

IN FORESTED AND CLEARCUT PLOTS IN WESTERN OREGON

By

R. Dennis Harr^{1/} and Steven N. Berris^{2/}INTRODUCTION

Snowmelt during rainfall is an important hydrologic process in the mountains of the central west coast of North America. It has accounted for not only considerable downstream flooding in western Washington, western Oregon, and coastal British Columbia but also many instances of stream channel erosion and landslides (Harr, 1981). Initiation of both earthflows and debris avalanches and rate of movement of earthflows are influenced by internal hydraulics of soil masses which in turn are dependent on rate of water input from rainfall and snowmelt. Highest rates of water input to forested slopes have generally resulted from rapid melting of snow during rainfall.

Concern about the effects of clearcut logging on flooding in the Pacific Northwest led to numerous studies of the effects of logging and associated activities on runoff. But nearly all studies were designed to assess changes in watershed response to rainfall only; no provisions were made to measure snow accumulation and melt or the micrometeorological variables that influence melt (Harr and McCorison, 1979; Harr et al., 1982). Despite a report by Anderson and Hobba (1959) that the size of rain on snow and snowmelt peak flows of several large streams in western Oregon had been increased by logging, snow hydrology in this region has received little attention. Except for a snow accumulation-melt study by Rothacher (1965) and a comparative evaluation of peak flows caused by rain and rain-on-snow (Harr and McCorison, 1979), no snow hydrology research has been done west of the Cascade Range in Oregon and Washington since the studies conducted in the permanent snow zone by the United States Army Corps of Engineers (1956) in the late 1940's and early 1950's. Consequently, little is known about the effects of logging on the rain-on-snow environment of the Pacific Northwest.

Forest land managers from western British Columbia to northern California have become increasingly concerned about effects of timber harvest on snow accumulation and subsequent melt during rainfall. Using melt indices developed by the United States Army Corps of Engineers (1956) for snowmelt during cloudy, rainy weather, Harr (1981) illustrated the potential increase in snowmelt during rainfall and subsequent increases in total water input (rain plus snowmelt water) that may follow clearcut logging. According to these melt indices, total melt (M_t) in cm/24 h for a point in the forest can be estimated by

$$M_t = T_a (0.339 + 0.0126 P) + 0.23 \quad (1)$$

where T_a = average 24-h air temperature (0°C) and P = 24-h rainfall (cm). On the other hand, total melt for a point in the open is given by

$$M_t = T_a (0.133 + 0.086 u + 0.0126 P) + 0.23 \quad (2)$$

where u = mean 24-h windspeed (m/s) 15 m above the snow surface. (In heavily forested areas the United States Army Corps of Engineers (1956) considered windspeed so low under the forest canopy that an average speed of 2.4 m/s was assumed, thereby eliminating the wind variable in the melt equation.) If equation (2) is substituted for equation (1) when dense forest is cut, the difference in total melt would be due to increased air movement

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and the turbulent exchange of sensible and latent heats between warm, moist air and the snow surface. Thus, melt rate could be increased after removal of trees. A similar speculative analysis in western British Columbia led to proposed restrictions on rate of timber harvest in the transient snow zone to help protect anadromous fish habitat (Toews and Wilford, 1978). This heightened the logging-peak flow controversy in British Columbia and intensified rain-on-snow research in that province.

More recently, Christner and Harr (1982) described long-term changes in size of peak flows in large basins in western Oregon that appear related to rate of timber harvest in the transient snow zone. These authors believe that changes in flow relationships between two adjacent watersheds that have undergone different rates of harvest over several decades most likely reflect changes in accumulation and melt of snow in the transient snow zone.

This paper describes preliminary results of a study to determine differences in snow accumulation and subsequent melt during rainfall between a forested area and a clearcut area and to compare measured snowmelt lysimeter outflows with outflows predicted by energy balance analysis.

SNOWMELT DURING RAINFALL

Snowmelt in any environment may be described by

$$Q_m = K^* + L^* + H + \lambda E + G_b + F + G_s \quad (3)$$

where K^* = net shortwave radiation flux, L^* = net longwave radiation flux, H = convective transfer of sensible heat from the air, λE = convective transfer of latent heat from the air, G_b = soil heat flux, F = heat transfer by warm rain, G_s = rate of change of the heat content of the snowpack, and Q_m = the heat equivalent of snowmelt.

These sources of heat for melt vary considerably from region to region. For example, net shortwave radiation flux, a major source of heat for melt in most regions, is a minor source of heat for melt during rainfall in western Oregon. Contrary to what is implied by the phrase rain on snow, rainwater is not the largest single source of heat for snowmelt except when rainfall totals more than 7 cm in 24 h. According to the United States Army Corps of Engineers (1956) the turbulent transfer of combined sensible and latent heats from air to the snowpack constitute the greatest source of heat for melt.

THE STUDY

The study uses a pair of plots located at the 900-m elevation in the H. J. Andrews Experimental Forest near Blue River about 72 km east of Eugene, Oregon. One plot is located in a 22-ha area that was clearcut in 1981 and broadcast burned in 1982. The other plot is located in an adjacent forest stand of old-growth Douglas-fir and western hemlock trees 30 to 60 m tall located 100 m from the clearcut plot. The clearcut plot has a view to the south-southwest, the direction of prevailing winter winds, that is unobstructed by trees, whereas the forest plot is located 150 m from the windward edge of the forest. Both plots are on nearly level ground although surrounding slope gradients are as much as 80 percent.

Each plot contains a Campbell Scientific^{3/} CR-21 battery-operated microprocessor and recorder in a heated shelter. A heated, tipping bucket rain gage atop the shelter measures rainfall and snowfall. A buried tipping bucket measures rain and snowmelt water outflow from a lysimeter consisting of eight flat-vee, fibreglassed plywood pans each 0.25 m² in area; total area of each lysimeter is 2 m². Air temperature 1.75 m above ground and soil temperature at a depth of 1 cm are measured with Campbell Scientific Model 101 thermistors. Dewpoint temperature at 1.75 m is measured with a lithium chloride dew-point hygrometer (dewcel) (Holbo, 1981). Incoming and outgoing shortwave radiation are each

^{3/} The use of trade and company names is for the benefit of the reader. Such use does not constitute an official endorsement or approval of a product by the United States Department of Agriculture or Oregon State University to the exclusion of others that may be suitable.

measured with a LI-COR Model LI-2005 silicon pyranometer. Windspeed at 1.75 m is measured with a Weathertronics Model 2031 low-threshold, DC-generator, cup anemometer, and wind direction with a Weathertronics Model 2020 low-threshold wind vane. In addition, each plot is equipped with time-lapse photographic equipment that consists of a super 8 mm movie camera, a timer, and two quartz-halogen automobile auxiliary driving lights. Each plot with its staff gage and clock is photographed every 15 minutes.

The microprocessor scans all sensors every 10 seconds. It is programmed to record onto a cassette tape the mean windspeed and the standard deviation of windspeed every 5 minutes; the mean and the standard deviation of air temperature, dewpoint temperature, soil temperature, incoming and outgoing shortwave radiation, cumulative precipitation, and cumulative snowmelt lysimeter outflow every 60 minutes.

The study site is visited at least every 3 weeks to change batteries, cassette tapes, and movie film and to check sensors and recording equipment. When snow is present, the site is visited more often so that snow density, water equivalent, free water content, and snow temperature can be determined periodically throughout the pack's existence.

RESULTS

In this study, components of the energy balances of snowpacks melting during rainfall are determined from measurements of micrometeorological variables. The components of equation (1) are as follows:

$$K^* = K\downarrow - K\uparrow \quad (4)$$

$$L^* = \sigma(T_a^4 - T_s^4) \quad (5)$$

$$H = \rho_a C_a K_h (\partial T_a / \partial z) \quad (6)$$

$$\lambda E = (\rho_a \lambda \epsilon / p) K_e (\partial e / \partial z) \quad (7)$$

$$F = \rho_w C_w T_d P \quad (8)$$

where $K\downarrow$ = incoming shortwave radiation flux density (W/m^2)
 $K\uparrow$ = outgoing shortwave radiation flux density (W/m^2)
 σ = the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W/m^2 K^4$)
 T_a = air temperature ($^{\circ}K$)
 T_s = snow temperatures ($^{\circ}K$)
 H = sensible heat flux density (W/m^2)
 ρ_a = density of air ($1.29 kg/m^3$)
 C_a = specific heat of air ($1.005 kJ/kg ^{\circ}C$)
 K_h = eddy conductivity for heat (m^2/s)
 z = distance (m)
 λ = latent heat of vaporization of water ($2709 kJ/kg$)
 E = water vapor flux density ($kg/m^2 s$)
 ϵ = ratio of molecular weights of water and air (0.622)
 p = atmospheric pressure (kPa)
 K_e = eddy diffusivity for water vapor (m^2/s)
 e = vapor pressure of water in air (kPa)
 ρ_w = density of water ($10^3 kg/m^3$)
 C_w = specific heat of water ($4.218 kJ/kg ^{\circ}C$)
 T_d = air dewpoint temperature ($^{\circ}C$)
 P = amount of rainfall (m) falling in a given time interval.

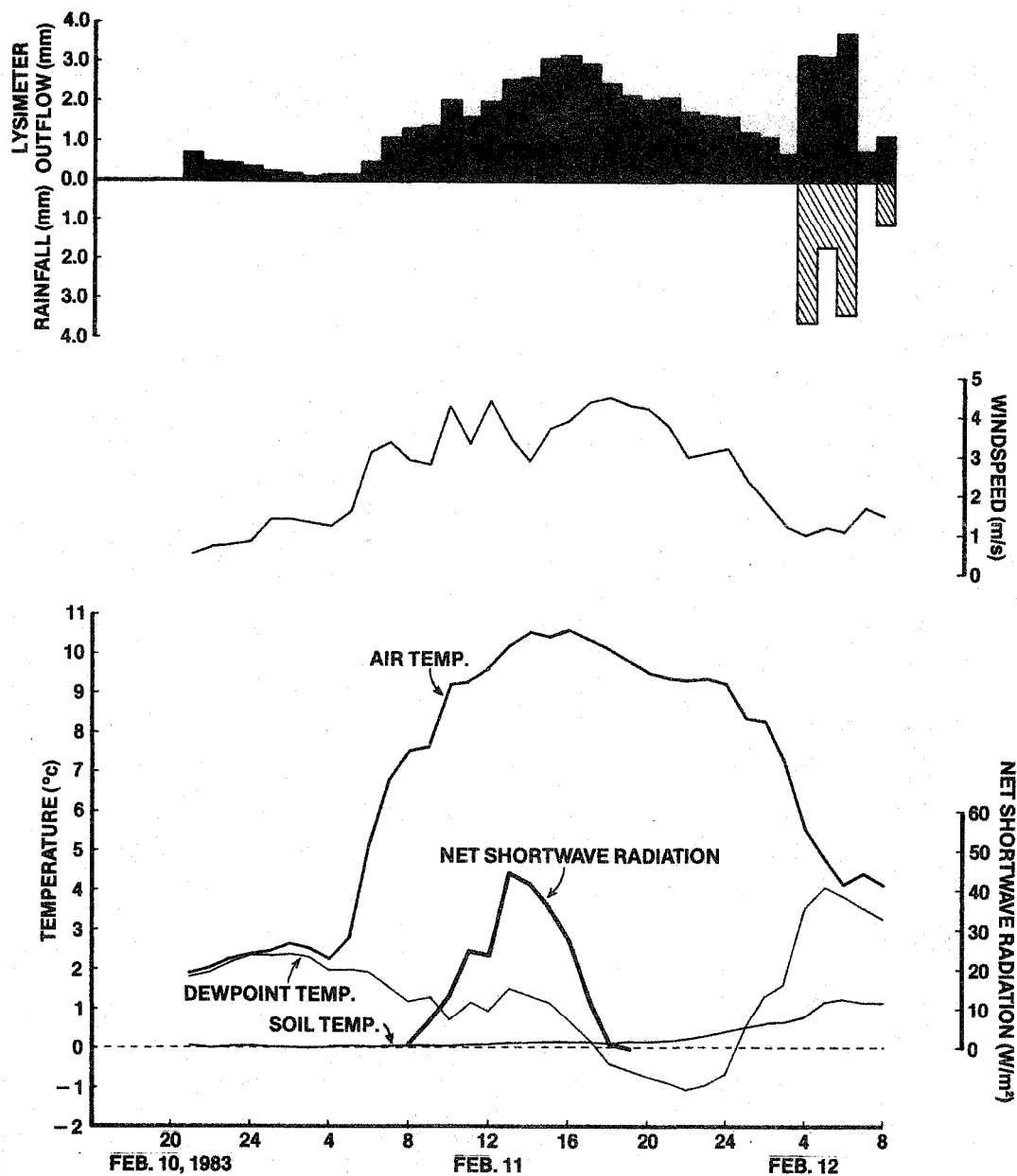
Equation (6) may be simplified by assuming air temperature gradient is approximated by $(T_a - T_s)/z$ where z is instrument height. If $T_s = 0^{\circ}C$, as it did throughout the melt period, air temperature gradient may be approximated by T_a/z . Similarly, in equation (7), water vapor pressure gradient may be approximated by $(e_a - e_s)/z$ where e_a is water vapor pressure of air at z and e_s is the water vapor pressure at a snowpack temperature of $0^{\circ}C$.

Since data collection began in mid-November, 16 snow accumulation-melt sequences have occurred. In only four instances, however, did a significant amount (depth of at least 100 mm) of snow accumulate in the clearcut plot, and only in those four instances did any snow accumulate in the forest plot. Snow was intercepted by the forest canopy and melted; it reached the forest floor primarily as water. At the time of maximum snow accumulation in the clearcut plot, what little snow was present in the forest was mainly restricted to the ground directly below spaces between individual tree crowns.

The melt event of February 10-12, 1983, is used to compare predicted and measured melts in the clearcut plot. Melt rates of the clearcut and the forest plots cannot be compared because of insufficient accumulation of snow in the forest.

Figure 1

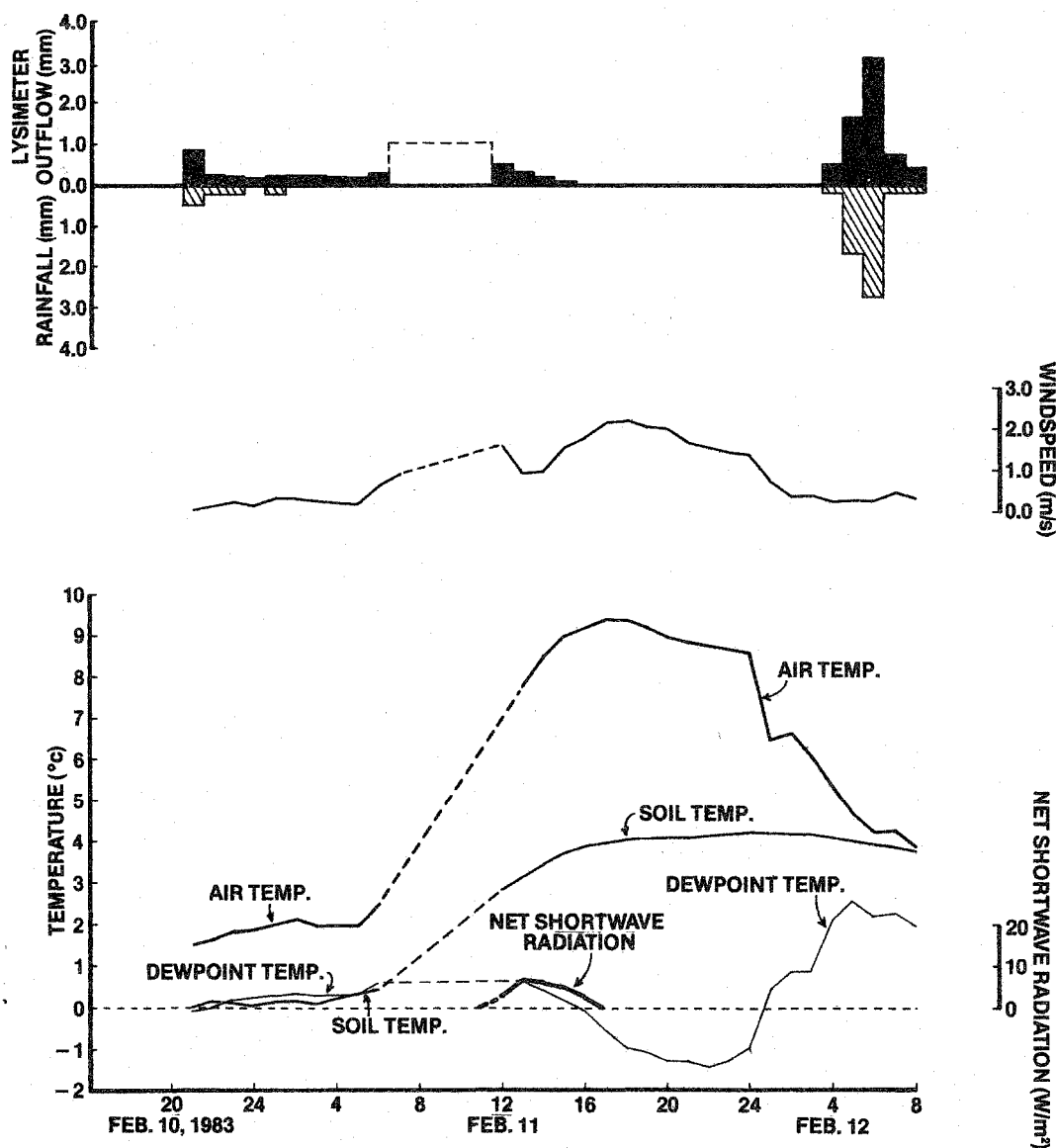
Micrometeorological conditions associated with snowmelt in the clearcut plot.



Following a series of snowfalls between February 5 and 9, snow depth at 1300 on February 10 was 130 mm in the clearcut and 0-30 mm in the forest. Density of the snowpack averaged 33 percent, and water equivalent was 43 mm. Free water content as determined by field calorimetry averaged 5 percent by volume. Similar measurements were not made in the forest plot because of a minimal accumulation of snow. Over the next 8 h, 16 mm of rain fell, but melt could not be measured because the lysimeter tipping bucket was not operating properly. By 0900 on February 11, depth of the snowpack in the clearcut plot had decreased to 110 mm and water equivalent to 36 mm, but the pack density was still 33 percent. Air temperature rose sharply after 0400 on February 11 and reached 10°C by early afternoon (Figure 1). Air temperature followed a similar trend in the forest (Figure 2). Dewpoint

Figure 2

Micrometeorological conditions associated with snowmelt in the forested plot.



temperature in the clearcut was close to air temperature during the first 8 h of melt but dropped as air temperature rose abruptly at 0600 on February 11. In the forest, dewpoint initially was about 2°C lower than air temperature in the forest but generally followed dewpoint temperature in the clearcut. Net shortwave radiation flux density was about 10 times greater in the clearcut than in the forest plot. In the clearcut plot, hourly mean windspeed was 0.5 m/s at the start of the 36-h melt period and ranged from 3.0 to 4.5 m/s most of the time air temperature was above 8°C. In the forest, hourly mean windspeed was about 0.2 m/s at the start and ranged from 1.0 to 2.0 m/s during the time that air temperature was above 8°C. There was no rainfall between 1930 on February 10 and 0300 on February 12. Meltwater ceased dripping from the forest canopy at 0100 on February 11. According to time-lapse photographs, snow did not disappear from the lysimeter pans in the clearcut until 0800 on February 12 but had disappeared from the forest pans by 1500 on February 11. All calculations and comparisons are made for the 36-h period beginning at 2000 on February 10 and ending at 0800 on February 12.

The break in the record at the forest plot on February 11 (Figure 2) is due to our leaving the microprocessor in its sensor-monitoring mode while we were repairing the air temperature sensor. Although the microprocessor was able to continue logging and processing incoming data, it was unable to record internally stored data on the cassette tape. Consequently, data for a 4-h period were lost. We estimated data for this period by simply connecting the plotted lines in Figure 2. Time-lapse photos indicate there was little snow left in the lysimeter pans; thus, we estimate that the rate of lysimeter outflow was about 1 mm/h during this 4-h period.

Net shortwave and longwave flux densities and the heat content of rain water were determined for the clearcut from equations (4), (5), and (8), respectively, by using hourly mean values of shortwave radiation, air temperature, dewpoint temperature, and hourly rainfall totals. Flux densities were time-integrated for the 36-h period and added to the computed heat content of rain water.

During the 36-h melt period, lysimeter outflow totaled 57 mm of which 10 mm was rainfall and 2 mm was free water. Converting the 45-mm difference, which represents primarily meltwater, to its heat equivalent yields 15 010 kJ/m² of which 4 225 kJ/m² resulted from net longwave radiation flux, 825 kJ/m² from net shortwave radiation flux, and 155 kJ/m² from rain (Table 1). The remaining 9 805 kJ/m² reflects combined sensible and latent heat transfers.

Table 1
Heat Content and Depths of Meltwater Produced

Source of heat	Heat content (kJ/m ²)	Meltwater depth (mm)
Longwave radiation (L*)	4 225	13
Shortwave radiation (K*)	825	2
Rain (F)	155	1
Sensible and latent heat (H + λE)	<u>9 805</u>	<u>29</u>
Total	15 010	45

Equations (6) and (7) contain transfer coefficients K_h and K_e whose values cannot yet be determined from the wind data in this study. (A cooperative study^{4/} with Oregon State University is attempting to estimate K_m , eddy viscosity for momentum, from

^{4/} Harr, R. Dennis and H. Richard Holbo, A Study of Indices of Turbulent Exchange of Energy in Clearcut and Forested Areas in the Transient Snow Zone of the Cascades of Western Oregon, Study No. 1653-79. On file at Forestry Sciences Laboratory, Corvallis, Oregon.

the mean and variance of windspeed over short time periods so that K_m as well as K_h and K_e might be indexed by data obtained with the type of inexpensive anemometers used in this study.) The average size of K_h and K_e for the 36-h period can be estimated from the 9 805 kJ/m² described above. If, according to Male and Granger (1979), K_e/K_m is approximately 0.5 and K_h/K_m is 0.9 for the type of stability conditions that probably existed during this melt period, the relative sizes of K_h and K_e can be estimated by equating the 9 805 kJ/m² to the sum of equations (6) and (7), and solving for K_m . Values of K_h and K_e then become 0.014 m²/s and 0.008 m²/s, respectively. Thus, about 90 percent of melt attributed to combined sensible and latent heat transfers resulted from sensible heat and about 10 percent from latent heat. In contrast, the United States Army Corps of Engineers (1956) found latent heat transfer averaged 78 percent of combined sensible and latent heat transfers during cloudy, rainy conditions. In our study, there was no rain during the period when air temperature and windspeed were highest. Consequently, dewpoint temperature was much lower than air temperature (Figure 1). When rainfall began at 0300 on February 12, dewpoint temperature had approached air temperature. Had rainfall occurred throughout February 11, dewpoint temperature would have been much higher, and latent heat transfer would have been greater.

PREDICTED AND MEASURED SELTS IN THE CLEARCUT PLOT

Because the melt indices developed by the United States Army Corps of Engineers (1956) form the basis for Harr's (1981) speculation about the potential effects of clearcut logging on rate of snowmelt during rainfall, melt predicted from these indices is compared with measured total melt and components of total melt estimated from micrometeorological data. As is evident in Table 2, melt predicted by the melt indices agrees well with melt measured in this study. Also, the proportions of melt resulting from the various sources of heat are similar. At least for the conditions of this one event, the indices for melt during rainfall estimated measured melt well.

COMPARISON OF TOTAL WATER INPUTS

The combined effects of removal of forest vegetation on total water input during the 36-h melt period are illustrated by a comparison of lysimeter outflows shown in Figures 1 and 2. Prior to 2100 on February 10, the forest had already routed most of its snow water equivalent and rainwater to the soil. During the 36-h melt period, slightly more than 1 mm of water from canopy drip of intercepted snow and 6 mm of melting residual snow in the lysimeter pans were added to 5 mm of rainfall for a total water input to soil of 12 mm. In contrast, the corresponding total for the clearcut plot was 57 mm.

Table 2

Comparison of Melt Predicted by United States Army
Corps of Engineers (1956) Melt Indices and Measured Melt

Source	Predicted melt		Measured melt	
	Depth (mm)	Percent	Depth (mm)	Percent
Longwave radiation	14	27	13	29
Shortwave radiation	3	6	2.5	5.5
Rain	1.5	3	0.5	1
Sensible and latent heats	33	63	29	64
Soil heat	0.5	1	--	--
Total	52	100	45	100

SUMMARY

In 16 snowfalls, there were large differences in snow accumulation between the forested and clearcut plots. Most snow was intercepted by the forest canopy and reached the forest floor as meltwater whereas snow in the clearcut accumulated on the soil surface. In the four instances when there was sufficient snow in the forest to measure, snow depth was 3-10 times greater in the clearcut, and water equivalent was at least three times greater in the clearcut. During a 36-h melt period, total water input to soil was 57 mm in the clearcut plot and 12 mm in the forest plot. Melt predicted by the United States Army Corps of Engineers (1956) agreed well with melt measured in this study. Preliminary energy balance and mass balance analyses indicate this study should be able to determine differences in snowmelt during rainfall between forest and clearcut plots if sufficient snow accumulates in the forest during future winters.

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