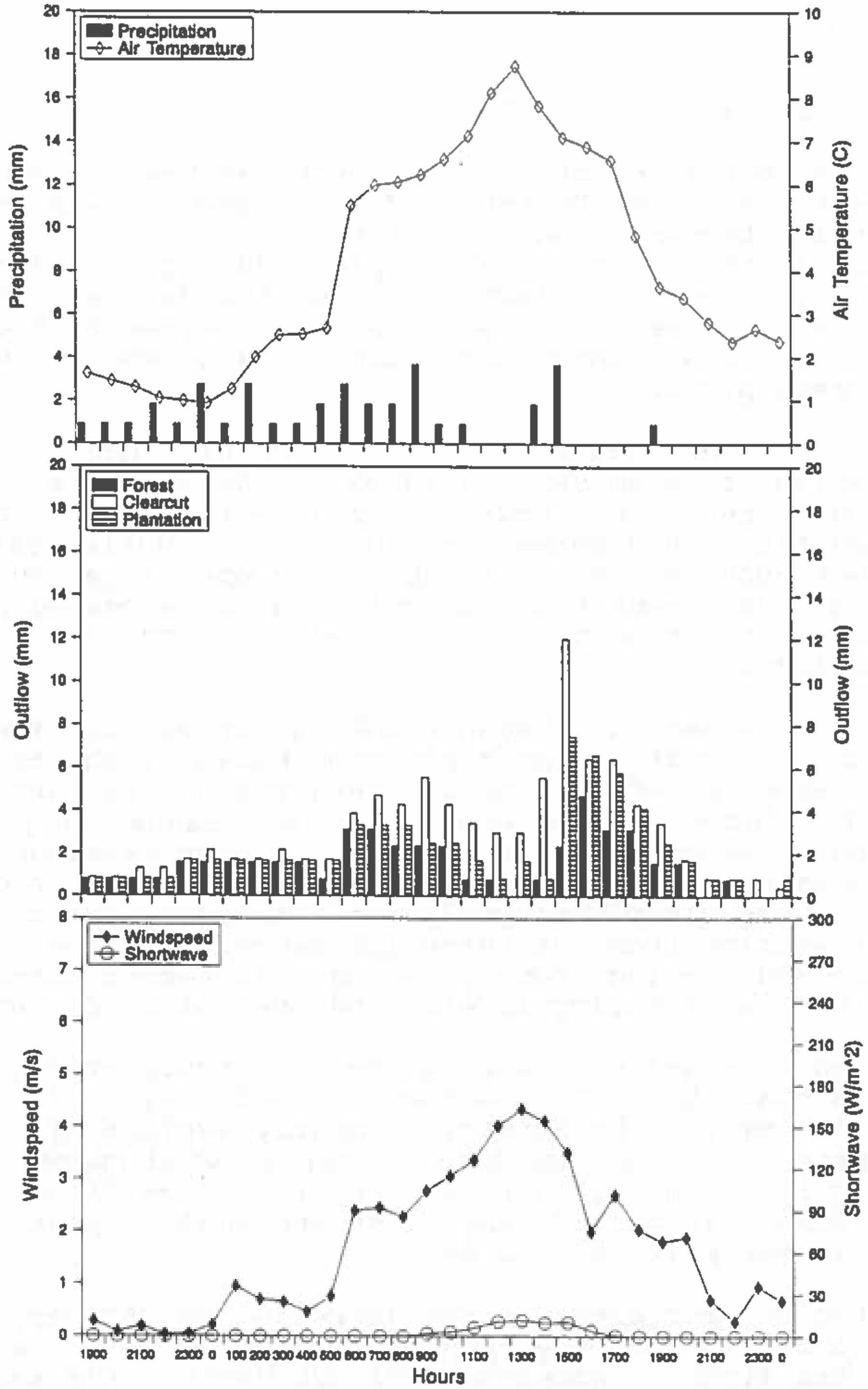

Figure 9. Rain-on-snow event, Finney Creek 460-m elevation, 1900 January 2 - 2400 January 3, 1989:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

lysimeter in the forest by 141%. Hourly average wind speeds in excess of 4.0 m/s in the open during this time undoubtedly enhanced the transfer of latent and sensible heats from the warm air to the snow.

Over a 27-hr period beginning at 1900 hr January 2, outflow from the forest lysimeter totaled 46 mm. During this time, outflow totaled 90 mm at the open site, while that from the plantation lysimeter totaled 64 mm (Table 4).

Table 4. Comparison of lysimeter outflows during January 2-4, 1989 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			32-hr totals
Forest	69		
Open	114	+65	
Plantation	82	+19	
460-m Finney Creek			27-hr totals
Forest	46		
Open	90	+96	
Plantation	64	+39	
610-m Finney Creek			28-hr totals
Forest	85		
Open	106	+25	
Plantation	100	+18	
610-m Canyon Creek			Outflow data missing
760-m Canyon Creek			Outflow data missing
760-m Finney Creek			Outflow data missing

During the same general time period but over a 28-hr period for analysis, outflow from the forest site at the 610-m elevation Finney Creek location was 85 mm. Outflows from the associated open and plantation plots were 106 mm and 100 mm, respectively. At the 460-m elevation plots at Canyon Creek, outflow from the forest was 69 mm over a 32-hr period. The open site generated 114 mm during this time while the plantation lysimeter registered 82 mm.

The relatively smaller differences in outflow among the Finney Creek 610-m elevation plots can likely be attributed to different weather conditions at that location. Hourly average wind speed maximums of over 4.0 m/s at the 460-m elevation plots were double the hourly average wind speeds measured at the 610-m elevation. Similarly, hourly average air temperatures were higher at the 460-m plots, peaking at over 8.0° C, while remaining below 6.0° C throughout the event at the 610-m site. In addition, precipitation at the 610-m location was 90 mm over the 32-hr period of analysis, more than twice that at the lower elevation plots.

As the role of rainfall in causing snowmelt increases relative to other heat sources, snowmelt differences between forested and non-forested sites would be expected to decline. Conversely, as the turbulent exchange of sensible and latent heats becomes the dominant heat exchange mechanism, differences in rate of melt would be expected to increase.

In this case, rainfall accounted for 82% of the lysimeter outflow at the 610-m elevation open site, but only 35% of the corresponding outflows at the two 460-m elevations. In addition, higher temperatures and wind speeds at the lower elevation plots suggest a potential for greater heat transfers by turbulent exchange at these plots. If more of the snowmelt occurring at the lower elevation plots is in response to turbulent transfer processes as opposed to heat delivered from the rainfall itself, then greater outflow differences would be expected from these plots.

The Canyon Creek outflow hydrograph before and during this event illustrates a phenomenon seen often in the data (Figure 10). As was the case at the 460-m elevation at Finney Creek, precipitation the evening of January 1 and through the early morning hours of January 2 was snowfall while air temperature remained slightly above freezing. As snow melted in the canopy of the forest, the forest exhibited higher outflows than either the open or plantation plots where snow accumulated on the ground and melted more slowly. Some plots, such as the 460-m forest plot at Canyon Creek, show the phenomenon of canopy interception-snowmelt consistently and distinctly, whereas at other locations it is less evident. This is presumed to be largely a result of the specific location of the lysimeters with respect to individual tree canopies and the drip patterns from them. It is also a function of the stand's interception and storage capacity in the canopy, as well as the conditions prevailing when the snow fell. Windy, cold weather would tend to favor less snow being retained in the canopy, but under other conditions, storage in the canopy could be on the order of 15-20 mm SWE.

Partly because of these frequent inputs of water, a snowpack under a forest canopy may reach a ripe condition, with its

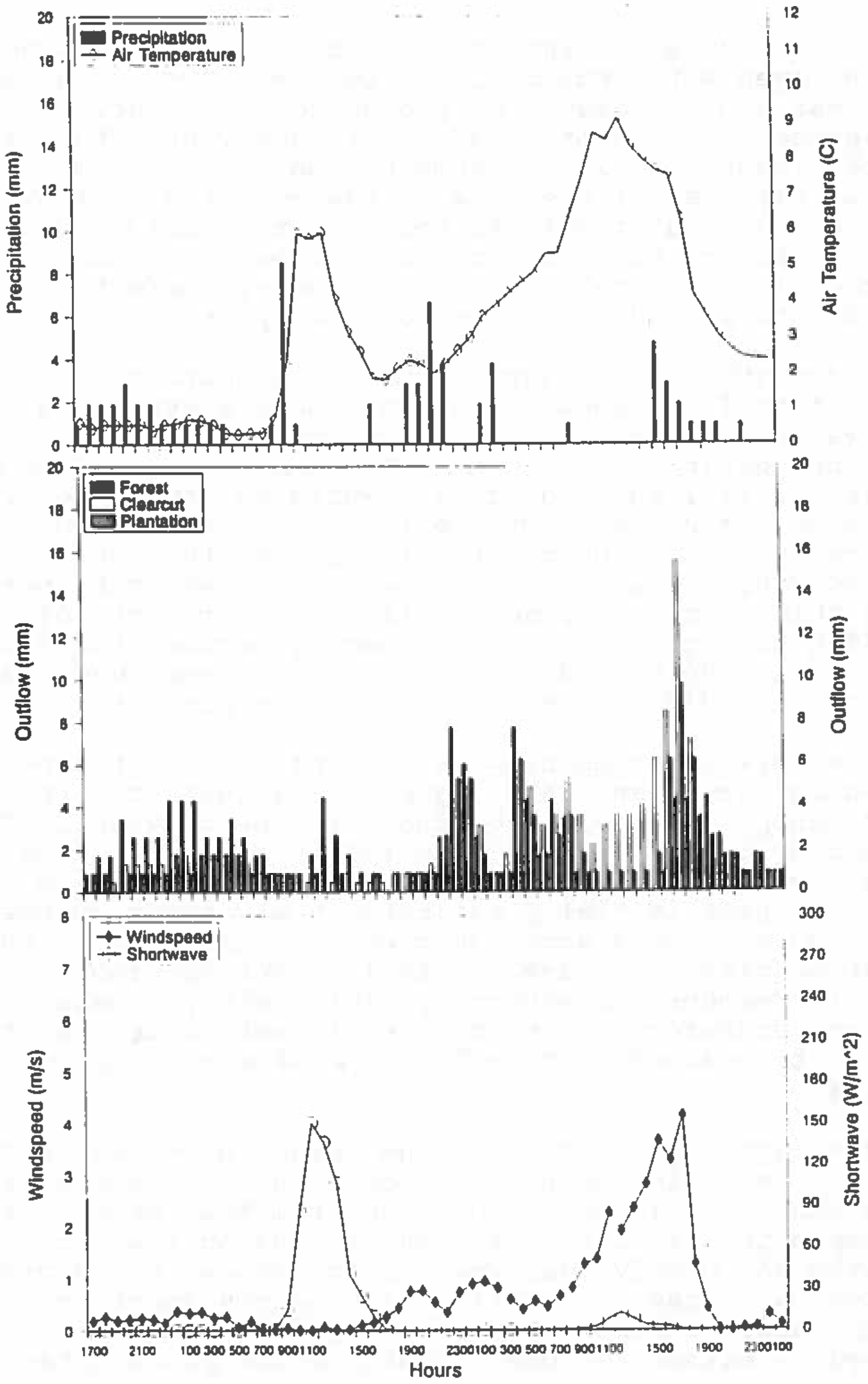

Figure 10. Rain-on-snow event, Canyon Creek 460-m elevation, 1900 January 1 - 0100 January 4, 1989:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

liquid-water-holding capacity filled, before a snowpack in an adjacent open site (Smith, 1974, Berris, 1984). These packs in the forest can be capable of producing water outflow more quickly in response to incident rainfall or canopy drip than snowpacks in the open (Haupt, 1972). A combination of canopy melt and the advanced ripeness of the snow in the forest may allow forest plots to route water offsite well before outflow occurs from adjacent open plots. In fact, data from this study suggest that forested plots can melt and route snowmelt offsite even as snow continues to accumulate in nearby open plots.

The weather on January 2 further conditioned the snowpacks. The first half of January 2 at the 460-m elevation at Canyon Creek was partly sunny as evidenced by incident shortwave radiation peaking at 150 W/m^2. This radiation melted some snow that helped fill the liquid-water-holding capacities of the respective snowpacks. (Precipitation shown in Figure 10 is only an approximation of what actually fell at the 460-m elevation plots at Canyon Creek. The raingage here was not operational during this event, so precipitation data from the 610-m open plot was added to Figure 10. The disparity between the 9-mm pulse of rainfall at 1000 hr and outflows at this time suggests that this pulse of rain did not occur at the 460-m plots.)

The relative responses of the three plots to the rainfall late on January 2 and early January 3 illustrates the role of the forest canopy in helping to condition the snowpack. The canopy melt and drip on January 1 resulted in a wetter, riper snowpack at the forest plot so that when rainfall occurred on January 3, the forest plot initially exhibited a greater response than did either the open or plantation plots. Outflows from the open and plantation plots increased as their water-holding capacities were filled in response to snowmelt. This melt was caused by turbulent transfer of sensible and latent heats that resulted from air temperatures of 4-6° C as wind speeds increased slightly to 1 m/s.

The remainder of snow at the forest plot had melted by 1000 January 3 as indicated by the lack of outflow during a 5-hr period when no rain fell. Outflow from the forest resumed when rain began to fall again at 1600 hr, and outflow from the forest lysimeter was nearly identical to the amount of rainfall during this period. That all outflows are nearly identical during the last few hours depicted in Figure 10 indicates that no snow remained at either the open or plantation plots after 2100 hr.

The effect of high air temperatures and wind speeds on snowmelt is most evident between 0900 hr and 1700 hr January 3. During this period, average hourly air temperature climbed steadily to a maximum of 9° C as wind speed increased to a maximum of more than 4 m/s. The highest rates of outflow from both the open and plantation plots coincided with the highest mean hourly wind speeds when mean hourly air temperatures were above 8° C.

During the January 2-4 event, outflows from the plantation lysimeters at the three locations ranged from 18-39% greater than the respective outflows from the associated forest plots. In every case, outflow totals from the plantation plots were intermediate between the forest and open site outflows. That is, the plantation plots generated more outflow than the associated forest site, but less outflow than the open plots.

Although outflow from the 460-m plantation site at Canyon Creek was 16% less than from the forest during the December 29-30 event, outflow from the plantation plot was 19% greater in the January 2-3, 1989 event. This shift in outflow differential between the forest and plantation plots is likely a result of different antecedent conditions. The December 29-30 event followed several days when average daily temperatures were below freezing, and daily minimums at times dipped below -7.0° C. During the subsequent rain-on-snow event, hourly average air temperatures reached 7.0° C, and 63 mm of rainfall were recorded. Although air temperatures dropped to freezing during the next three days, the snowpack had been conditioned to produce outflow by the beginning of the January 2-3 event. It is probable that much of the rainfall and melt that occurred at the plantation during the earlier event went to satisfying the snowpack's capacity for holding liquid water.

Events 3 and 4: January 15-18, 1989

A series of outflow peaks occurred over a four-day period of nearly continuous rainfall. For analysis and ease of discussion, this period is broken into two events. The first, January 15-17, occurred over 48 hr, and the second event, January 17-18 was analyzed over 24 hr. An 8-hr period separated the two events, during which precipitation and lysimeter outflows continued, but at very low rates. As in the previous two events, outflow drains in the upper elevation lysimeters were frozen, so data are available only from the 460-m elevation plots.

Event 3: January 15-17

Following the January 2-4 event, hourly average air temperatures at the 460-m elevation at Canyon Creek dropped to below freezing for several days, and precipitation ceased. Snow fell January 9-11 while temperatures fluctuated around freezing. By 0400 hr January 12, over 50 mm of SWE had accumulated in the open at this elevation.

Because the precipitation gage at the 460-m elevation was malfunctioning, precipitation has been estimated using data from the 610-m elevation gage. Based on comparison of gage data between the two sites during other periods of precipitation, this gage appeared to underestimate precipitation rates recorded at the 460-m elevations by as much as 50%. A better correlation was generally found between gages at the 460-m and 760-m elevations. However, during this event, the gage at the 760-m elevation appeared to be malfunctioning also, probably because of the cold temperatures previous to the event.

Large differences in measured precipitation between the 460-m and 610-m open plots may be due in large part to the higher wind speeds occurring at the 610-m site and the associated higher gage catch deficiency there. In fact, during field visits, observed snow accumulation differed only slightly between the two sites. Nevertheless, the gage values and accumulation estimates given here are used only as rough estimates.

Light rain and snow continued falling through January 12 and into the early hours of January 13, when air temperatures dropped and precipitation subsided. Precipitation began again at 0300 hr January 15, and continued throughout the day as wet snow and rain. Hourly average air temperatures through the day fluctuated between 0.0° and 1.5° C, and outflow occurred from all three lysimeters (Figure 11).

Precipitation averaged over 3 mm/hr through the afternoon and night of January 15. By 0900 hr January 16, precipitation intensity had diminished, but air temperature and wind speeds had increased. Between 1500 hr and 2000 hr, hourly average air temperature peaked at 4.9° C and hourly average wind speeds rose to 5.3 m/s. Outflows from the open lysimeter peaked at more than twice the outflow rate from the forest lysimeter during this time. Following this outflow peak, outflows from all lysimeters quickly decreased. Continued precipitation through the night of January 16 and the morning of January 17 was accompanied by decreasing air temperatures and low wind speeds.

Over this 48-hr period, outflow totaled 204 mm at the forest plot while outflows at the open and plantation plots totaled 235 and 176 mm, respectively (Table 5). During roughly the same time period, rain-on-snow also occurred at the 460-m Finney Creek plots. Outflow from the forest lysimeter during the first 46-hr period at this location totaled 113 mm. Outflow from the open site totaled 159 mm, while plantation outflow was 151 mm.

Examining the entire 48-hr event reveals a sequence of three fairly distinct outflow peaks. Analysis of this range of outflow peaks and the changes in climatic variables during this time illustrates how rates of melt at different plots respond to changes in the sources of heat available for melt. Weather data and measured outflows from the snow lysimeters support the following scenario.

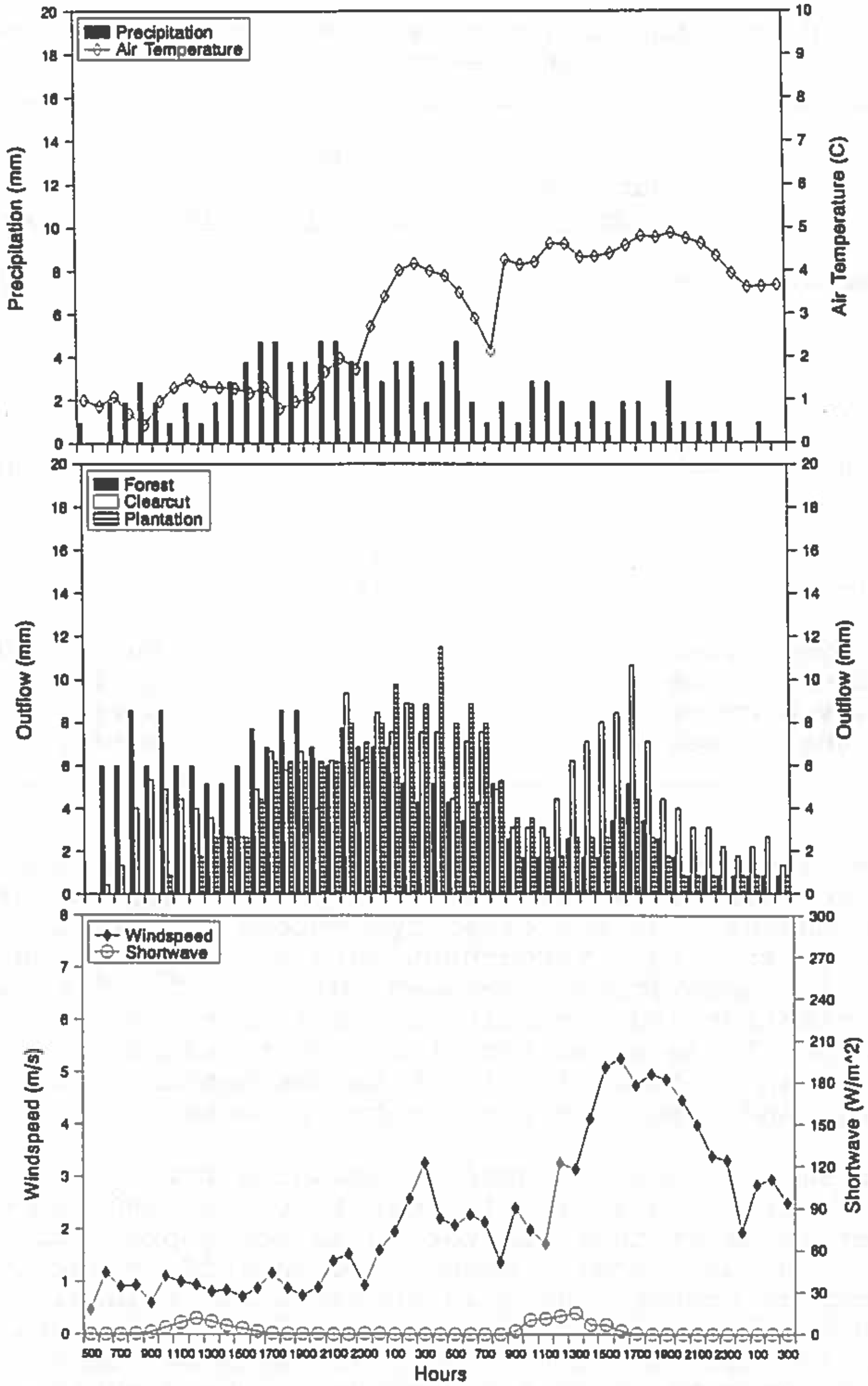

Figure 11. Rain-on-snow event, Canyon Creek 460-m elevation, 0500 January 15 - 0300 January 17, 1989:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

Table 5. Comparison of lysimeter outflows during January 15-16, 1989 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			48-hr totals
Forest	204		
Open	235	+15	
Plantation	176	-14	
460-m Finney Creek			46-hr totals
Forest	113		
Open	159	+41	
Plantation	151	+34	
610-m Canyon Creek			Outflow data missing
610-m Finney Creek			Outflow data missing
760-m Canyon Creek			Outflow data missing
760-m Finney Creek			Outflow data missing

The first of the three peaks occurred during the period from 0500 hr to 1300 hr January 15, when forest outflow surpassed outflows measured at the other lysimeters (Figure 11). Light rain or wet snow fell throughout this 8-hr period, as hourly average air temperatures averaged only 1.0° C. The combination of precipitation and snowmelt in the forest canopy caused outflows totalling 52 mm from the forest lysimeter. During the same time, an outflow of only 28 mm was measured from the open lysimeter, and 5 mm from the plantation site.

The small amount of outflow measured from the plantation lysimeter during this time is most likely a function of characteristics of this plantation as noted previously. The large pile of snow that commonly accumulated on the lysimeter at this location probably delayed snowmelt and rainfall from reaching the lysimeter outflow. In addition, because tree branches in this plot retain very little snow, there was probably only minor amounts of melt occurring in the plantation canopy when the canopy melt was occurring at the forest site.

The second period is from 1400 hr January 15 to 1000 hr January 16, when rainfall increased. Hourly average air temperature remained relatively low over the first half of this 20-hr period, but climbed to 4.2° C during the following 10-hr period. Likewise, wind speeds were relatively low during the early part of this period, but increased during the latter part, peaking at over 3 m/s. Precipitation averaged over 3 mm/hr during the entire 20 hr, and outflow, driven largely by the rainfall, occurred at all lysimeters. Total outflows from the three lysimeters during this time were nearly equal, with the forest, open and plantation plots recording 120, 126, and 140 mm respectively.

The third peak in the sequence occurred as rainfall decreased and wind speeds and air temperatures increased. From 1100 hr January 16 to 0400 hr January 17, hourly average air temperatures averaged 4.3° C, and hourly average wind speeds reached 5.3 m/s. Precipitation during this time averaged just over 1 mm/hr. Differences in outflow between the forest and open lysimeters were maximized during this time, with outflow from the open site exceeding outflow from the forest by 156%. Outflow from the plantation during this time was actually 5% less than the forest outflow. It is unclear how much of the outflow difference between the forest and open plots during this time can be attributed to higher snowmelt rates in the open, and how much is due to more snow being available for melt in the open.

By breaking the event into the three time periods for analysis, it appears that during each peak, a different factor was dominant in causing outflows. The first peak is characterized by low-temperature canopy melt. Throughout this study, outflow from forest plots commonly exceeded outflow from open plots during these periods, but the duration was relatively short, and the total differences are limited at least by the amount of snow in the canopy. Melt during the second period is driven primarily by rainfall, and outflow totals from the three lysimeters are nearly equal. Since heat exchange is dominated by conduction of heat from rain water, melt rates are similar in forested and non-forested plots. It was during the third period when large outflow differences occurred between the forested and non-forested plots. During this time, rate of precipitation was relatively low, and turbulent exchange mechanisms dominated the heat transfer process. Higher wind speeds in the open combined with the moderately high air temperatures to cause increased snowmelt there relative to the forested plots.

Event 4: January 17-18, 1989

Following the rain-on-snow event that occurred on January 15-17, precipitation continued at the 460-m elevation of Canyon Creek (Figure 12). By 1800 hr January 17, air temperature began climbing and wind speeds increased. Precipitation increased to a rate of 5.7 mm/hr at 0100 hr January 18. Outflow from all three lysimeters peaked at 0300 hr as hourly average air temperature and wind speeds reached maximums of 4.9° C, and 2.7 m/s respectively. Lysimeter outflows then quickly dropped following the rate of precipitation, wind speed and air temperature.

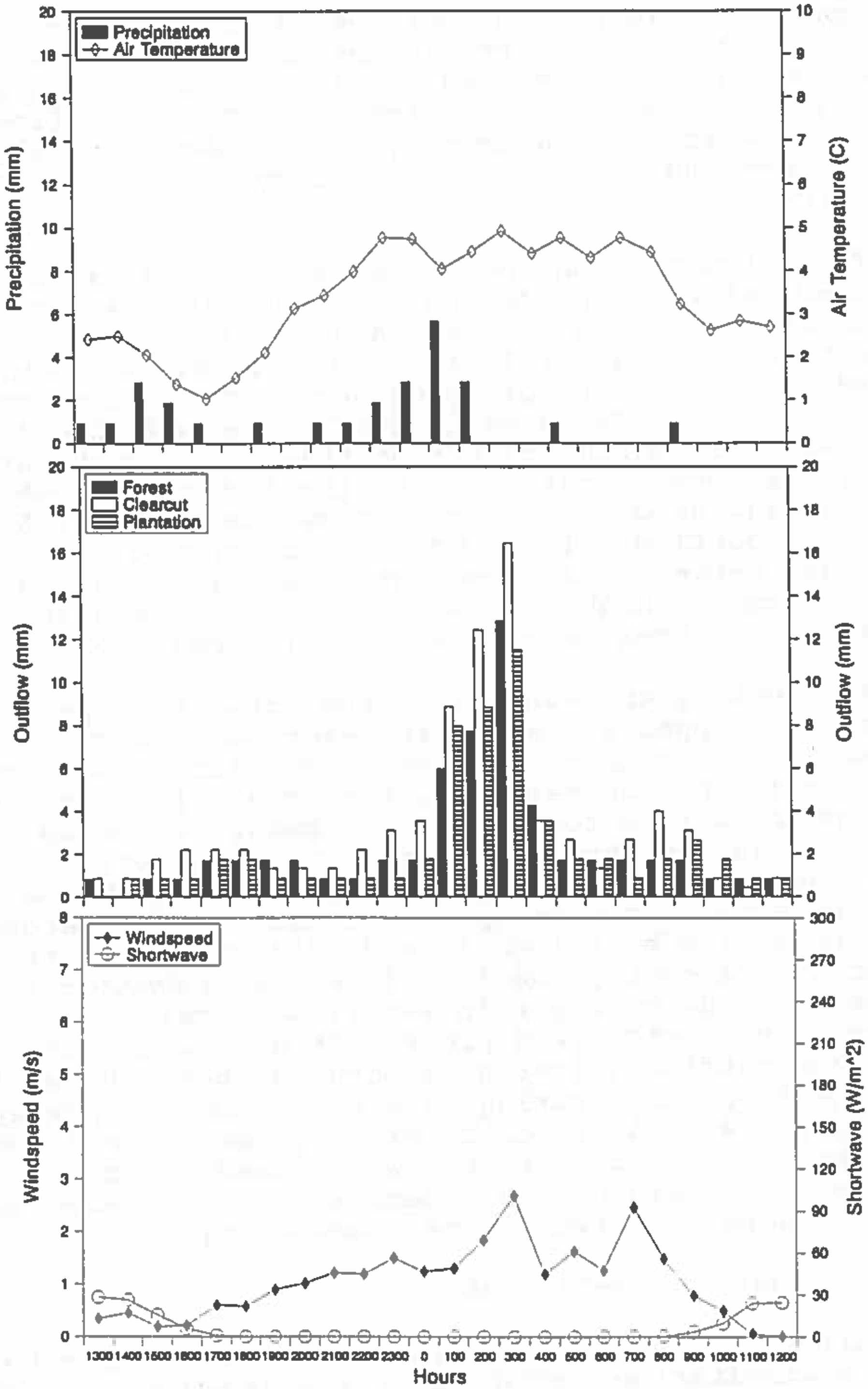

Figure 12. Rain-on-snow event, Canyon Creek 460-m elevation, 1300 January 17 - 1200 January 18, 1989:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

During this 24-hr period, forest outflow totaled 57 mm, while the open site and plantation outflows were 81 and 57 mm, respectively (Table 6). At the 460-m elevation of Finney Creek, 38 mm outflow was recorded from the forest lysimeter over 24 hr, while the open site and plantation plots recorded 46 and 45 mm, respectively.

During this event, outflow from the open lysimeter at the 460-m elevation of Canyon Creek was 42% greater than outflow at the corresponding forest lysimeter. In the previous event (January 15-17), the open site showed only 15% more outflow than was measured from the forest plot. The larger difference between forest and open outflows during this event as compared to the January 15-17 event is the lack of canopy melt in this event.

Table 6. Comparison of lysimeter outflows during January 17-18, 1989 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			24-hr totals
Forest	57		
Open	81	+42	
Plantation	57	0	
460-m Finney Creek 24-hr totals			
Forest	38		
Open	46	+21	
Plantation	45	+18	
610-m Canyon Creek			Outflow data missing
610-m Finney Creek			Outflow data missing
760-m Canyon Creek			Outflow data missing
760-m Finney Creek			Outflow data missing

Early canopy melt observed on January 15 accounted for over 25% of the total outflow from the forest lysimeter in that event, while outflows at the open site during the same period account for only 12% of the total open site outflow. Snowmelt occurring in the forest during the January 17-18 event was from the snowpack accumulated on the forest floor only; no additional snow had accumulated in the canopy.

As the outflow hydrographs indicate, there are considerable differences in the volume of water released during the events and in the rate at which the plots responded to changing weather conditions. The January 15-17 event was a long series of peaks, wherein the different plots responded differently to changes in precipitation, air temperature, and wind speed. When the January 17-18 event began, snowpacks were primed and ready to produce outflow. Outflows from all lysimeters responded quickly during this event, when moderate temperatures and wind speeds were accompanied by a 4-hr pulse of rain. This illustrates the increased efficiency of the snowpack in generating outflow once it has been primed by several days of rainfall.

Event 5: January 30-31, 1989

The rain-on-snow events of January 15-18 were followed by several days when clear weather alternated with cloudy days. Recorded hourly average air temperatures during some clear days exceeded 10° C, while nighttime temperatures dropped below -7.0° C at the Canyon Creek 460-m elevation open site. Light, sporadic precipitation during this period fell alternately as rain and snow. Low temperatures continued to take a toll on lysimeter outflows and data collection, and in this event only the Canyon Creek 460-m elevation plots were operational.

Outflow began to trickle from the open lysimeter at the Canyon Creek 460-m elevation in the early hours of January 29, increasing slightly through the afternoon as hourly average air temperature climbed to over 6.0° C and light precipitation began falling. Hourly average wind speeds were 1 m/s during this time. Air temperature leveled off in the afternoon and then resumed climbing through the evening and early morning hours of January 30. Wind speeds increased during this time while precipitation at the 610-m open plot was very light. Outflow trickled from the forest and plantation lysimeters while continuing at slightly over 2 mm/hr from the open site (Figure 13).

By 1600 hr, hourly average wind speeds had more than doubled, averaging over 4.0 m/s, and precipitation increased. The combination of rainfall and increased latent and sensible heat transfers (as indexed by increased air temperatures and wind speed) caused lysimeter outflows to increase rapidly. Peaking at 1700 hr, outflow from the three lysimeters then dropped sharply as air temperature and wind speeds fell, and precipitation diminished. Following this event, hourly average air temperature continued dropping to as low as -17.0° C on February 2 and 3 as the Arctic air mass stagnated over western Washington.

From 1400 hr January 30, when precipitation began, through 2000 hr January 30, when snow began to fall, 31 mm outflow were recorded from the forest lysimeter. During the same period 53 mm were recorded from the open site, and 43 mm were recorded from

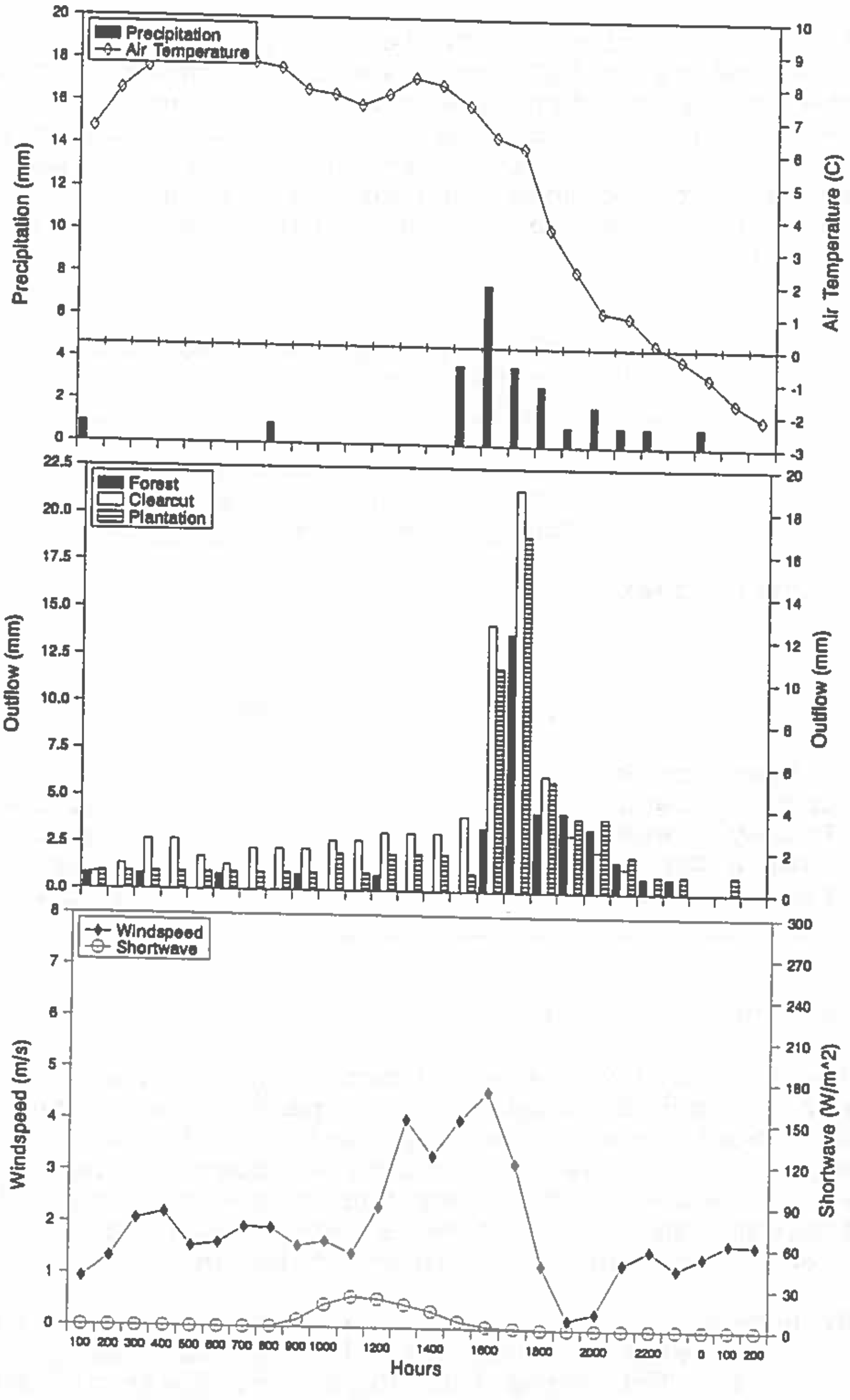

Figure 13. Rain-on-snow event, Canyon Cr 460-m elevation
0100 January 30 - 0200 January 31, 1989:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

the plantation lysimeter (Table 7). Summing outflows for the 24-hr period ending at 2000 hrs January 30 shows 138% more water from the open plot than from the forest, but no more water from the plantation than from the forest. The larger difference in outflow from the open plot over the longer time period reflects greater melt at the open site during a 14-hr period of high temperatures and moderate winds prior to the advent of rainfall (Figure 13).

Table 7. Comparison of lysimeter outflows during January 29-30, 1989 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			7-hr totals
Forest	31		
Open	53	+71	
Plantation	43	+39	
460-m Finney Creek			Outflow data missing
610-m Canyon Creek			Outflow data missing
610-m Finney Creek			Outflow data missing
760-m Canyon Creek			Outflow data missing
760-m Finney Creek			Outflow data missing

Event 6: December 2-3, 1989

The relatively heavy and prolonged rain events occurring December 2-4 contributed to large peak flows in the streams of northwest Washington. However, prior to the event, little snow had fallen in the lower Cascades, so most of the rain-on-snow occurred at elevations higher than those monitored in this study. Nevertheless, shallow snowpacks were present at the 760-m elevation plots when the rain event began.

By November 27, 57 mm SWE had accumulated at the Finney Creek 760-m elevation open site during four days of intermittent snowfall. The following four days were clear and sunny with mid-day hourly average air temperatures reaching as high as 14° C and nighttime lows dropping at times to freezing. During the warm afternoons, outflows were observed from the forest and plantation lysimeters, and to a lesser extent from the open lysimeter.

Air temperatures remained relatively high throughout the night of December 1 and the morning of December 2. By 1100 hr

December 2, recorded hourly average air temperature in the open reached 10.5° C. Little sunlight penetrated the clouds on this day as evidenced by the 49 W/m^2 of incident shortwave radiation measured by the pyranometer. Snowmelt increased rapidly from all lysimeters in response to the beginning of rainfall at 1400 hr (Figure 14).

Precipitation and outflow from the three lysimeters peaked at 2200 hr as hourly average air temperature reached 8.2° C. Hourly average wind speeds increased to 2.6 m/s by 0400 hr December 3, generating continued outflows from the open and plantation lysimeters as a result of sensible and latent heat inputs. The lack of outflow from the forest site after 0100 hr is most likely an indication that no snow remained in the forest lysimeter. The heavy rains that followed melted what little snow remained in the open and plantation lysimeters, but without snow present at the forest plot, no comparisons could be made.

Over a 24-hr period beginning at 1000 hr December 2, 53 mm of outflow were measured from the forest lysimeter, while the open and plantation outflows totaled 84 and 79 mm respectively (Table 8). During the same time period, total outflow from the Canyon Creek 760-m forest lysimeter was 26 mm, while the open and plantation outflows were 62 and 26 mm, respectively.

Table 8. Comparison of lysimeter outflows during December 2-3, 1989 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
760-m Canyon Creek			24-hr totals
Forest	26		
Open	62	+138	
Plantation	26	0	See discussion on page 57.
760-m Finney Creek			24-hr totals
Forest	53		
Open	84	+58	
Plantation	79	+49	
460-m Canyon Creek			No snow on plots
460-m Finney Creek			No snow on plots
610-m Canyon Creek			No snow on plots
610-m Finney Creek			No snow on plots

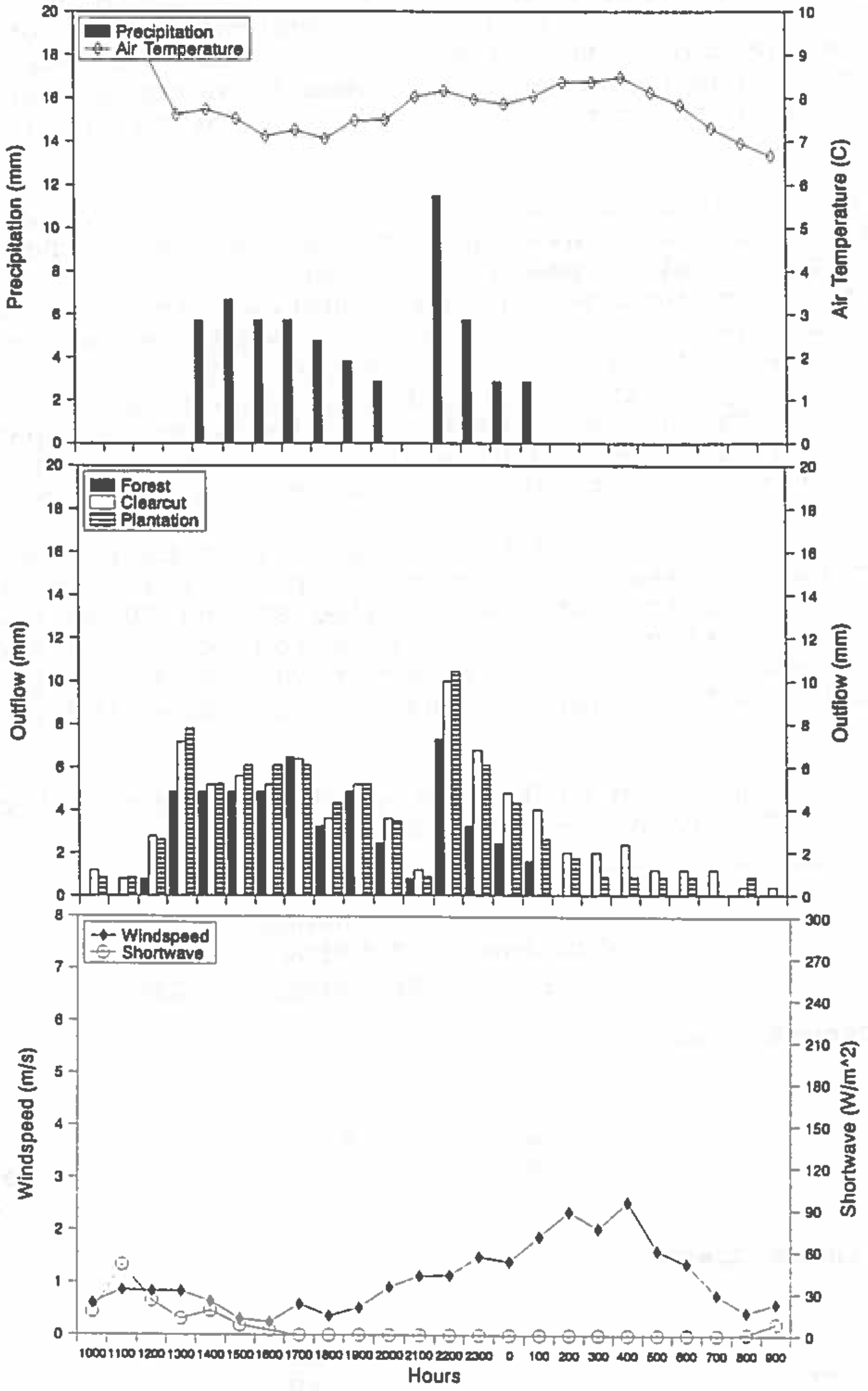

Figure 14. Rain-on-snow event, Finney Cr 760-m elevation.
1000 December 2 - 0900 December 3, 1989
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

This event was characterized by high air temperatures and low wind speeds. Under these conditions, snowmelt rates in the forest are not expected to be greatly different from those in the open. However, outflow totals in this event are quite different between the forested and non-forested plots. This is true especially for the forest and open plots at the 760-m elevation of Canyon Creek. The reason for the plantation at this location showing such low outflows was most likely a problem with the magnetic contact switch on the tipping bucket, causing some bucket tips to go unrecorded. This problem was discovered during a subsequent field visit to the site, and the switch was replaced. Data for this event from this elevation was eliminated from further analyses.

The large differences in outflow between the forest and open plots at Canyon Creek and between the forest and plantation plots when compared with the open site at Finney Creek were probably due to differences in snow availability instead of differences in heat available for snowmelt. This is supported by a comparison of outflows during the event with outflows that occurred during the period of rain following the event, when most or all of the snow had already been melted from the lysimeters.

Table 9 compares outflows from the lysimeters with precipitation at the 760-m elevation plots at both Finney and Canyon Creeks. The comparison uses two time periods; the first is the 24-hr rain-on-snow event just described, and the second is the 40-hr period following the event, when rainfall became more intense, but when most lysimeters were nearly devoid of snow.

Weather conditions were similar between the two periods of analysis. For example, at the 760-m Canyon Creek open site, hourly average air temperatures peaked at 10.4° C during both the first and second periods. Hourly average wind speeds peaked at 2.4 m/s during the first 24 hr, and 2.8 m/s during the subsequent 40-hr period, and shortwave radiation reached just 38 and 44 W/m^2 during the first and second time periods, respectively. Under such similar weather conditions, heat available for melting snow would be expected to be similar.

Table 9 shows total lysimeter outflows, and then presents these as percentages of the measured precipitation. The comparison of outflows with precipitation is made to give a general idea of how much of the outflow can be attributed to rainfall versus snowmelt. Of interest is the comparison between the "during rain-on-snow" and "following rain-on-snow" percentages.

At Finney Creek, outflows from the open and plantation lysimeters of 71% and 61% more than measured precipitation indicate snowmelt at those plots during the 24-hr rain-on-snow period. However, during the following 40-hr period, outflows from these lysimeters are within 10% of the measured precipitation, even though weather conditions were similar to those during rain-on-snow. This suggests that little or no snow remained in the lysimeters. Outflow from the forest lysimeter, compared to precipitation, changes much less dramatically between the two events, suggesting that less snow was available there for melt during the first 24-hr period of analysis.

Table 9. Lysimeter outflows compared to precipitation during and following the December 2-3, 1989 rain-on-snow event.

Plot	Outflow (mm)	Outflow (% of Precipitation)	Remarks
760-m Finney Creek			During rain-on-snow
Precipitation	49		
Forest	53	108	
Open	84	171	
Plantation	79	161	
760-m Finney Creek			Following rain-on-snow
Precipitation	187		
Forest	175	94	
Open	192	103	
Plantation	198	106	
760-m Canyon Creek			During rain-on-snow
Precipitation	29		
Forest	26	90	
Open	63	217	
Plantation	26	90	
760-m Canyon Creek			Following rain-on-snow
Precipitation	176		
Forest	162	92	
Open	189	107	
Plantation	174	99	

Using the same type of analysis for the Canyon Creek location supports a similar scenario there. However, comparing forest outflow as a percent of precipitation between the two periods reveals only a 1% difference. This would imply that no snow was available there even during the 24-hr period analyzed as rain-on-snow. This helps explain the large difference in outflows between the forest and open plots that were reported in Table 8.

Events 7 and 8: January 5-7, 1990

During the week of January 3-9, a series of rain storms were observed at all study locations. Across western Washington, these events caused moderate flooding and related damage as the rainfall combined with snowmelt from the middle and upper elevations of the Cascades. Most of the flooding occurred in streams to the north and south of those draining the study locations. Snowpacks at the 760-m elevation plots were again fairly shallow and melted quickly during the rain. Very little snowfall had occurred at plots at the 610- and 460-m elevations previous to the rainstorms, and most that had accumulated had melted by the time rainfall began.

Rainfall beginning on December 31 turned to snow on January 1 when temperatures dropped to -3.6° C at the open site at the Canyon Creek 760-m elevation. Sporadic accumulation of snow continued through January 3, leaving over 60 mm SWE at the open site. As hourly average air temperature rose to just above freezing early on January 4, outflows began from all three lysimeters (Figure 15). Air temperature continued to rise to a peak of 3.8° C at 1300 hr, but outflows from the lysimeters decreased as precipitation decreased. Outflows were intermittent through the evening of January 4 and the morning of January 5.

Air temperature rose through the morning of January 5, and light rainfall began at 0700 hr and continued throughout the day. As precipitation increased to 2 mm/hr, outflow increased from the three lysimeters. Hourly average wind speeds began increasing, and reached a peak of 3.8 m/s at 1800 hr. Outflow followed the general pattern of precipitation through the day, and peaked at 1700 hr. By 2000 hr, rainfall had stopped, and air temperature and wind speeds were decreasing. At this point, outflows from all three lysimeters dropped sharply.

Event 7: January 5, 1990

During a 24-hr period beginning at 0700 hr January 5, outflow from the forest lysimeter totaled 36 mm. Outflows from the open and plantation plots totaled 64 and 37 mm (Table 10). During the same time period, outflow from the Finney Creek 760-m forest site totaled 76 mm, while the open and plantation outflows were 94 and 90 mm. All snow appeared to have melted from the Finney Creek 760-m forest plot during this rain event.

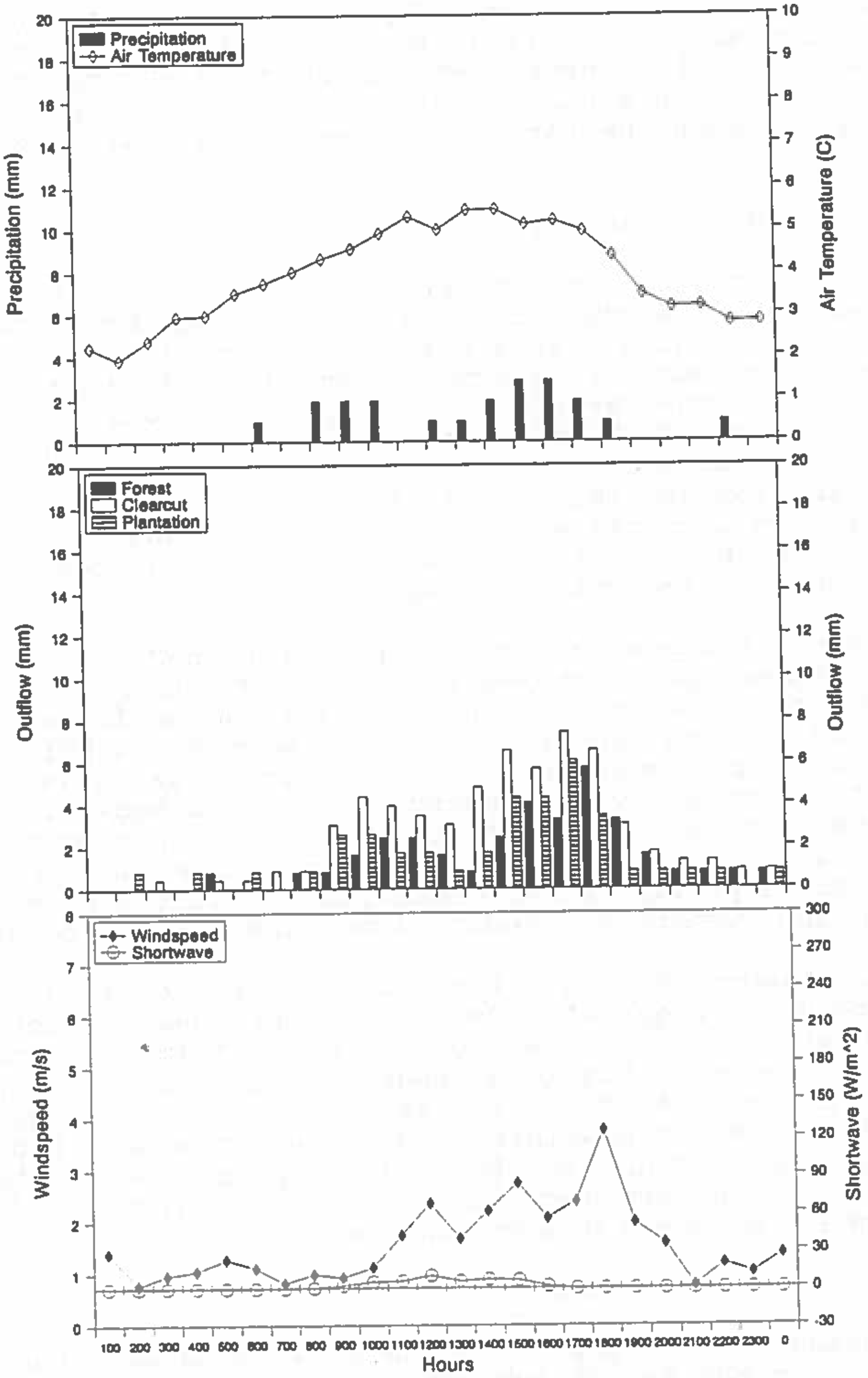

Figure 15. Rain-on-snow event, Canyon Cr 760-m elevation.
0100 January 5 - 2400 January 5, 1990
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

Event 8: January 6-7, 1990

Rain began again on the evening of January 6 and continued through the early morning of January 7 at the 760-m elevation at Canyon Creek. Hourly average air temperatures and wind speeds reached peak levels of 6.4° C and 3.8 m/s, respectively, between 2400 hr January 6 and 0100 hr January 7. Precipitation peaked at 0300 hr along with outflows from the open and plantation lysimeters.

Lysimeter outflows decreased during the next few hours as precipitation, temperature and wind speeds decreased (Figure 16). In the 24-hr period from 1600 hr January 6 through 1500 hr January 7, 55 mm of outflow was recorded from the forest lysimeter. Outflow from the open site totaled 87 mm during this time, while 49 mm were recorded from the plantation lysimeter (Table 11). All snow in the forest and plantation lysimeters appeared to have been melted during this event. This is evidenced by the close correlation between lysimeter outflows and outflow from the precipitation gage following the event.

Table 10. Comparison of lysimeter outflows during January 5, 1990 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outlfow	Remarks
760-m Canyon Creek			24-hr totals
Forest	36		
Open	64	+78	
Plantation	37	+3	
760-m Finney Creek			24-hr totals
Forest	76		
Open	94	+24	
Plantation	90	+18	
460-m Canyon Creek			No snow on plots
460-m Finney Creek			No snow on plots
610-m Canyon Creek			No snow on plots
610-m Finney Creek			No snow on plots

Although outflow corresponded closely to precipitation rate in both events, it was a combination of rainfall, melt from the rain, and melt by the turbulent transfer of latent and sensible

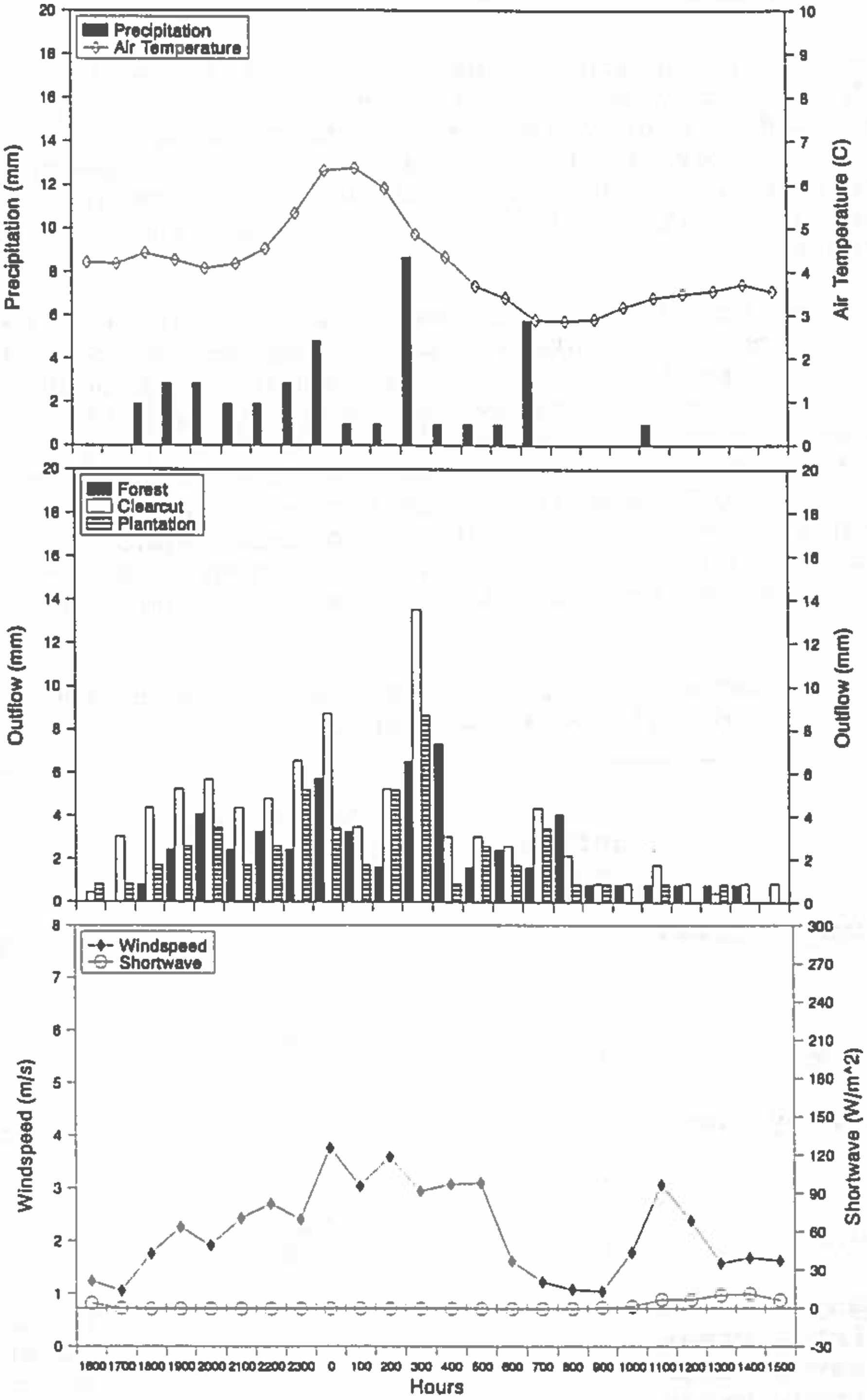

Figure 16. Rain-on-snow event, Canyon Creek 760-m elevation, 1600 January 6 - 1500 January 7, 1990:
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

heats that generated the outflow. In fact, precipitation during the events accounted for less than half the outflow at the open plots. Peak lysimeter outflows occurred when precipitation rate, air temperature, and wind speed were all high.

Table 11. Comparison of lysimeter outflows during January 6-7, 1990 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
760-m Canyon Creek			24-hr totals
Forest	55		
Open	87	+58	
Plantation	50	-9	
460-m Canyon Creek			No snow on plots
460-m Finney Creek			No snow on plots
610-m Canyon Creek			No snow on plots
610-m Finney Creek			No snow on plots
760-m Finney Creek			No snow on plots

Events 9 and 10: November 21-24, 1990

The November 21-24, 1990 rain-on-snow event, which caused severe and widespread flooding throughout western Washington, consisted of two periods of heavy rainfall separated by about 8 hr of lesser rainfall. Rainfall at both the Finney and Canyon Creek plots totaled 200-300 mm over a 50-hr period. These two periods of rainfall are treated as separate rain-on-snow events, although flood damage in western Washington was attributed to rainfall and snowmelt that occurred over the entire November 21-24 period.

Event 9: November 21-23, 1990

Snowfall began at both Finney Creek and Canyon Creek on November 19 as air temperature hovered around freezing. When the Finney Creek plots were visited around noon on November 20, snow accumulations totaled roughly 10 mm of SWE at the 460-m plot at Finney Creek and about 25 mm at the 760-m plot. At Canyon Creek, SWE was about 18 mm at the 460-m elevation and about 30 mm at the 760-m elevation. Light snowfall continued until noon November 21 when air temperature rose to slightly above freezing. By 1800 hr November 21, SWE had reached 75 mm and 25 mm at the 760-m and 460-m Finney Creek open plots, respectively, and 80 mm and 30 mm at the 760-and 460-m Canyon Creek open plots, respectively. These SWE values correspond roughly to snow depths of 0.6 m at the 760-m elevation and 0.2 m at the 460-m elevation.

The November 21-23, 1990 rain-on-snow event at both locations is illustrated by outflows and weather conditions at the Finney Creek 760-m plots (Figure 17). Melting of intercepted snow remaining in tree canopies is visible as outflow from the forest plot from 1700 hr to 2000 hr November 21. Air temperature fluctuated between 3 and 5.5° C during early morning hours on November 22 while rainfall rate was 2-6 mm/hr. During this period, when wind speed averaged 2 m/s, outflow from the open plot exceeded those from the forest and plantation plots. During daylight hours on November 22, when wind speed diminished, air temperature dropped to 2.5° C, and rainfall rate was 2-4 mm/hr, outflows from the three plots were nearly identical. For a 10-hr period ending at 0200 November 23, when hourly mean air temperatures remained fairly constant at 5.5-6.1° C, average windspeed generally remained above 2.5 m/s, and rainfall intensity increased to 6-11 mm/hr, outflows peaked at each plot. During this 10-hr period, outflow from the open plot exceeded outflows from both the forest and plantation plots. Finally, as rainfall decreased, outflows from all plots diminished.

Table 12 summarizes outflows during the November 21-23, 1990 rain-on-snow event. Highest relative increases in outflow from open plots were observed at the Finney Creek 460-m plot (+24%) the Canyon Creek 760-m elevation (+26%), and the Canyon Creek 610-m elevation (+11%). At all other elevations at both locations, outflows from open and plantation plots differed from outflows from corresponding forest plots by 10% or less.

That most outflows from open and reforested plots were of similar size to those of forest plots was not unexpected. Harr (1981) speculated that size of differences between open and forested areas should be least during major rainfall when rain heat surpasses wind-aided transfer of combined sensible and latent heats as the largest source of heat for snowmelt. Because both forest and open areas in close proximity to one another receive nearly identical amounts of rainfall, they would also have similar amounts of snowmelt caused by that rainfall. Furthermore, because rainfall usually contributes much more water to outflow than does snowmelt during rain-on-snow conditions, relative effects of any differences in rate of snowmelt during rainfall would be overshadowed by the heavy rainfall.

But the relatively small differences between outflows from forest and open plots also may result from the analysis itself. Without knowing exactly when snow had completely melted, we had to estimate the end point for the rain-on-snow event. Consequently, there may be a period of time included in the analysis when snowmelt was not contributing to lysimeter outflow.

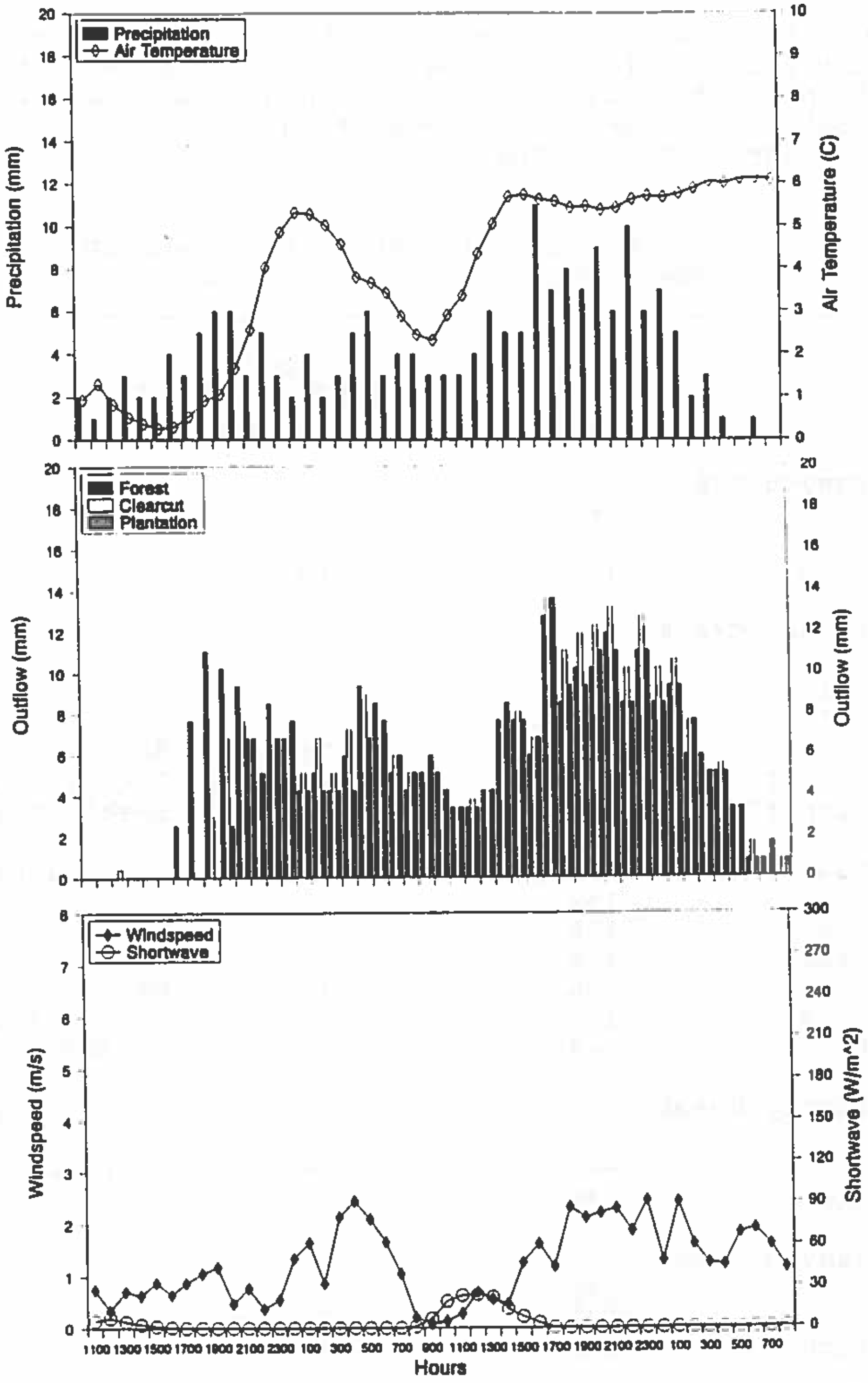

Figure 17. Rain-on-snow event, Canyon Creek 460-m elevation, 1300 November 21 - 1200 November 23, 1990
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

If rainfall is the sole source of outflow, there is no opportunity for differential melt rates to play a part in determining differential outflows. Thus, snow availability may play a role in the relative sizes of increased outflow from the open plot during this event.

Table 12. Comparison of lysimeter outflows during November 21-23, 1990 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			36-hr totals
Forest	167		
Open	182	+9	
Plantation	183	+10	
460-m Finney Creek			35-hr totals
Forest I	100		
Forest II	153		
Forest III	149		
Open	166	+24	Based on forest mean
Plantation I	---	--	Outflow data missing
Plantation II	130	-3	Based on forest mean
610-m Canyon Creek			32-hr totals
Forest I	152		
Forest II	138		
Forest III	156		
Open	166	+11	Based on forest mean
Plantation I	167	+5	Based on plantation and forest means
Plantation II	144		
610-m Finney Creek			33-hr totals
Forest	197		
Open	---	--	Outflow data missing
Plantation	178	-10	
760-m Canyon Creek			33-hr totals
Forest	138		
Open	174	+26	
Plantation	135	-2	
760-m Finney Creek			32-hr totals
Forest	220		
Open	224	+2	
Plantation	225	+2	

Event 10: November 23-24, 1990

Judging by the trickles of outflow from lysimeters that persisted at the end of the November 21-23, 1991 rain-on-snow event, snow remained only at the 760-m elevations at both Canyon Creek and Finney Creek, although it's impossible to tell how much remained at each plot. Following an 8-hr period of relatively light rain, rainfall intensity increased drastically around 1400 hr on November 23, particularly at Finney Creek (Figure 18). During this 24-hr storm, rainfall totaled 150 mm at Finney Creek and 175 mm at Canyon Creek. Air temperature peaked above 7.5° C during the heaviest rainfall at both sites and again in the early evening of November 24, just prior to falling rapidly throughout the evening. Wind speed was relatively high (for this event) during the period of heaviest rainfall and again during the second peak in air temperature on November 24.

During the 12-hr period from 0900 hr to 2000 hr November 23, outflow from the 760-m Finney open plot exceeded that from the forest plot by 25%. For the entire 24-hr period from 1400 hr November 23 to 1300 hr November 24, however, outflow from the open plots was only 1% greater than that from the forest plot (Table 13). It's likely that very little snow remained in either the forest or open plots at the Finney 760-m plots, and outflows measured at those plots were almost entirely rainfall. It appears only the plantation plot had appreciable amounts of snow, and this snow melted early in this 24-hr period so that outflow during the latter 12 hr represents only rainfall.

Table 13. Comparison of lysimeter outflows during November 23-24, 1990 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
760-m Canyon Creek			24-hr totals
Forest	167		
Open	193	+16	
Plantation	191	+14	
760-m Finney Creek			24-hr totals
Forest	152		
Open	154	+1	
Plantation	174	+14	
610-m Canyon Creek			No snow on plots
610-m Finney Creek			No snow on plots
460-m Canyon Creek			No snow on plots
460-m Finney Creek			No snow on plots

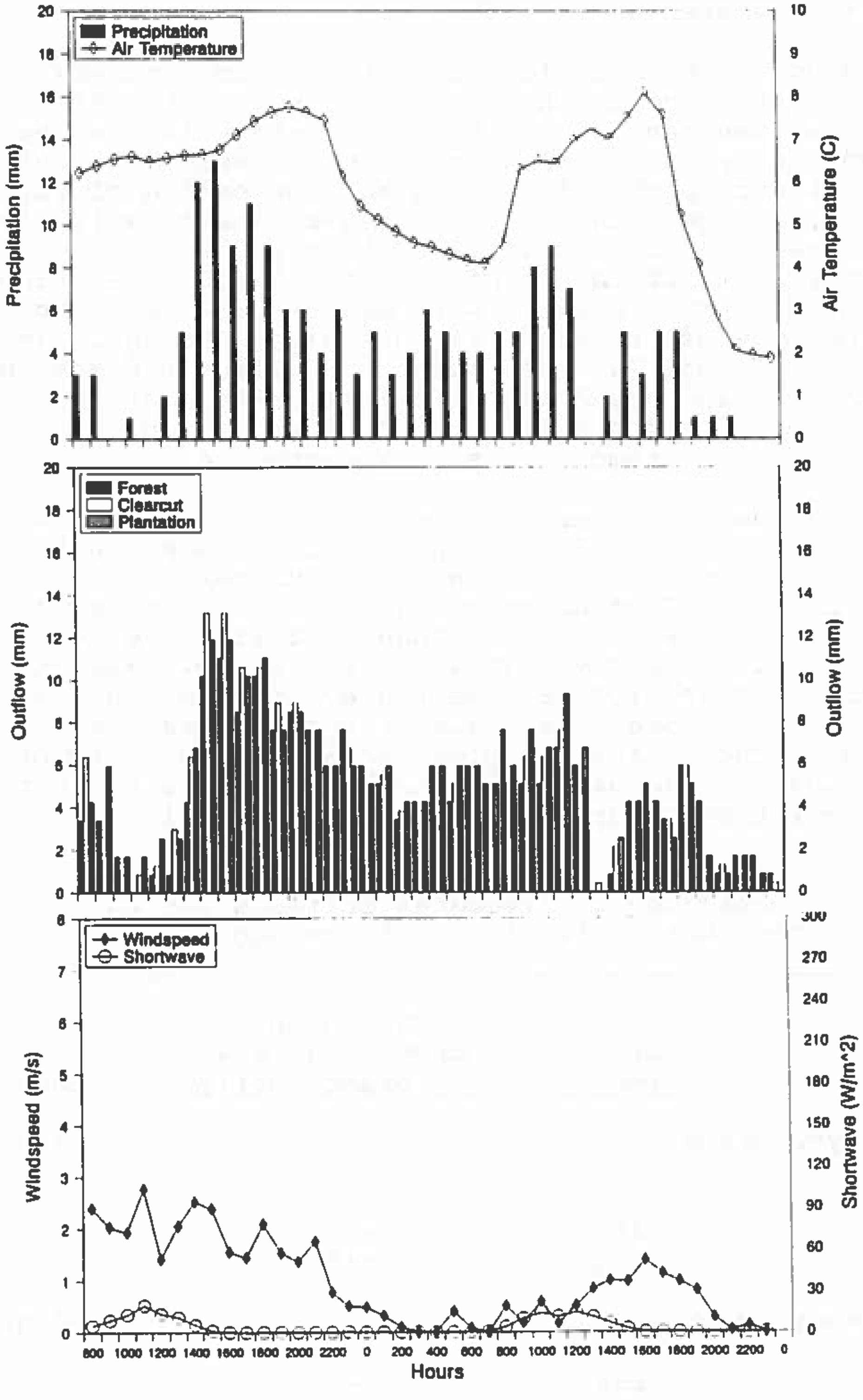

Figure 18. Rain-on-snow event, Canyon Creek 460-m elevation, 0900 November 23 - 2400 November 24, 1990
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

Event 11: December 3-4, 1990

At the end of the November 23-24, 1990 rain-on-snow event, all plots were devoid of snow. By 0300 hr on November 25, air temperatures at the 760-m elevation dropped to near-freezing and snow began to fall. By 0600 hr, snow was falling at all elevations at both locations, and, with the exception of a minor rain-on-snow event over a 6-hr period on November 29, continued falling intermittently until midnight December 2. By this time, SWE totaled about 125 mm at the Finney Creek 760-m open plot and 80 mm at the Canyon Creek 610-m open plot. Rainfall, which began around 0500 hr at all elevations, stopped at 1600 hr and then resumed around midnight. Thus, the December 3-4, 1990 rain-on-snow event consists of two distinct periods of rainfall (Figure 19).

Outflows from the plots shown in Figure 19 varied according to weather and the condition of the snowpacks. During the first period when rainfall rates were somewhat higher and both air temperature and wind speed remained relatively low, only small differences in outflows were observed. During this period, little heat was necessary to bring the snowpack to isothermality at 0° C because most snowfall had occurred at temperatures just slightly below 0° C; thus the temperature of the snowpacks were only slightly below freezing. Snowpacks were being conditioned, however, as their liquid-water-holding capacities were being satisfied. During the second period of rain, air temperature climbed to 4-5° C, and wind speed more than tripled. The result was a 15-hr period when outflow from the open plot was 76% greater than that from the forest plot.

Table 14 shows outflows from the various plots during the December 3-4, 1990 rain-on-snow event. Outflows were 32-44% greater from open plots at the 760-m elevation at both Canyon Creek and Finney Creek and at the 610-m elevation at Canyon Creek. These figures are somewhat conservative in that they have been calculated for 29- to 33-hr periods instead of for the 15-hr period when air temperature and wind speeds were highest as described above. Plantation outflows were variable.

Event 12: December 7-9, 1990

Following the December 3-4, 1990 rain-on-snow event, daytime temperatures stayed above freezing, and nighttime temperatures dropped to slightly below freezing. Melt water continued to trickle from all plots. Following sunny weather on December 6 and 7 during which daytime temperatures exceeded 11° C at nearly all open plots, a warm front transited western Washington, bringing with it warm nighttime temperatures from 2000 hr December 7 to 0300 hr December 8 (Figure 20). As temperatures dropped around 0400 December 8, rainfall began, and outflow

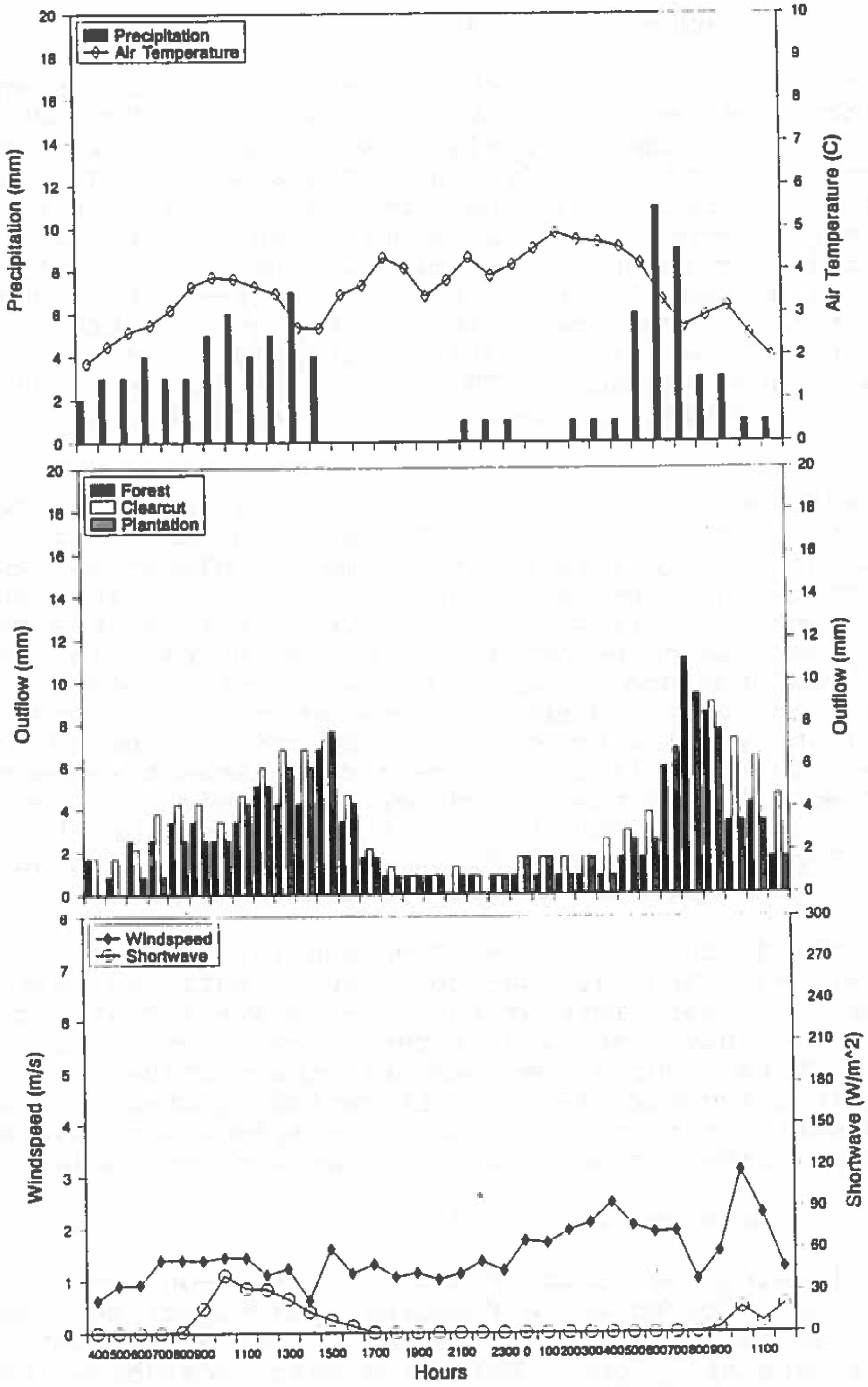

Figure 19. Rain-on-snow event, Canyon Creek 460-m elevation, 0500 December 3 - 1300 December 4, 1990
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

increased at all plots. During a 41-hr period from 0500 hr December 8 to 2100 hr December 9, rainfall averaged 3 mm/hr while air temperature ranged from 3° C to over 6° C. During this period, wind speed was variable, ranging from less than 1 m/s to over 2 m\s.

Table 14. Comparison of lysimeter outflows during December 3-4, 1990 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
760-m Canyon Creek			29-hr totals
Forest	42		
Open	57	+36	
Plantation	35	-17	
760-m Finney Creek			33-hr totals
Forest	94		
Open	124	+32	
Plantation	87	0	
610-m Canyon Creek			33-hr totals
Forest I	89		
Forest II	73		
Forest III	94		
Open	122	+44	Based on forest mean
Plantation I	100	+18	Based on forest and plantation means
Plantation II	100		
610-m Finney Creek			Outflow data missing
460-m Canyon Creek			Outflow data missing
460-m Finney Creek			Outflow data missing

Relative rates of outflow from the plots at the 610-m elevation at Canyon Creek generally followed weather conditions (Figure 20). During the initial rainfall, outflow from the open plot exceeded that from the forest plot by 37%. During the 7-hr increase in wind speed toward the end of the rain-on-snow event, outflow increased from all plots partly in response to the slight increase in rainfall rate and partly in response to the increase in wind speed. During this period, the open plot exceeded that from the forest by about 25%. For the entire 43-hr melt period, outflow from the open was 37% greater than that from the mean of the three forest plots (Table 15). All plantation plots exhibited outflows ranging from 8% less than forest outflows to 19% less than forest outflows.

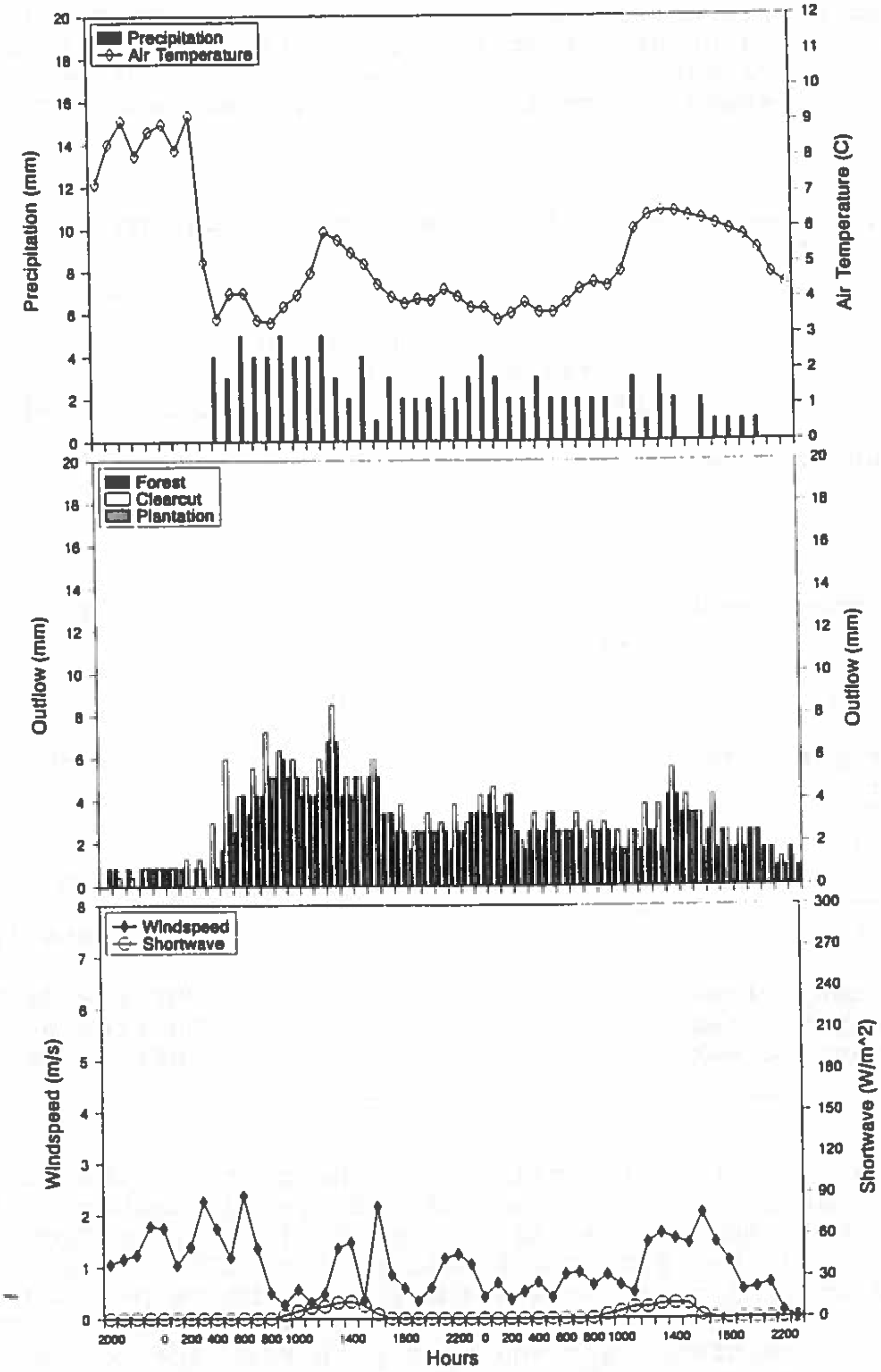

Figure 20. Rain-on-snow event, Canyon Creek 610-m elevation, 2000 December 7 - 2300 December 9, 1990
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

Table 15. Comparison of lysimeter outflows during December 7-9, 1990 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
760-m Canyon Creek			43-hr totals
Forest	106		
Open	130	+23	
Plantation	90	-15	
760-m Finney Creek			38-hr totals
Forest	138		
Open	---	--	Outflow data missing
Plantation	112	-19	
610-m Canyon Creek			43-hr totals
Forest I	121		
Forest II	94		
Forest III	142		
Open	163	+37	Based on forest mean
Plantation I	141	-8	Based on forest and plantation means
Plantation II	80		
610-m Finney Creek			Outflow data missing
460-m Canyon Creek			No snow on plots
460-m Finney Creek			No snow on plots

Event 13: January 10-14, 1991

Following the rain-on-snow event of December 8-9, 1990, snow remained on all plots, and outflow continued to trickle from all lysimeters. Slight increases in outflow did occur in response to minor rain-on-snow conditions December 10. For the next eight days, air temperatures fluctuated between -3° C and 3° C except for clear weather December 13 when nighttime temperature reached -7° C and daytime temperature reached 7° C. By mid-afternoon December 18, air temperature began to drop as an Arctic air mass approached western Washington. By 0500 December 19, air temperature had fallen to -15° C at the Finney Creek 760-m open plot. The next four days were sunny, daytime temperatures reached only -9° C, and nighttime temperatures reached -20° C.

By late December 26, snowfall began and continued through December 27. On December 28, temperatures again fell, reaching -21° C at the Finney Creek 760-m open plot. During a warming trend on December 30, snowfall began again at Finney Creek and continued until noon on January 1, 1991. This warming trend produced rainfall at Canyon Creek, but the cold weather had taken such a high toll on tipping buckets and lysimeter drains that few plots exhibited any outflow. Snowfall began again on January 6 and continued through January 9.

This cold period was followed by a warming trend beginning on January 10. By 1000 hr January 10, air temperature had risen to 3° C at the 460-m elevation open plots. By the time rainfall began at 2200 hr January 10 at all plots, only the Canyon Creek 460-m forest and open plots were providing any outflow information; lysimeter drains at other plots remained frozen.

Although this rain-on-snow event actually began at 2000 hr on January 10, outflow did not begin at the forest plot until 1600 hr January 11 nor until 1000 hr on January 12 at the open plot. Lysimeter drains at both plots had been frozen, and the first hour's outflow at each plot was followed by a huge pulse of water as the ice plug finally broke. Consequently, the rain-on-snow event depicted in Figure 21 begins at 1300 hr January 12 after melt water from the lysimeter in the open plot had drained. Total melt prior to this time was measured and will be used in subsequent discussion.

By the time the lysimeters began to drain on January 12, air temperature had risen above 7.5° C, and wind speeds had averaged over 3.2 m/s. In fact, an hourly mean wind speed of 5.3 m/s, the highest recorded in this study, occurred between 0900 hr and 1000 hr on January 12 just before the ice plug in the open plot's lysimeter drain finally broke. Wind speed remained above 3 m/s for much of the next 10 hr.

During the first part of this rain-on-snow event (up to 0600 hr on January 13), rainfall was very light, air temperature was relatively steady at 6.5-7.0° C, and average hourly wind speed was 3-4 m/s (Figure 21). Outflow from the open plot was 174% greater than outflow from the forest. During the next 11 hr of high rainfall intensities, outflow from the open plot was 85% greater than outflow from the forest. During the next 21 hr, wind speed was variable, and temperatures were somewhat lower than in the two previous periods. Consequently, relative responses of the two plots were also variable, although during this period, too, total outflow from the open plot surpassed that from the forest. During the last 9-hr pulse of rainfall, particularly when both wind speed and air temperature increased, outflow from the open plot again was substantially greater than that from the forest plot.

For the 64-hr period shown in Figure 21, outflow from the open plot was 52% greater than that from the forest plot. If the melt from the period before the ice plugs melted is included, outflow from the open plot was only 34% greater than that from the forest plot (Table 16).

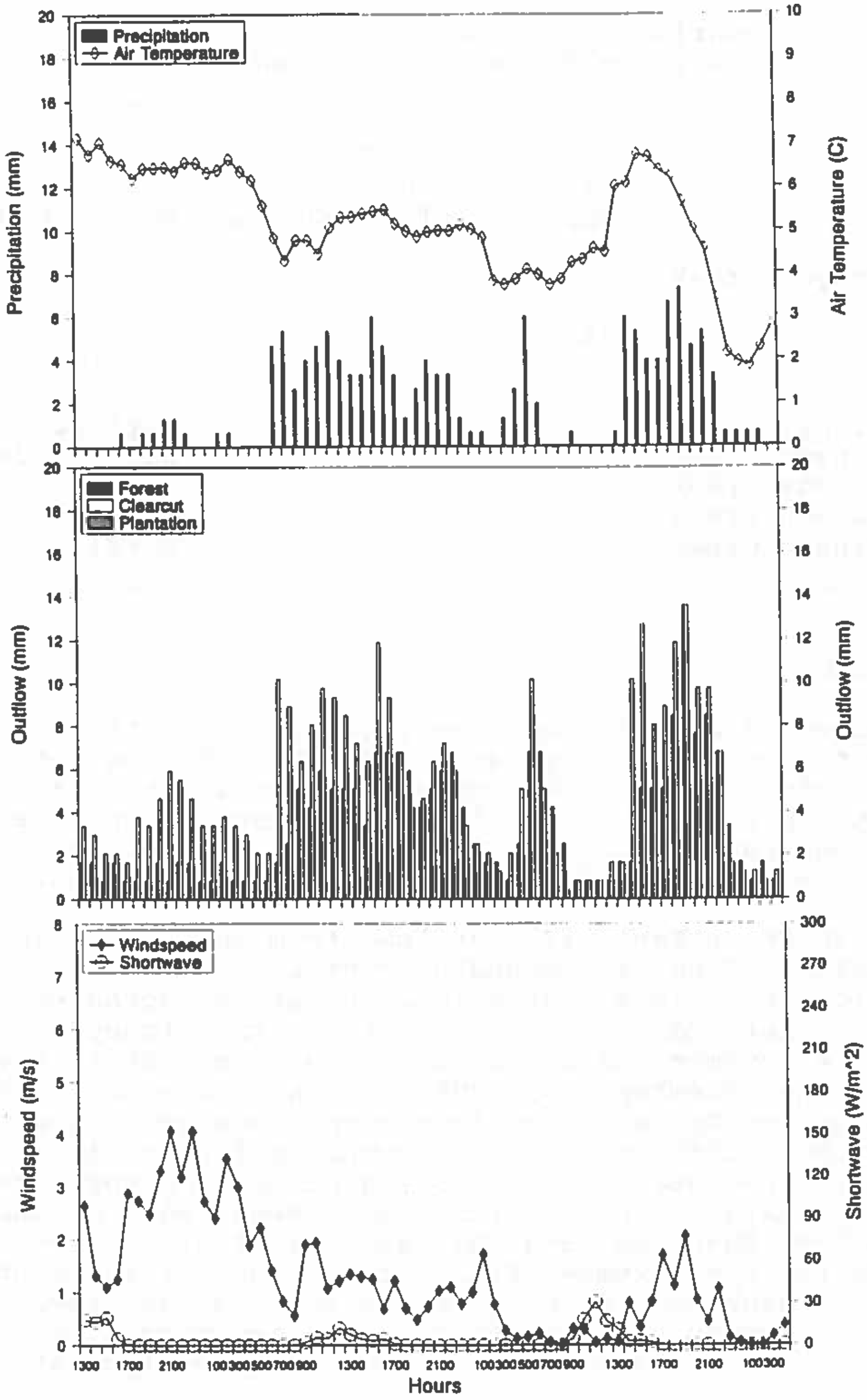

Figure 21. Rain-on-snow event, Canyon Creek 460-m elevation,
1300 January 12 - 0400 January 15, 1991
(a) Air Temperature and Precipitation
(b) Lysimeter Outflow
(c) Wind Speed and Shortwave Radiation.

Table 16. Comparison of lysimeter outflows during January 12-15, 1991 rain-on-snow event.

Plot	Outflow (mm)	Change in Outflow as a % of Forest Outflow	Remarks
460-m Canyon Creek			64-hr totals
Forest	334		
Open	446	+34	
Plantation	---	--	Outflow data missing
460-m Finney Creek			Outflow data missing
610-m Canyon Creek			Outflow data missing
610-m Finney Creek			Outflow data missing
760-m Canyon Creek			Outflow data missing
760-m Finney Creek			Outflow data missing

DISCUSSION

Tables 17 and 18 summarize increases in outflow from open and plantation plots in relation to outflows from corresponding forest plots for all plot-events. A plot-event is a rain-on-snow event at a particular plot; one rain-on-snow event that occurred at four separate plots would result in four plot-events. There were 29 plot-events for open plots and 30 for plantation plots.

As shown in Table 17, outflows from open plots were greater than outflows from corresponding forest plots in all 29 plot-events for open plots (Table 17). Relative increases in outflow from open plots ranged from only 1% for the Finney 760-m plot during the November 23-24, 1990 rain-on-snow event (Event #11) to 138% for the December 2-3, 1989 rain-on-snow event (Event #6). In 19 plot-events, outflows from open plots were more than 25% greater than outflows from corresponding forest 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 less than 15%, and this group of four includes the 1% increase for the November 23-24, 1990 event at the Finney 760-m elevation which may not have been a rain-on-snow event at the open plot because of the lack of snow remaining after the November 21-23, 1990 rain-on-snow event (see discussion on p. 67).

Outflows from plantation plots were much more variable than those from open plots. Of the 30 plot-events observed in the plantation group of plots, outflows from plantation plots were greater than outflows from corresponding forest plots in 17 plot-events, lesser in 10 plot-events, and identical in three plot-events (Table 18). Outflows from the plantation were more than

30% greater than from forest plots in six of the 17 plot-events when plantation outflows exceeded forest outflows.

Table 17. Summary of changes in outflow from open plots in relation to outflows from corresponding forest plots.

Plot	Rain-on-Snow Event No.	Change in Outflow as a % of Forest Outlfow
Canyon Creek, 460-m	1	+27
Finney Creek, 460-m	1	+96
Finney Creek, 610-m	1	+73
Canyon Creek, 460-m	2	+65
Finney Creek, 460-m	2	+96
Finney Creek, 610-m	2	+25
Canyon Creek, 460-m	3	+15
Finney Creek, 460-m	3	+41
Canyon Creek, 460-m	4	+42
Finney Creek, 460-m	4	+21
Canyon Creek, 460-m	5	+71
Canyon Creek, 760-m	6	+138
Finney Creek, 760-m	6	+58
Canyon Creek, 760-m	7	+78
Finney Creek, 760-m	7	+24
Canyon Creek, 760-m	8	+58
Canyon Creek, 460-m	9	+9
Finney Creek, 460-m	9	+24
Canyon Creek, 610-m	9	+11
Canyon Creek, 760-m	9	+26
Finney Creek, 760-m	9	+2
Canyon Creek, 760-m	10	+16
Finney Creek, 760-m	10	+1
Canyon Creek, 760-m	11	+36
Finney Creek, 760-m	11	+32
Canyon Creek, 610-m	11	+44
Canyon Creek, 760-m	12	+23
Canyon Creek, 610-m	12	+37
Canyon Creek, 460-m	13	+34

The variability of outflows from plantation plots relative to those from corresponding forest plots, including less outflow from plantation plots in 10 plot-events than from forest plots, might be construed by some to mean that the plantation plots in this study were hydrologically recovered. We doubt that these plantation plots have fully recovered from the standpoint of rain-on-snow and do not believe they should be considered fully recovered. Data in Tables 3-16 show many plantation outflows intermediate between outflows from associated open and forest plots.

Table 18 summarizes changes in plantation outflows in this study. If data in Table 18 were to be used in predicting cumulative effects of timber harvest on water delivery to soil or on streamflow for a basin during rain-on-snow, then a conservative approach, i.e. using the positive changes in outflow, would likely be prudent, at least until better information on recovery is obtained.

Table 18. Summary of changes in outflow from plantation plots in relation to outflows from corresponding forest plots.

Plot	Rain-on-snow Event No.	Change in Outflow as a % of Forest Outlfow
Canyon Creek, 460-m	1	-16
Finney Creek, 460-m	1	+96
Finney Creek, 610-m	1	+36
Canyon Creek, 460-m	2	+19
Finney Creek, 460-m	2	+39
Finney Creek, 610-m	2	+18
Canyon Creek, 460-m	3	-14
Canyon Creek, 460-m	3	+34
Canyon Creek, 460-m	4	0
Finney Creek, 460-m	4	+18
Canyon Creek, 460-m	5	+62
Canyon Creek, 760-m	6	0
Finney Creek, 760-m	6	+49
Canyon Creek, 760-m	7	+3
Finney Creek, 760-m	7	+18
Canyon Creek, 760-m	8	-9
Canyon Creek, 460-m	9	+10
Finney Creek, 460-m	9	-3
Canyon Creek, 610-m	9	+5
Finney Creek, 610-m	9	-10
Canyon Creek, 760-m	9	-2
Finney Creek, 760-m	9	+2
Canyon Creek, 760-m	10	+14
Finney Creek, 760-m	10	+14
Canyon Creek, 760-m	11	-17
Finney Creek, 760-m	11	0
Canyon Creek, 610-m	11	+18
Canyon Creek, 760-m	12	-15
Finney Creek, 760-m	12	-19
Canyon Creek, 610-m	12	-8

Even though plantation plots differed markedly in age, species, and denisty, a single plantation did not show the same type of response to snowmelt during rainfall. For example, consider the changes in outflow at the Finney Creek 760-m plantation plot. The six plot-events at this plot showed changes ranging from -19% to +49%. Similarly, changes at the Canyon

Creek 460-m elevation plot ranged from -16% to +62%. The Canyon Creek 760-m plot, the oldest of the plantation plots, did show somewhat subdued changes in outflow compared to other plantation plots, but here the range was still -17% to +14%.

At this point, neither the slope nor the shape of a curve for hydrologic recovery as each relates to rain-on-snow is known, but some estimates can be made. Figures 22 and 23 show how we believe such recovery curves for wind-aided transfers of sensible and latent heats and snow interception might appear. These curves are based on quantitative and qualitative information from this study and other rain-on-snow studies in western Oregon (Berris and Harr, 1987). We emphasize that the shapes of the two recovery curves is most likely accurate, values shown on the x- and y-axis of these curves are hypothetical.

In Figure 22, the intitial change in sensible and latent heat transfer has been assigned a value of 100 immediately following clearcutting. It is likely that 8-10 yrs may elapse before noticeable (>10%) reductions in rate of water delivery to soil during rain-on-snow will occur following clearcut logging. In general, this elapsed time will increase with increasing elevation or with decreasing site quality and will be inflfuenced by exposure to prevailing winds and other factors. The large increases in transfers of sensible and latent heats that typically occur immediately after clearcut logging probably persist until the forest regrowth has lost its open appearance, probably around 10-15 yrs following clearcutting.

In Figure 22 we've estimated that initial increases in potential sensible and latent heat transfers that result from clearcutting would have been reduced by at least 70%, perhaps even more, by 18 yr after clearcutting. This downward trend is sharply reversed by thinning as the stand is opened up, air movement is enhanced, and combined transfer of sensible and latent heats returns to perhaps 70% of the initial post-logging value. As stand growth is enhanced by thinning, sensible and latent heat transfers would be expected to decrease as air movement becomes more restricted. In this case, we have estimated that they are about 20% as great after 50 years as they were immediately after clearcutting.

Figure 23 is our estimate of how clearcutting and subsequent forest regrowth might affect the other mechanism involved in rain-on-snow, namely snow accumulation on the ground, by influencing interception and canopy melting of snow. Again, this figure is based on quantitative and qualitative information from this study and from other studies elsewhere (Berris and Harr, 1987). In this example, the mature forest's capability is assigned a value of 100. This value corresponds to maximum interception, maximum canopy melt, and minimum accumulation of snow on the ground. In other words, a value of 100 translates into little snow available to melt during a future rain-on-snow event. Clearcutting then reduces this capability to zero. As

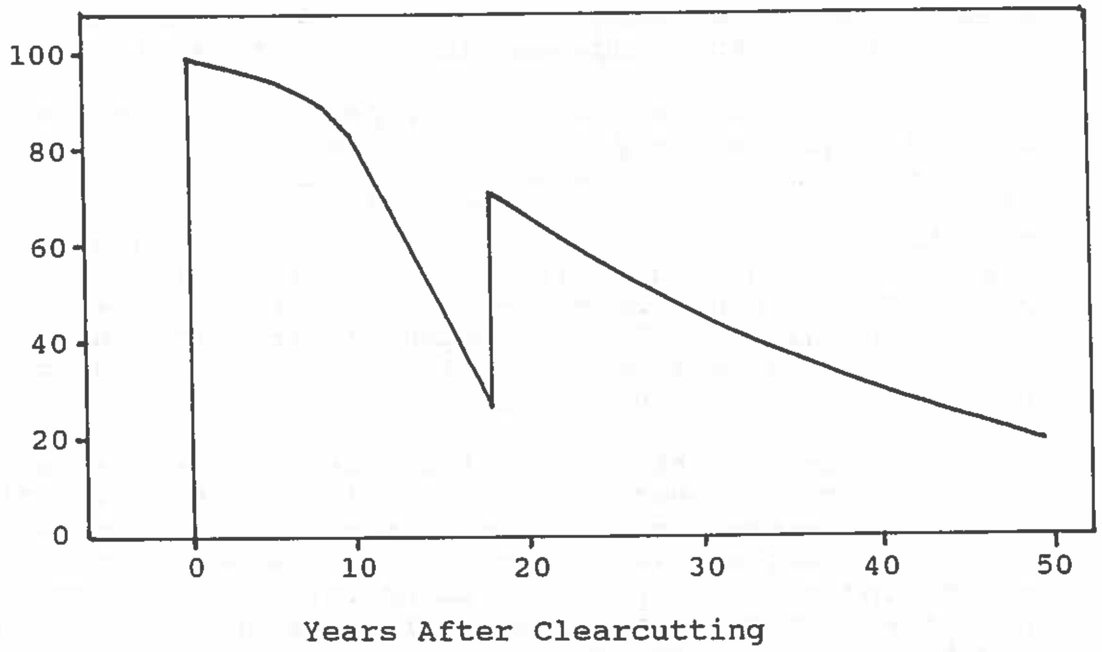

Figure 22. Hypothetical recovery curve for combined transfers of sensible and latent heats.

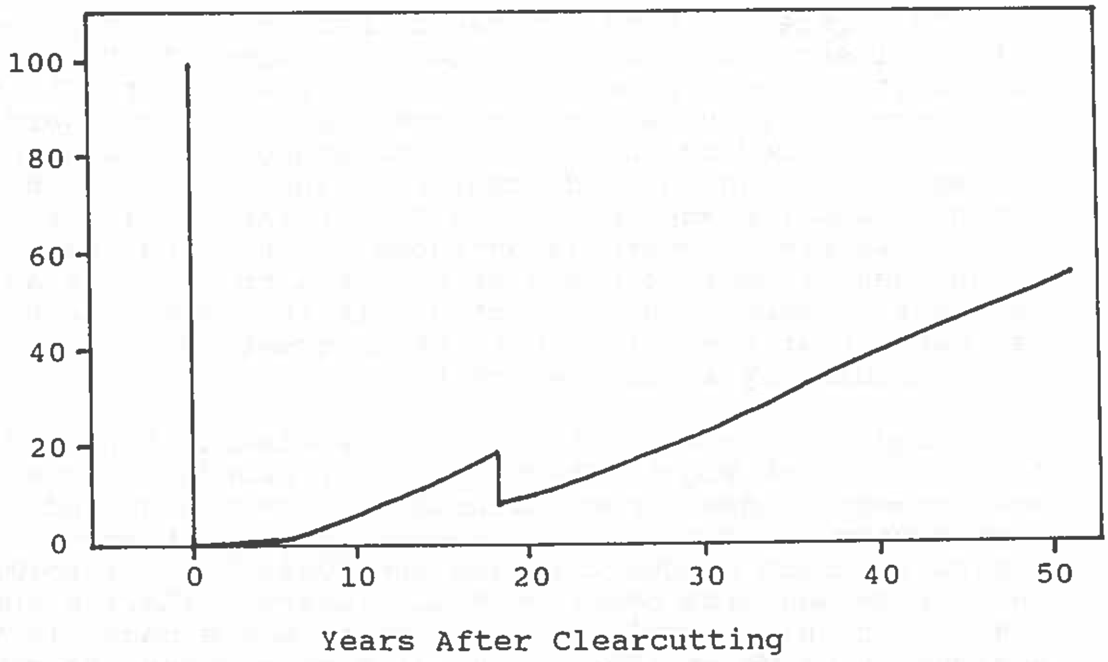

Figure 23. Hypothetical recovery curve for snow interception and canopy melt.

regrowth occurs, the new stand's capability to intercept snow increases slowly because the branches of individual trees are insufficiently rigid to withstand the weight of snow. Branches flex downward, and snow slides off onto the ground.

Figure 23 represents only one scenario of snow accumulation, one that results from a series of short-duration snow storms at temperatures above freezing with very low wind speeds. If snow falls in one large storm that surpasses the forest canopy's ability to intercept and hold snow, then snow accumulation would be influenced less by the nature of forest vegetation, and snow accumulation would not differ much from forest to plantation to logged areas. This would be especially true if snow fell when air temperature were below freezing and snow was dry or if wind blew snow from tree canopies onto the ground.

The rapid increase in lysimeter outflow when air temperature and wind speed increased can be used to illustrate how different several large rain-on-snow events in this study could have been had the snow accumulation and/or melt scenarios been only slightly different. For instance, consider the November 21-23, 1990 rain-on-snow event (event #9). This event sent rivers back to flood stage after an earlier flood November 10-11. During the November 21-23 event, rainfall was augmented by rapid snowmelt at all elevations as air temperatures were 5-6° C at 760-m elevation and 7-8° C at 460-m. However, at the 460-m and 610-m plots at both Canyon Creek and Finney Creek, availability of snow controlled the magnitude of rain-on-snow's contribution to the flooding.

The importance of both snow accumulation and melt and forest cover's influence on each can be illustrated by what would have occurred with slightly different weather conditions immediately before and/or during the various rain-on-snow events observed in this study. Such different conditions most likely would have resulted in much different responses of the various plots to rain-on-snow.

Again, consider the November 21-23, 1990 rain-on-snow event, an event that caused extensive flooding throughout western Washington. Slightly different weather conditions before this event, conditions that are not uncommon in the western Cascades of Washington, could easily have doubled snow accumulation at all elevations. This, coupled with slightly higher wind speeds and air temperatures only 1-2° C higher, would have resulted in two changes in rain-on-snow runoff compared to what actually occurred.

First, snowmelt's contribution to flood flows during the November 21-23 period could easily have been greater, resulting in higher flood levels and more flood damage. Secondly, greater snow accumulation prior to the start of the November 21-23 rain-on-snow event could easily have resulted in more snow remaining on the ground at all elevations after the November 21-23 event despite the greater snowmelt that would have occurred with higher air temperatures and wind speeds. Thus, the November 23-24, 1990 rain-on-snow event could have been substantially larger simply because more of the landscape would have been contributing snowmelt. And if weather conditions during the November 23-24 event would have differed just slightly as described above for the November 21-23 event, rivers would have reached even higher levels, flooding could easily have been much more devastating than it was, and timber harvest could have been responsible for more of the flooding. In other words, for lack of a few degrees of air temperature and slightly higher wind speeds, flooding was not as devastating as it could have been.

ERROR ANALYSIS

Possible errors associated with this study can be of three types. The first involves the sampling method, and location of the lysimeters within their respective plots. Second is the instrument error, in which the instruments are not accurately measuring or reporting data, or are improperly employed in the field. Third, is error in interpreting the data. The third type of error is particularly important in studies such as this, because without visually seeing what is occurring at any given time, data must be interpreted and used to reconstruct events and conditions occurring on-site. Similar future studies should include some type of time-lapse photography like that described by Berris (1984) and Berris and Harr (1987).

Regarding the first type of error, much has already been said about the variability within and between the different study plots. Accurately determining the range of this variability in terms of snow accumulation and subsequent melt during rainfall would require a large number of replicated study plots. However, even with a large number of plots in a given forest stand, the variability among different forest types or different geographic locations would not be addressed. As noted previously, the position of a plot in a drainage can have a considerable effect on the intensity of winds and precipitation experienced.

In this study, we opted to increase the probability of recording rain-on-snow along with weather information to help explain the dynamics of outflow from the various plots. To do this, we distributed study plots over a range of elevations at two different locations. This was done to overcome the problem experienced by Berris and Harr (1987) where the one location and elevation monitored experienced only one rain-on-snow event of the size the study was designed for based on long-term weather records. Given the number of variables that affect snow ccumulation and subsequent melt during rainfall, replication at each location was not possible with the resources available for this study.

However, the dispersed approach used in this study will benefit future studies by providing an idea of what elevations are most likely to experience rain-on-snow. Follow-up studies will be able to focus on these elevations and more intensively monitor the individual plots. Results from this study, comparing outflows over a relatively large number of events and locations, do tend to support one another, and relative outflows can be explained reasonably well from antecedent and storm conditions.

Although forest plots are not homogeneous, they tended to exhibit more even distributions of snow and drip patterns than did plantations. For example, in one rain-only event, outflows from three lysimeters at the 460-m elevation forest site at Finney Creek were compared over 24-hr. Outflow differences among the three lysimeters were 3.0%, 4.9%, and 8.3%. During the same time period, outflows from two lysimeters in the adjacent plantation were 21% different. It must be emphasized that these differences were during rain-only events. During snowfall, different relationships may hold.

However, because the tree branches within the mature forest are stronger, their positions once loaded with snow will change less than the positions of the more flexible branches in the plantation canopies. As tree branches in the plantation flex downward in response to the snow load, snow is easily unloaded onto the ground. Additionally, the downward-flexed branches increase the size of openings in the canopy between trees, and may allow more snowfall to reach the ground directly.

Because of these kinds of differences, coupled with visual observations of a more uniform snow cover in the forest stands as opposed to the plantations, data from lysimeters in the forest are more easily accepted as being representative of these stands. With greater variability in snow loading and canopy cover in the plantations, larger differences can be expected from point to point within the plantations.

The second type of error, instrument error, focuses largely on the precipitation gages and the lysimeters. Weather instruments including the wind sensors, pyranometers, and temperature/humidity probes were factory-calibrated before use and checked for calibration in the laboratory following the second year of data collection. Factory calibrations for all instruments were maintained through the first two years of this study. (At the time this report was written, calaibrations of the weatehr instruments had not been checked following the third winter.) One possible exception is the relative humidity probes, but data from these probes were not used in this study. Moreover, data from all of the weather instruments were used collectively only as an indicator of general weather conditions prior to and during the rain-on-snow events.

Tipping buckets used with the lysimeters were calibrated in the laboratory prior to being installed in the field, and then recalibrated in the field following the second and third years of data collection. Results of this calibration showed that the calibration on many of the tipping buckets had changed over the first two years. The changes in calibration were generally within 5% of the initial, but in one case as large as 10%. Correction factors were applied to the data for the entire two-year period, because it was suspected that the changes occurred shortly after installation, as the bucket supports were "broken in". According to recalibrations following the third winter, some calibrations were unchanged, some changed positively, and some changed negatively. Tipping buckets used with the precipitation gages were factory calibrated before installation, and also recalibrated in the field following the second year of data collection. Calibration on these tipping buckets had changed as well, and correction factors were applied to the data accordingly.

Of possibly greater consequence to the study than these very small calibration differences, however, were problems with precipitation gage catch deficiencies due to winds, and with the performance of two of the tipping buckets used with the precipitation gages. Error from these two sources could have been very large.

The U.S.A.C.E. (1956) estimated losses from shielded rain gages during snowfall to be as high as 50%. They reported that not only are gage catch deficiencies considered the greatest source of error in measuring precipitation, but that losses are greatest when measuring snowfall, and increase with increasing wind speed. Because our gages were purposely established in open plots, they are particularly subject to high winds and corresponding high losses. As a result, the amount of snow accumulation in the lysimeters was likely underestimated throughout the study.

The problem with the tipping buckets used with the rain gages occurred at both the 460-m open plot at Canyon Creek, and the 610-m open plot at Finney Creek. The magnetic contact switch on these tipping buckets moved during the field season, causing the switch to record the incorrect number of pulses per tip of the tipping bucket. In most cases, field checks of the instruments revealed the ratio of pulses per tip from the tipping bucket, and the magnet could be re-adjusted to record one pulse for every tip. Data could be corrected by applying the appropriate multiplier, depending on the ratio of pulses per tip. When no snow was in the open lysimeter, the correction factor could be determined in the office by comparing outflows from the open lysimeter with precipitation gage outflow when air temperatures were greater than 1.7° C.

However, the magnet on the tipping bucket at the 460-m Canyon Creek plot required re-adjustment on several occasions, and data from this gage was often inconsistent with other gages in the drainage. For example, precipitation data from the three elevations in Canyon Creek were compared over 12 precipitation events consisting of both rain and snow. Precipitation recorded at the 460-m plot was anywhere from 80% to over 300% of that recorded at the 760-m elevation, and 96% to over 250% of the precipitation recorded at the 610-m elevation. Certainly part of this difference can be attributed to actual differences in precipitation among the three plots, and different wind speeds allowing a different catch at each plot. However, considering that there is less than 2.5 km separating the 460-m and 760-m plots, and no topographic barrier between them, this difference would appear to be a recording or instrumentation error. Furthermore, during the same 12 precipitation events, there was much less variation between the amounts of precipitation recorded at the 610-m and 760-m plots. Because the recorded differences between the 460-m gage and the others had such a wide range of variation, it was unclear at any time how much of the difference was a function of the switch malfunctioning, and how much was due to actual precipitation differences or differences in catch deficiency.

One of the most basic of all environmental measurements is that of precipitation. However, in this study, precipitation seemed to be the most difficult variable to measure. In addition to the problems noted above, there were a number of periods in the study, particularly during the first year, when precipitation data were not available for some gages because of freezing liquid in the gage or outflow tube. In these cases, precipitation was estimated from nearby gages.

Because measurement of lysimeter outflows were the basis for the study, they are the most important measurements made. In fact, lysimeter outflows were generally considered the most reliable data. During rain-only events when no snow was present in the lysimeter, outflow from the lysimeters was considered to be a good measure of precipitation. However, following very cold periods, problems were caused by some drains and their associated tipping buckets freezing. In the case of freezing drains, outflow volume was not lost; only the timing of the outflow prior to the drain opening was lost. However, when tipping buckets filled with water and froze solid, there was an opportunity to "lose" outflow as it poured out over the stationary tipping bucket. Whereas frozen drains could be detected in the outflow data by the large pulse of water once they thawed, there was no such evidence for the frozen tipping bucket.

The third type of error possible was the error in interpreting the data. As noted earlier in this report, events and on-site conditions were interpreted from the numerical data in combination with field notes. Refer to the "Data Analysis" section for an in-depth discussion of the methods used and problems encountered.

CONCLUSIONS

This study has shown that forest management activities (such as clearcuting 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. Rates of water delivery to soil will be increased most when greater accumulation of snow in an open (logged) area is followed by moderate rainfall at relatively high air temperatures and wind speeds that combine to increase the transfer of sensible and latent heats to the snow. These weather conditions are common during late fall and early winter months in western Washington.

Over a number of rain-on-snow events, a wide range of conditions, and at a number of different locations, this study has shown higher rates of water delivery to the soil in non-forested plots than forested plots during rain-on-snow. Water outflow from open plots exceeded rates of water outflow from forest plots by 1% to 138%. Increased outflows from open plots in this study were generally much greater than those reported in similar studies elsewhere (Beaudry, 1984; Berris, 1984; Berris and Harr, 1987). Except for the extreme rainfall in November, storms monitored in this study were not considered extraordinary in terms of weather conditions, so snowmelt processes and rates of water outflow should not be considered extraordinary.

Differential snow accumulation and rate of melt during rain-on-snow were both invovled in greater outflows from open plots. Differential snow accumulation and subsequent rate of melt during rainfall were not of equal importance in every rain-on-snow event nor at every location.

Maximum differences in outflows between open and forest plots occurred during periods when air temperatures and wind speeds were both relatively high. Even though some plot-events did not exhibit large differences in outflow between open and forest plots, there were commonly 7- to 12-hr periods when outflow from the open plots exceeded that from the forest plot by 25-75%.

When snow fell at temperatures above freezing and was intercepted and allowed to melt in tree crowns, outflows from forest plots exceeded those from open plots. However, such differences were of little hydrologic significance in terms of immediate water delivery to soil because they were usually of low magnitude and short duration. These differences were often of much greater hydrologic significance in terms of later water delivery to soil because they often dictated how much snow water equivalent would be on the ground when a future rain-on-snow event occurred.

Outflows from the 18- to 40-year-old plantation plots were often intermediate between outflows from the forest and open plots, but at times were actually less than the outflow measured from the forest. Outflows from plantation plots ranged from 19% less to 96% greater than from corresponding forest plots. The wide range of outflow responses reflect variability between storm events, but also the variability among the stands and within individual stands.

That outflows from some plantation plots during some events were less than from corresponding forest plots does not mean that plantation are hydrologically recovered, or even more extreme, that plantations are in a "hydrologically better" condition than forests during rain-on-snow. This reduced outflow may reflect an interaction between the method of measurement of outflow (i.e., the snow lysimeter) and the nature of plantation stands. In most cases, plantations had been thinned to a uniform spacing, and the places where the 1.14-m by 2.06-m lysimeter box could be installed were limited to spaces between trees. This may have biased outflow dynamics at many plantation plots. Snow accumulation was highly variable in plantations (see Figure 31 in the Appendix), and some lysimeters may have overestimated snow accumulation because of their necessary placement at the crown margins of several trees.

More intensive study will be required in plantation stands to understand better the range of variability between stands and within individual plantations. In such a study, lysimeters would have to designed and placed such that they would span the range of snow accumulation better than those used in this study.

Although energy balance equations were not calculated in this study, it was evident that in each event and at each location, the various sources of heat differed in their relative importance to causing snowmelt. Even during individual rain storms, the relative importance of different heat inputs appeared to change. Outflow from a plot also appeared to be dependent on the amount of snow on the plot. The presence, absence or quality of forest cover clearly played a key role in influencing not only snow distribution, but also snowmelt in this study.

Another important conclusion to be drawn from this study is that the systems being monitored--both the biologic and meteorologic--are extremely complex and highly variable. The wide range of outflow differences recorded during this study suggest the complexity of determining differences in rates of water outflow from forested, non-forested, and re-forested plots. These systems are highly variable within themselves, have a high degree of variability with respect to their surroundings, and exhibit a high degree of variability in their response to inputs.

There is often a tendency to simplify research results into a number or threshold value that can easily be translated into a regulation, guideline, or method to assess cumulative effects of forest management activities on streamflow. Although it is important that we are able to apply our research findings to solving land management problems, it is also essential that we consider the complexity of natural systems when developing guidelines or regulations. Planning should be done not only for the "average" expected response, but for the range of possible responses. As this study has shown, the range can be quite large. Further study of this issue will add to our understanding of the full range of outflow differences that can be expected from forested and non-forested plots during rain-on-snow.

RECOMMENDATIONS FOR FUTURE RESEARCH

Continued studies of the effects of forest cover on both rate of snow accumulation and snowmelt during subsequent rainfall will supplement results from this study. In this study, emphasis was put on maximizing the number of opportunities for measuring snowmelt during rainfall. This necessitated establishing plots at three elevations at two locations.

Future studies are needed to monitor individual stands more intensively. Installing more lysimeters in an individual stand will provide a range of values for the stand that reflect the variability in both snow accumulation and snowmelt that occur across the stand. Assessing the variability in snow accumulation may be particularly important in the forest plantations, where snow accumulation on the ground is extremely variable.

Once a better understanding is reached regarding the range of variation within plantations, comparisons among plantations can be made. Management practices such as thinning probably have important implications on the effectiveness of the stands in limiting air movement, and may also affect snow accumulation.

Another subject needing study is the effect of shelterwood cuts and leave trees on snow accumulation and melt. Harvest prescriptions on some Federal and private lands are using "new forestry" concepts including leaving 20-40 trees per acre. The response of these plots in terms of snow accumulation and subsequent melt during rainfall is important in how these are dealt with in cumulative effects analyses and in modelling streamflow.

Any future studies involving rain-on-snow will likely encounter the same type of problems encountered during this study. In this regard, we offer a few suggestions for the benefit of other researchers who might become involved with field studies of rain-on-snow.

The first suggestion concerns frequency of field visits. Checking for correct operation of instrumentation and to visually monitor snow conditions requires frequent visits. Unexpected extremes in temperature and snowloading can damage field equipment if not fully protected, and regular field visits may limit loss of data due to instrumentation problems. Ideally, sites should be located such that weekly site visits through the winter are possible.

The second suggestion involves time-lapse photography. If accessibility is limited during winter months, as it was in this study, time-lapse cameras on site would be extremely helpful in interpreting data. These could be used in the forested plots to monitor snowpacks and to give a visual check of numeric data. Regardless of winter accessibility, time-lapse photography would facilitate monitoring fast-changing rain-on-snow conditions.

Results from this study are being used in three other studies, two of which are being partially supported by TFW. One being conducted by the Tacoma office of the U.S. Geological Survey seeks to use this study's data to calibrate snow accumulation and melt models that will be used in conjunction with long-term weather records of the National Weather Service to help determine the probability of occurrence of rain-on-snow across the State of Washington. This will lead to delineation of the transient snow zone in Washington based on probability of occurrence of rain-on-snow. The second TFW-sponsored study is being conducted by the University of Washington to assess the effect of forest management activities on major flood flows in western Washington. How well data from the rain-on-snow field study can be used in these two studies will determine in part the priority of future rain-on-snow field research. The third study is also being conducted by the University of Washington to examine streamflow routing and the scale of watershed response to changes in rate of water input to soil.

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Figure 25. Forest plot at Canyon Creek, 460-m elevation.

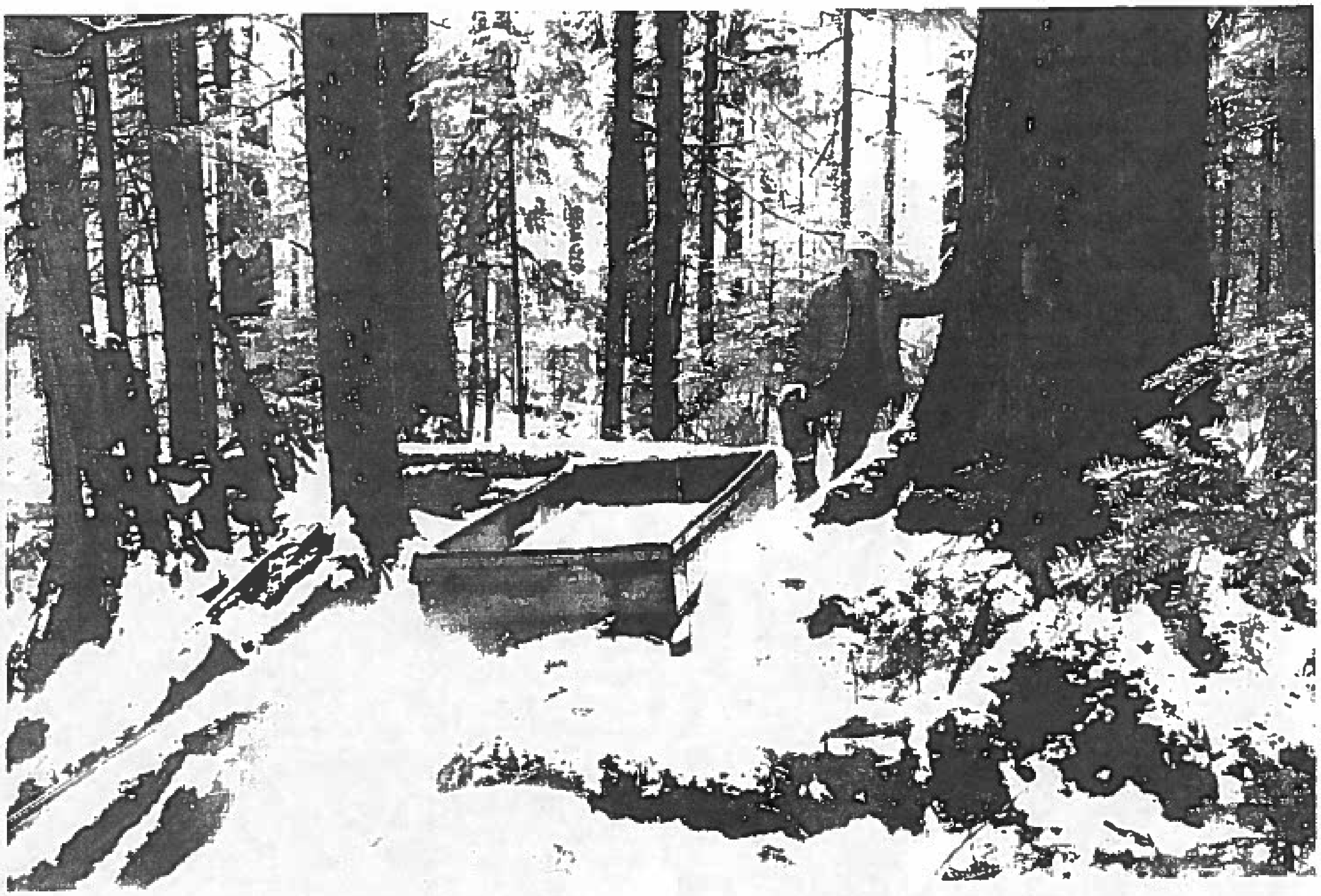

Figure 26. Forest plot at Canyon Creek, 460-m elevation.

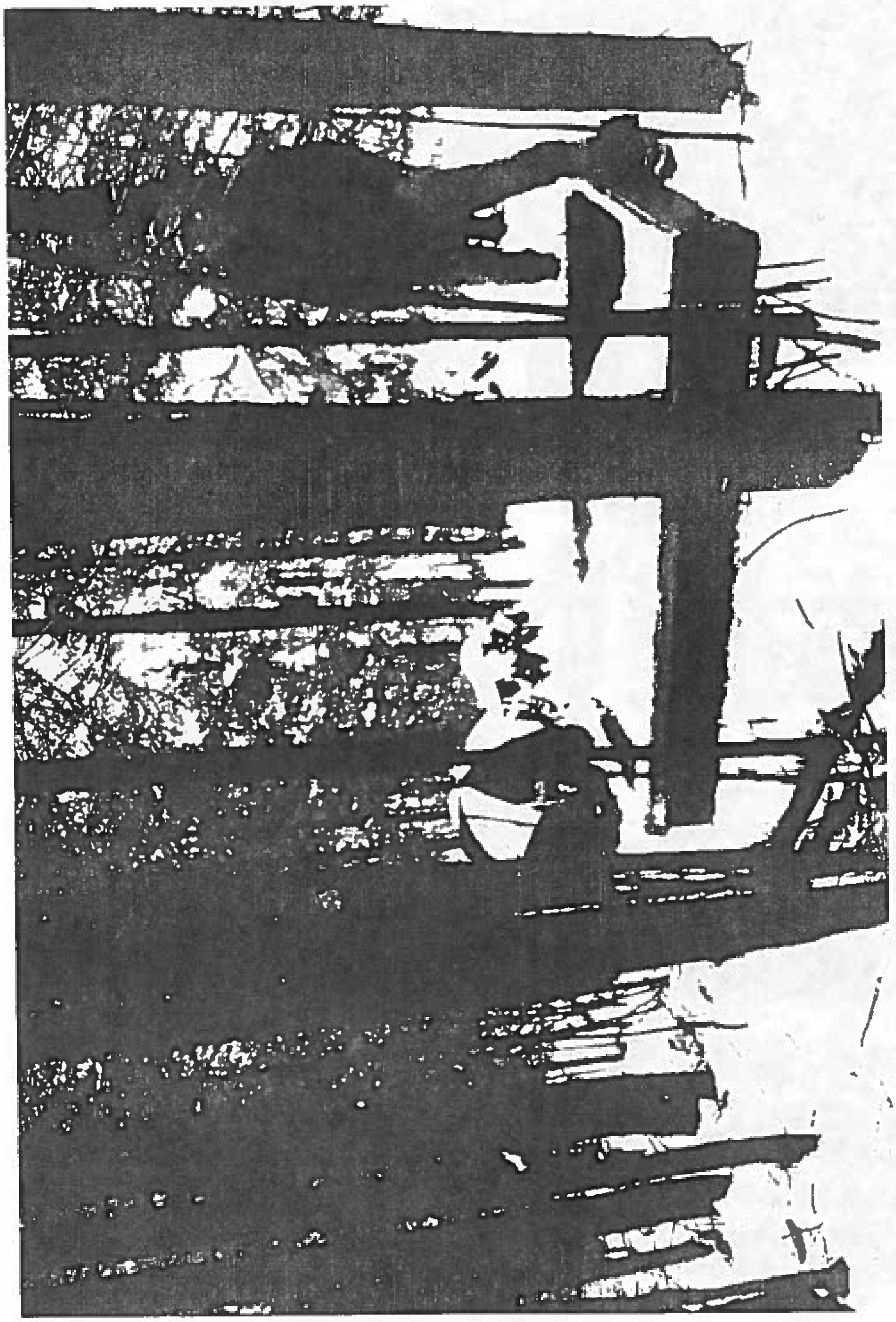

Figure 27. Plantation plot at Canyon Creek, 460-m elevation.

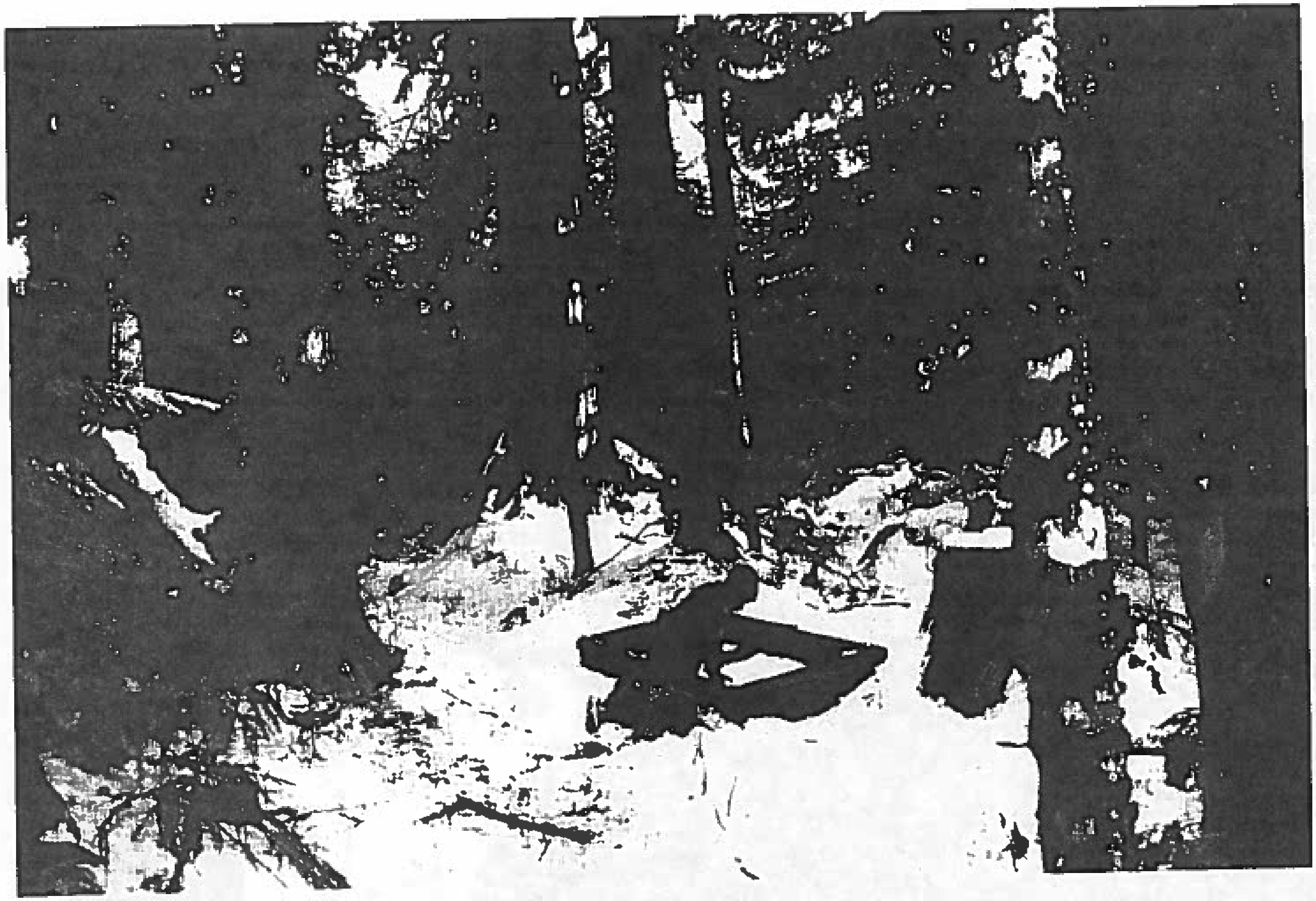

Figure 28. Forest plot at Finney Creek, 460-m elevation.

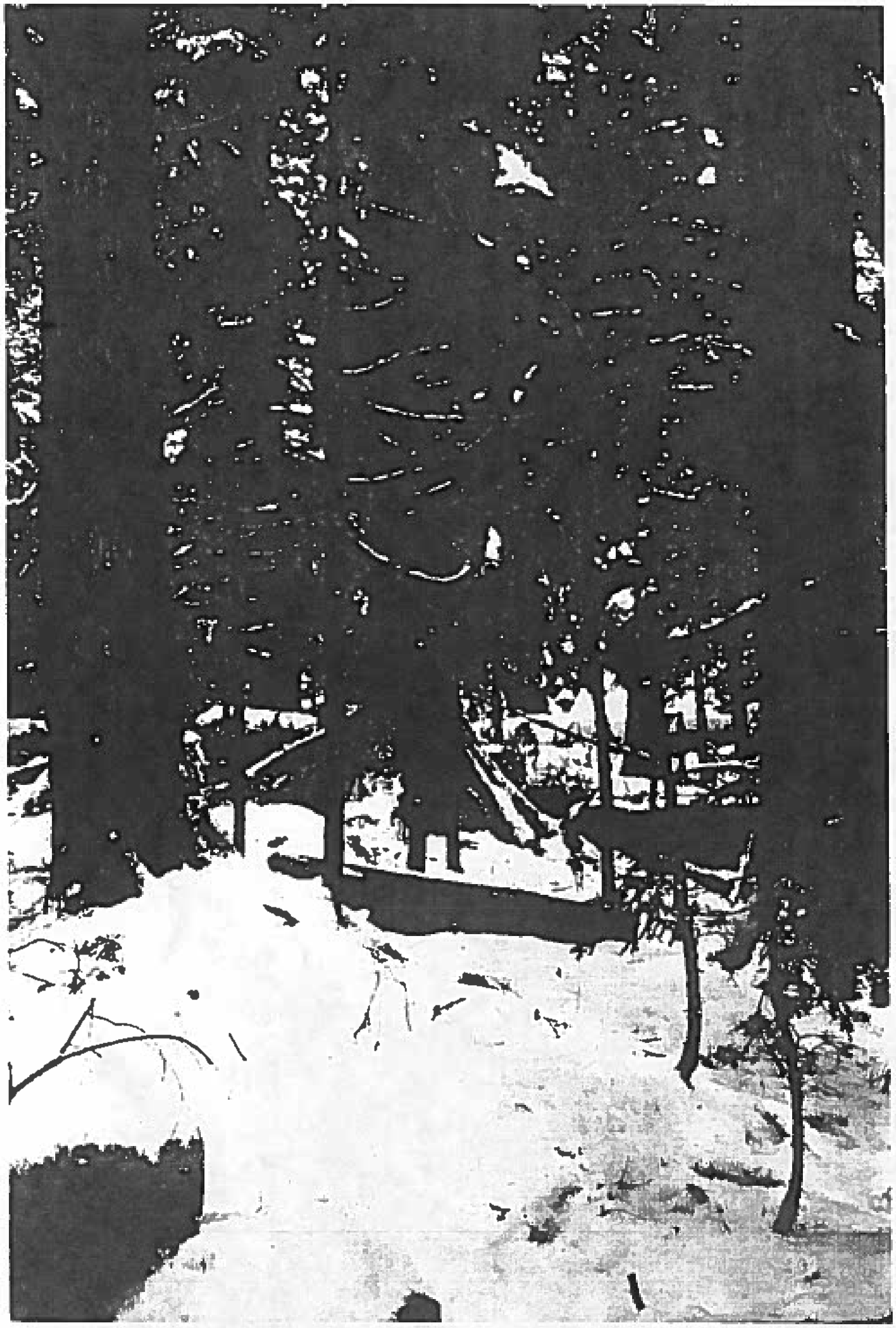

Figure 29. Forest plot at Canyon Creek, 610-m elevation.

Figure 30. Plantation plot at Canyon Creek, 610-m elevation.

Figure 31. View to the southwest, open plot, Finney Creek, 760-m elevation.

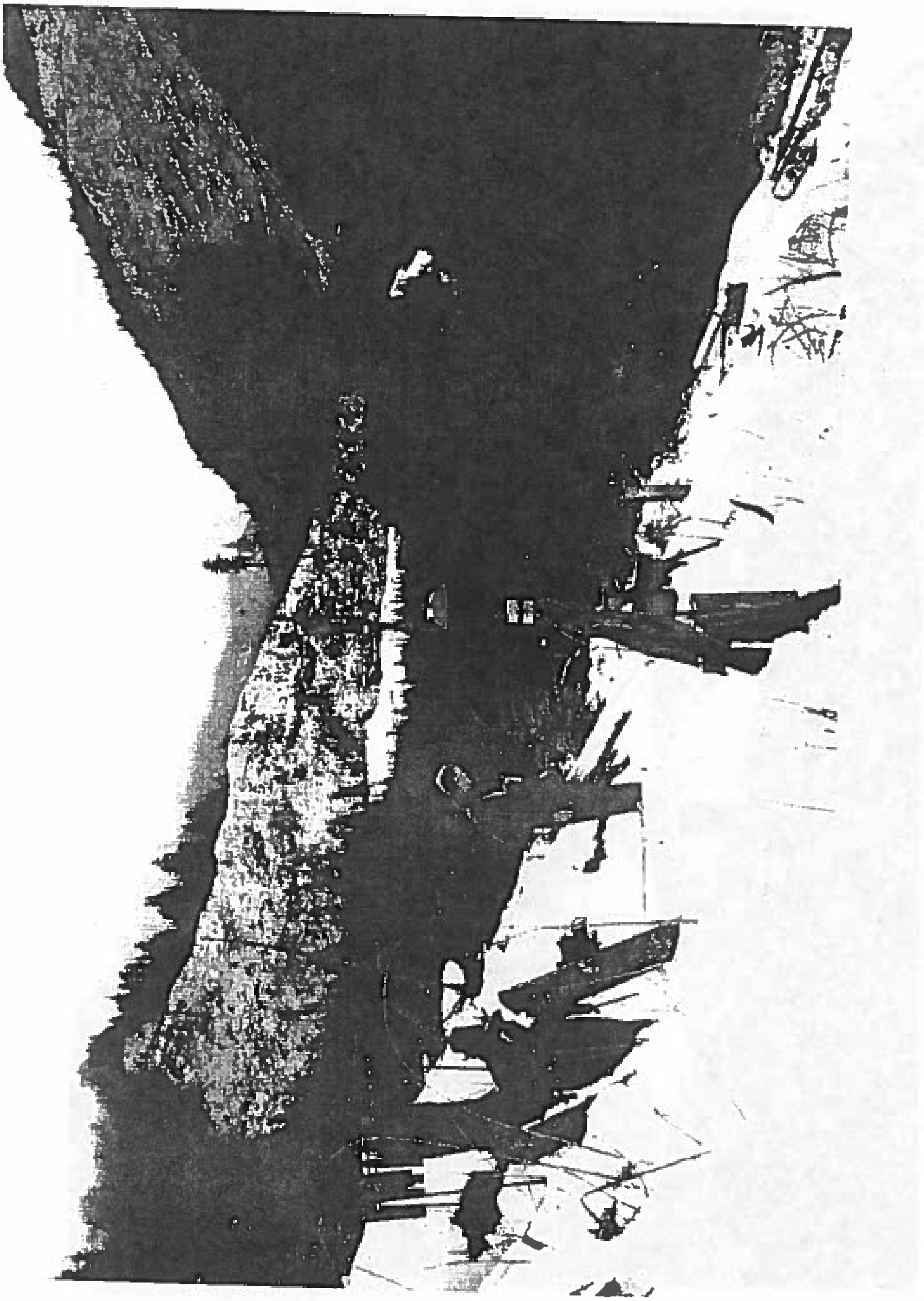

Figure 32. Open plot at Finney Creek, 460-m elevation.

Figure 33. Plantation plot at Canyon Creek, 760-m elevation.

Figure 34. Repairing the magnetic switch on the tipping bucket, plantation plot at Canyon Creek, 760-m elevation.

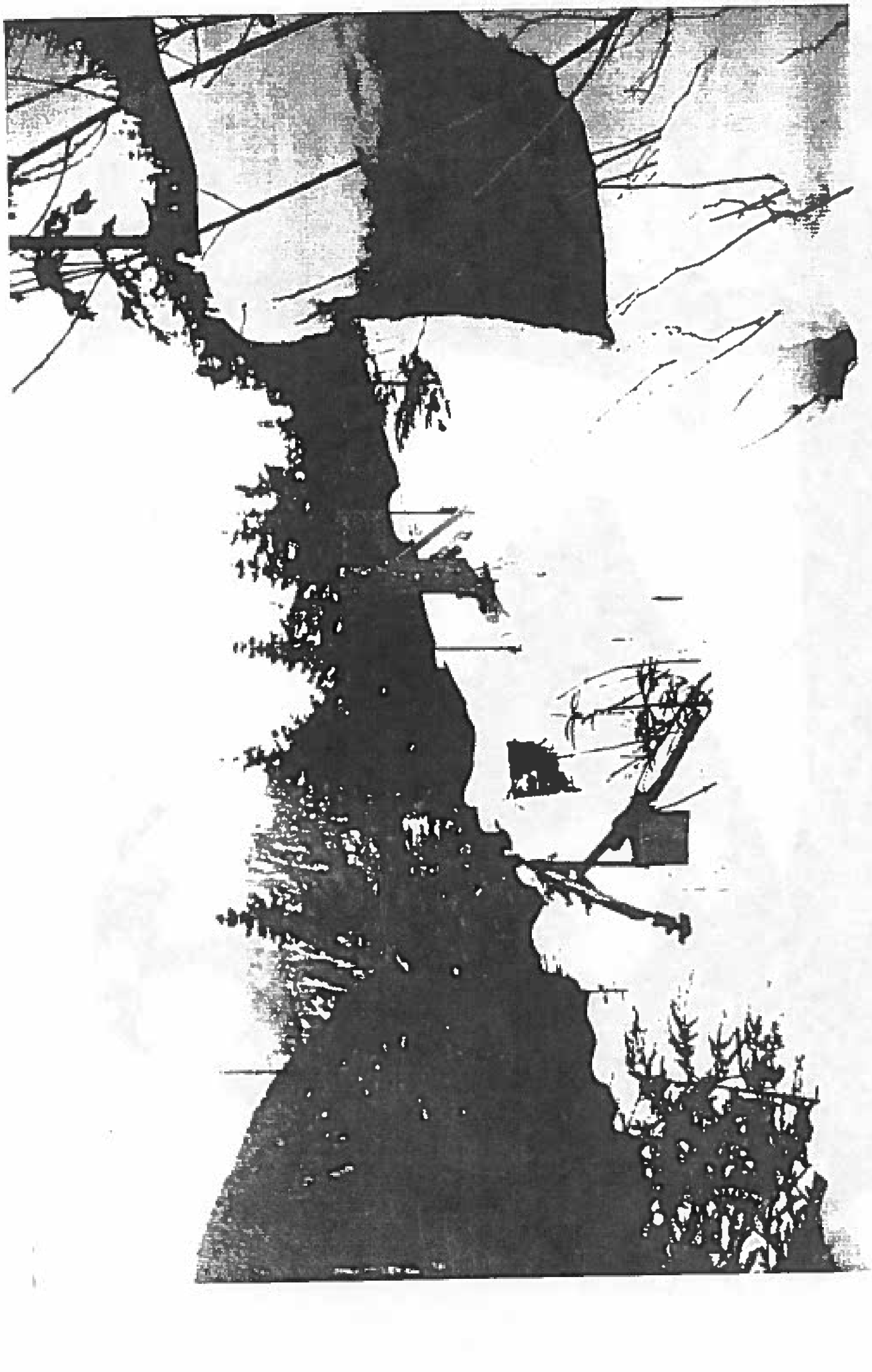

Figure 35. Open plot at Canyon Creek, 760-m elevation.