

by

Pierre Beaudry¹ and Douglas L. Golding¹INTRODUCTION

In the coastal mountains of British Columbia, Washington, and Oregon, where the snowpack can vary from nil at lower elevations to many meters depth at higher elevations, annual peak streamflows often occur in winter during heavy rains on a warm snowpack. The question has been raised by managers of fishery and forest resources as to whether snow melt rates during rain-on-snow events are greater on clearcut areas than in the uncut forest (Toews and Wilford, 1978). If so, should the rate of cut (i.e., the fraction of a watershed harvested on the first pass) be limited to no more than a specified fraction of the watershed area to protect fish habitat? Generally, the greater the rate of cut the cheaper is the per unit cost of logs, but the greater is the probability of significantly increased peak stream flow, erosion, and sedimentation.

The U.S. Army Corps of Engineers' (USACE) snowmelt equations suggest that clearcut logging could increase peak flows during rain-on-snow, largely due to higher snowmelt rates caused by increased transfer of turbulent energy and water vapor to the snow surface (USACE, 1956). This does not seem to hold under some conditions as shown by results of studies reported by Harr *et al.* (1975), Harr and McCorison (1979), Rothacher (1973), and Anderson (1970). However, there has been little research relating micro-meteorological and physiographic variables to snowmelt during rain-on-snow. Thus the effect of clearcutting on snowmelt, and ultimately on peak flow, during such conditions is unknown.

Numerous studies have described the energy balance of a melting snowpack (Gold and Williams, 1961), (Makkonnen *et al.*, 1981), (Male and Granger, 1978), (Hendrie and Price, 1979), (de la Casiniere, 1974) for a small, well instrumented site. The energy fluxes at a snow surface that must be considered in any study of the energy balance are the radiation exchange, the sensible and latent heat exchanges which result from turbulence in the boundary layer immediately above the snow surface, the ground heat flux, and the energy transfer resulting from rain-on-snow. The total available energy for melt is the sum of these energy fluxes plus a storage term which relates to the amount of energy necessary for the snowpack to become isothermal at 0°C, and to its liquid water deficiency. The greatest difficulty lies in estimating the turbulent fluxes especially in the forest. Very few papers have reported direct measurement of turbulent energy fluxes. Estimates based on aerodynamic formulae do not constitute direct measurements. A set of flux gradient equations used to describe the convective and sensible heat transfers provide a possible means of evaluation. Assuming a logarithmic wind profile over snow under neutral conditions investigators (Kraus, 1972; Priestly, 1959) have shown that Q_h and Q_e can be calculated for various conditions of stability from measured wind speed, air temperature, and humidity ratios taken at corresponding heights using the equations:

$$Q_h = -\rho C_p (K_h/K_m) k^2 (U_b - U_a) (\theta_b - \theta_a) / \ln^2(b/a) \quad (1)$$

$$Q_e = -\rho L_v (K_e/K_m) k^2 [(U_b - U_a)(q_b - q_a)] / [\ln^2(b/a)] \quad (2)$$

$$\theta_z = T_z + \Gamma z \quad (3)$$

In these expressions a and b denote measurement height, k is Von Karman's constant, C_p is the specific heat of air at constant pressure, L_v is the latent heat of vaporization for water and ρ is air density; K_h , K_e and K_m are transfer coefficients or eddy diffusivities for sensible heat, water vapor and momentum respectively; q is the humidity ratio, θ is potential temperature, U is wind speed, T is air temperature, and

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Γ is the adiabatic lapse rate. The ratios of the transfer coefficients, K_h/K_m and K_e/K_m are dependent on the stability of the atmosphere. For stable conditions it was suggested by Dyer and Hicks (1970) that the relationship $K_h/K_m = K_e/K_m = 1.0$ was representative. In general during cloudy days over a melting snow pack a stable atmosphere prevailed thus permitting use of the principle of similarity. However, as suggested by Federer and Leonard (1971), the turbulent transfer theory developed for a uniform surface may not hold under a forest canopy, thus rendering the use of the above equation inadequate for the forest site. Because little work has been done to evaluate turbulent exchanges of heat and water vapor under forest cover, the literature offers no reasonable substitute to the use of aerodynamic formulae. Therefore, in this study, the sites were instrumented with the intent of using the aerodynamic approach to evaluate the relative turbulent fluxes of heat and vapor between clearcut and forest.

The objectives of this study are (1) to compare the energy and water balances of a melting snowpack in a forested and in a clearcut site during rain-on-snow, and (2) to determine the usefulness of the USACE snowmelt equations during such events.

METHOD

Study site

The study is being carried out on Jamieson Creek Watershed in the Seymour River basin near Vancouver. This typically-maritime watershed extends from 300 m to 1300 m above sea level, has a southerly aspect, an average slope of 48% and an area of 3 km². Rainfall accounts for about 70% of the mean annual precipitation with the wettest months being October, November and December. Rainfall intensities rarely exceed 25 mm/hr but storms are generally of a long duration, sometimes lasting several days.

The forest on Jamieson Creek is composed entirely of mature and over-mature stands. Two biogeoclimatic zones are represented: Coastal Western Hemlock below 900 m elevation, consisting of Douglas-fir, western hemlock, western redcedar, sitka spruce, and Pacific silver fir, and Subalpine Mountain Hemlock above 900 m, consisting of mountain hemlock and Pacific silver fir.

The harvested study site is 150 m from the edge of a recent 16-ha clearcut at 730 m elevation with southwestern aspect and 36% slope. The forest site has similar aspect and slope and is 500 m from the clearcut and 300 m from the edge.

Instrumentation

Each site was equipped with instrumentation to determine the energy balance over the melting snowpack. The radiation component was evaluated directly by the use of Fritchen-type net radiometers, with a constant flow of dry nitrogen to prevent condensation on the inner surface of the dome. Three radiometers were placed in the forest and one in the open site at heights

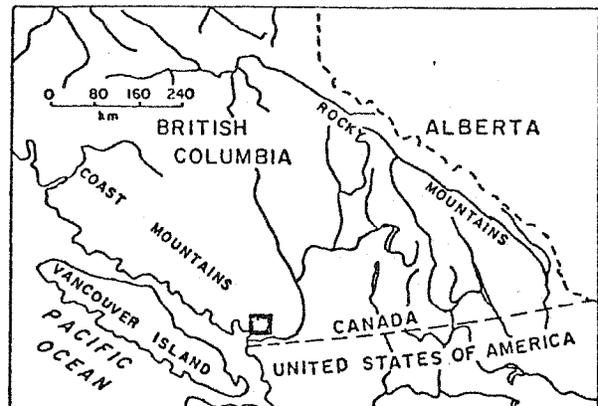


Figure 1. Location of Study Watershed (Cheng, 1975).

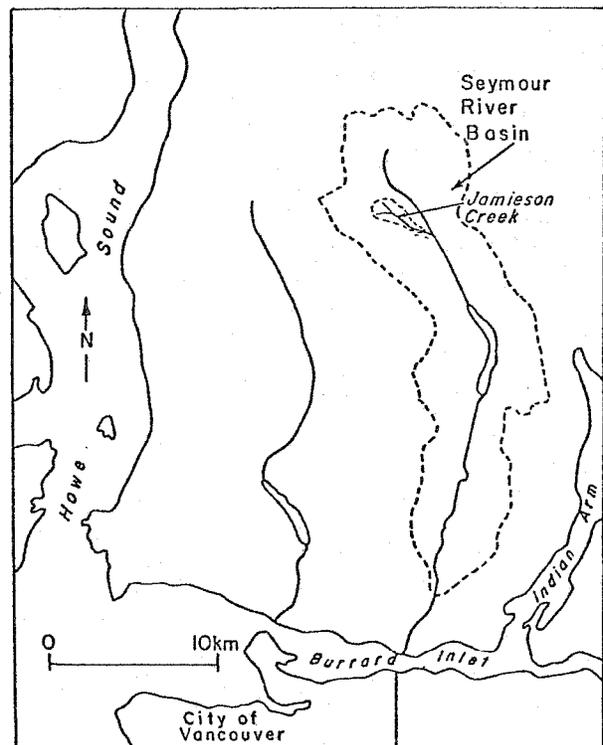


Figure 2. Seymour River Basin Showing Jamieson Creek Location (Cheng, 1975).

of 1.5 m above the snowpack parallel to the ground surface. A series of five Cambell Scientific model 101 thermistor probes were used to measure temperature at 5 and 10 cm below the ground surface, at the ground-snow interface, and at two levels in the snowpack. These temperature profiles served to estimate the ground energy available for melt and the cold content of the snowpack. Wind, air temperature, and relative humidity were measured at 60 cm and 150 cm above the snowpack at 1 minute intervals.

Although most of the instruments were not installed until the summer and fall of 1982, some preliminary snowmelt measurements had been made during the winter of 1981--82. The measurements consisted exclusively of air temperature and snowmelt lysimetry. Two small snow lysimeters, providing a total surface area of 0.9 m², had been installed in both the clearcut and forest. The 1981-82 winter saw a deep longlasting snow pack with very little precipitation falling as rain. However meltrates due to radiation were monitored and verified against a weekly snow survey. Results did not match: meltrates registered from the lysimeter were either much greater or much less than the direct snow survey measurements. It was hypothesized that due to drainage channels within the snowpack, as described in Smith (1974), the melt water was being routed either directly to or away from the small lysimeters. To overcome this problem, a much larger lysimeter was used the following winter, this being more representative and hopefully averaging out inconsistent meltwater routing. The large lysimeter is a 28 m² triangular-shaped tarpaulin of fiberglass-reinforced plastic. Runoff is fed into a 7.6-cm diameter pipe with the outflow being measured in a tipping-bucket arrangement. Instruments were connected to four Cambell Scientific CR-21 data loggers programmed to register samples, maximums, minimums and averages every 30 minutes. The data loggers along with the tape recorders required to store the data were housed in insulated Coleman coolers, heated with a propane heat exchanger and kept dry with silica gel. Snowpack depth, density, and water equivalent were measured weekly on a 30-point snow course in both the forest and clearcut, and precipitation was obtained from a recording precipitation gauge in the clearcut.

Three approaches were used to determine snowmelt rates: (1) the energy balance, (2) a water balance using snow lysimeters and precipitation data, and (3) a weekly snow survey.

RESULTS AND DISCUSSION

With only the first season's data available the objectives of the study have not been completely met although preliminary results have revealed some interesting relationships. Snowpack conditions this past winter (Table 1) were such that only a few rain-on-snow events occurred after instrumentation problems were overcome. Only those events that occurred when both clearcut and forest sites had significant snow cover were monitored.

The first major, rain-on-snow event monitored was that of 23 January, 1983. Three other events also met the criteria for analysis, 26 and 27 January, and the 10 February storm that caused the Alberta Creek disaster on British Columbia Highway No. 99 near Horseshoe Bay. For each event variables have been plotted showing the energy available at the snow surface and the resulting runoff (Figures 3-5). Snowmelt amounts from calculations using the Corps of Engineers' point snowmelt equations (USACE 1960) were compared to the lysimeter and snow survey results. Radiation melt was calculated directly from net radiation data. The equations used to calculate snow melt are the Corps of Engineers' equations (USACE 1956), transformed for metric input.

$$M_e = 0.957(Z_a - Z_b)^{-1/6}(e_a - e_s)U_b \quad (4)$$

$$M_h = 0.2007(p/p_o)(Z_a'Z_b)^{-1/6}(T_a - T_s)U_b \quad (5)$$

$$M_r = 0.001251 \text{ Tr} - \text{Pr} \quad (6)$$

where M_e , M_h , and M_r are condensation, convection, and rain melt (cm/day) respectively, e_a and e_s are vapor pressure of the air at height Z_a and snow-surface vapor pressure respectively (mb), T_a is air temperature (°C) at height Z_a (cm), T_s is snow-surface temperature (°C for melting snow), P and P_o are air pressure (mb) at the study site elevation and at sea level respectively, Pr is precipitation (mm), U is wind speed (m/sec) at height Z_b (cm). These equations were converted to give M_e , M_h , and M_r in

Table 1: evolution of the snowpack 1982-83 (elevation 730 metres)

DATES	OPEN			FOREST		
	DEPTH cm	W.E. cm	%SNOW COVER	DEPTH cm	W.E. cm	%SNOW COVER
18/11	20		100	16		100
23/11	42		100	17		100
25/11	25		100			50
30/11	30		100	15		50
07/12	15		100	PATCHY		0
14/12	28		100	PATCHY		0
23/12	88		100	34		100
04/01	114	28.32	100	46.7	10.6	100
11/01	91	28.8	100	50.4	13.7	100
19/01	72.3	21.6	100	24.3	7.39	80
25/01	66	21.3	100	25.2	7.20	70
01/02	57	18.5	100	PATCHY	5.5	40
08/02	53	18.8	100	PATCHY	-	15
10/02	88	-	100	33	-	90
12/02	63	-	100	PATCHY	-	50
16/02	61	22.0	100	PATCHY	-	25
22/02	62	22.0	100	PATCHY	-	10
01/03	57	20.0	95	PATCHY	-	0

Table 2: field observations on the effects of different micro-climatic conditions

CONDITION	OPEN	FOREST
1)SNOWING T° = -.5 TO 1.5° C VERY WET SNOW	-ACCUMULATION OF SNOW -NO RUNOFF	-SNOW TRAPPED IN CANOPY, FALLS THROUGH AS RAIN. -SOME RUNOFF
2)RAIN WHEN SNOW IN CANOPY T° > 1.5° C	-RAIN PRIMES SNOWPACK -RUNOFF MINIMAL	-RAIN ON WET WARM SNOWPACK -DRIP FROM CANOPY -RUNOFF GREATER IN FOREST
3)LIGHT RAIN NO SNOW IN CANOPY T° > 1.5° C	-RAIN RIPENS PACK OR GETS STORED AS FREE WATER DEPENDS ON SNOW QUALITY	-RAIN CAUGHT IN CANOPY=> EVAPORATION CANOPY DRIP
4)HEAVY CONSTANT RAIN NO SNOW IN CANOPY T° > 1.5° C	-DEEPER SNOW MORE STORED WATER -NO INTERCEPTION -GREATER AIR T° -RUNOFF IS IMPORTANT	-ABSENCE OF TURBULENT ENERGY -AIR T° LESS -W.E. LESS -CANOPY INTERCEPTION
5)SNOWING T° < .5° C	SNOWFALL IS STORED WATER COLDER SNOW, GREATER E DEFICIT	-SNOW STORED IN TREES TO BE : 1)EVAPORATION 2)CANOPY DRIP 3)FALL IN HEAVY BALLS

mm/half-hour, in keeping with our half-hourly data, and summed over the 48 half-hour periods to give mm/day. Vapor pressure of the air, e_a , was evaluated for each half hour using Teten's (1930) empirical formula

$$e' = (0.6108) \text{ antilog}_{10} [7.5 T_a / (T_a + 237.3)] \quad (7)$$

and the relationship

$$100 (e_a / e') = \text{R.H.} \quad (8)$$

where e' is saturated vapor pressure (kPa) at T_a and R.H. is relative humidity (%) at the study site.

Observations were made of the effects on the snowpack in the forest and in the open of five different micro-climatic conditions during a rain-on-snow event (Table 2).

Event 1: 22-25 January, 1983 (Figure 3)

On 19 January snowpack water equivalent (w.e.) in the open site was 216 mm (Table 1), evaporation from the pack between 19 and 23 January was calculated at 9.6 mm using Corps of Engineers' equations (USACE 1960), leaving 206.4 mm on 22 January. The afternoon of 23 January saw a 9.4 mm w.e. snowfall (Figure 3) resulting in a snowpack of 215.8 mm w.e. at the onset of rain at 0200 hr, 24 January.

The first step in the analysis of the 24 January rain-on-snow was calculation of the total liquid water requirements of the snowpack (S_p) for the open site as described by USACE (1960). S_p is the sum of the cold content of the snowpack (W_c) and the liquid water deficiency (S_f), both in mm of liquid water. Because the entire snowpack was very close to 0°C, W_c was zero so that S_p equalled S_f and was calculated as 6.6 mm of liquid water. The interpretation is that it would take 6.6 mm of rain or its equivalent in total melt energy before the pack would release any water. The rain of 38.5 mm on 24 January at the open site minus S_p of 6.6 mm is the amount of water released by the pack, 32.0 mm. Measured lysimeter runoff, 24.9 mm, minus water released by the pack, 32.0 mm, should give the amount of melt. In this case a negative value of 7.1 mm is obtained due to routing of rain and melt water over observed ice lenses in the pack to the outside of the lysimeter. As the ice lenses melted, melt water was routed through the lysimeter giving a more accurate measure of melt, as shown for the latter half of 24 January (Figure 3).

The energy balance for the 61 half-hour periods from 1750 hr, 23 January, to 2400 hr, 24 January, indicates that there was sufficient energy available to melt 3.3 mm w.e. of snow. A small amount of this energy would have been used to satisfy the liquid water requirement, S_p , before this had been completely satisfied by rain. This was estimated at 0.3 mm, the remaining energy being sufficient to melt 3.0 mm w.e.

Melt estimated by the three methods is summarised as follows:

snow survey: 215.8 mm - 213.0 mm = 2.8 mm

lysimeter: -7.1 mm (affected by ice lenses)

energy balance: 3.0 mm

These estimates suggest that the rain-on-snow event of 24 January satisfied the liquid water requirement of the snowpack and should have produced about 3.0 mm of snow melt.

It was deemed unfeasible to use the energy balance approach for the forest site. Because no wind was recorded at the forest site, M_e and M_h were zero according to equations 4 and 5. Because of great variability of precipitation beneath the canopy this variable was not measured on the forest site, this preventing an estimate of M_r . Even though melt at the forest site cannot be accurately evaluated quantitatively, the lysimeter record reveals some interesting relationships.

On 19 January the forest snow survey indicated a snowpack of 74 mm w.e. Between

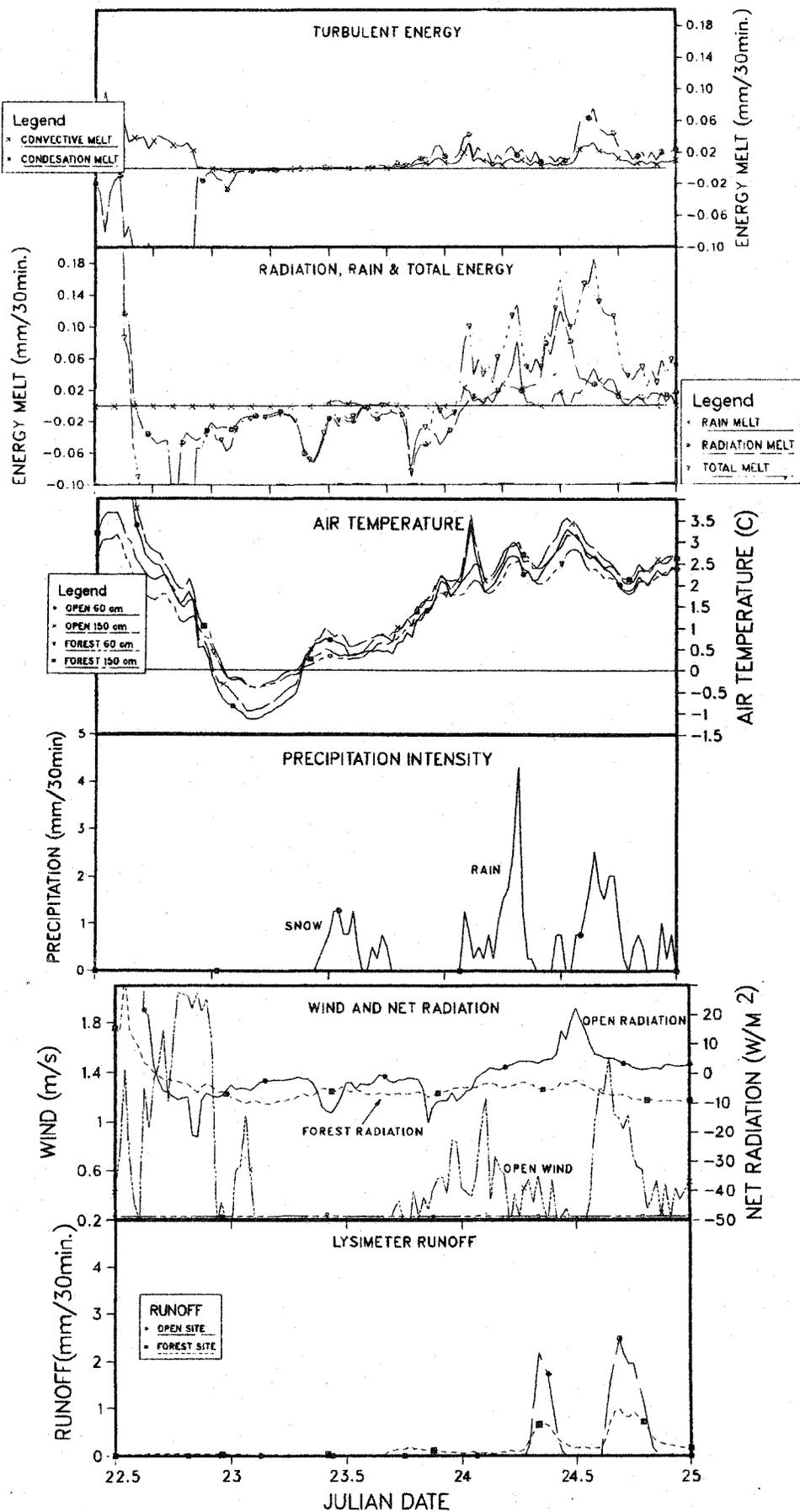


Figure 3. Calculated Energy Balance and Measured Variables, 22-25 January, 1983.

19 and 23 January snowpack evaporation occurred due to the mild, sunny weather. This amount can only be estimated in a crude way by taking a fraction of that calculated for the open site. In this case one-third of that in the open was assumed for the forest, or 3.3 mm. The 9.4 mm w.e. that was recorded in the open on 23 January fell on the canopy where a portion was trapped by branches. Such intercepted snow leaves the canopy by three routes: (1) evaporation by turbulent energy present at the top of the canopy, (2) melt and subsequent canopy drip (3) dropping to the ground as clumps of dense, wet snow. A portion of the liquid water released from the canopy may be routed along branches and down the trunk of the tree. Such stem flow does not reach the snowpack on the lysimeter because there are no trees within the lysimeter borders, although the canopy does overhang the lysimeter. This may account for some of the difference between precipitation recorded in the open and runoff recorded in the forest. In this case evaporation may be assumed to be negligible. However, canopy drip may have played an important role.

Only the forest lysimeter recorded any runoff on the afternoon of 23 January, indicating that canopy drip was taking place (condition 2, Table 2). During this event, the absence of turbulent energy and near-zero radiation at the snow surface in the forest suggest that runoff was only displacement of transient water storage after liquid water requirements ($S_p = 2$ mm) were satisfied. The w.e. of the snowpack after the 23 January input of snow can be estimated as:

$$(19 \text{ January snowpack, } 74 \text{ mm}) - (\text{evaporation, } 3.3 \text{ mm}) \\ - (S_p, 2 \text{ mm}) + (\text{snow input}) - (\text{lysimeter runoff, } 2.7 \text{ mm}).$$

The amount of snow input is crudely estimated, considering the factors discussed above, as 75% of the 9.4 mm w.e. recorded in the open, or 7.0 mm. Thus the snowpack in the forest at the onset of rain on 24 January was 73 mm. During this rain event the snow survey registered a snow w.e. in the forest of 72 mm, 1 mm less than when the rain began, or one-third of the 3 mm loss from the open snowpack (Table 1). This seems reasonable considering that the only energy available for melt in the forest is that supplied by the heat of rain. The lysimeters show 25% less runoff from the forest than from the open, attributable to the smaller amount of melt coupled with interception loss from the canopy and loss of stem flow.

Event 2: 25-28 January, 1983 (Figure 4)

During this period two main rain-on-snow events occurred, one of 15 hr duration with 30.4 mm of rain and the other of 17 hr with 40.6 mm of rain. This sequence of events is a good example of the field observations described as condition 4, Table 2. The initial snow w.e. for the open site was 213 mm (Table 1), with the liquid water requirements having been satisfied by the previous days' rain. All precipitation must have fallen as rain because air temperature remained well above 1.5°C for the duration of both events (Figure 4).

The energy balance (Figure 4) for the open site shows significant available energy, primarily in the condensation and radiative forms. For the 60-hour period, M_h , M_e , M_r , and M_{rn} (where M_{rn} is melt due to net radiation) are 1.8, 4.1, 1.8, and 5.6 mm w.e. of melt respectively, for a total of 13.3 mm. The first rain event gives melt of 8.5 mm from the calculation of lysimeter runoff (38.9 mm) minus rain (30.4 mm), and 5.8 mm from the energy balance calculations. The second event gives melt of 5.9 mm and 7.5 mm for lysimeter and energy balance computations respectively.

On 25 January the w.e. of the snowpack in the open was 213 mm; five days later it had diminished to 185 mm (Table 1), for a loss of 28 mm. Reducing this by the amount of evaporation calculated for the period 28-31 January, 8.0 mm, indicates 20.0 mm of melt.

For the 60-hour period the melt in the open was estimated as

snow survey: 20.0 mm

lysimeter: 15.0 mm

energy balance: 13.3 mm

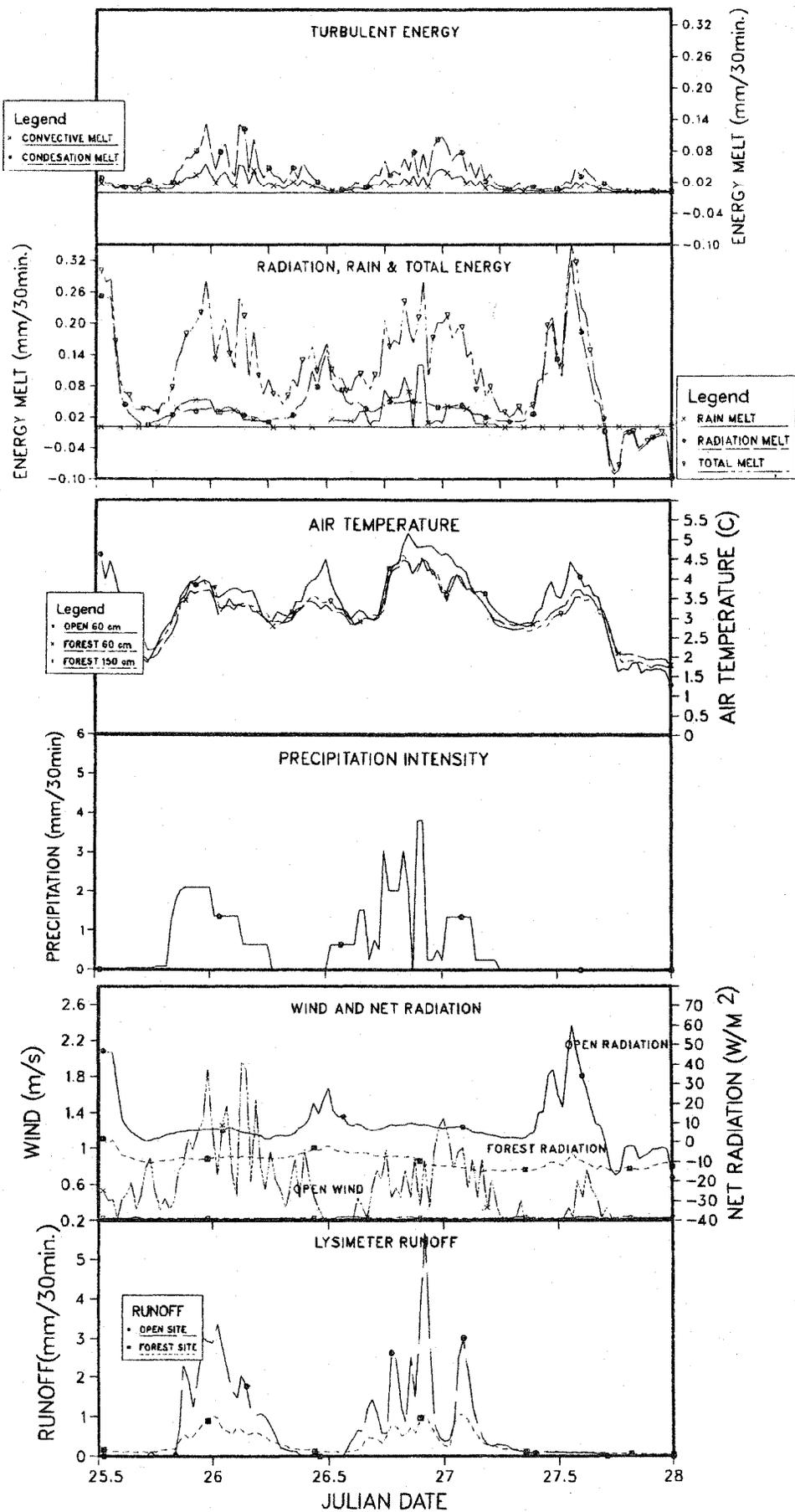


Figure 4. Calculated Energy Balance and Measured Variables, 25-28 January, 1983.

These results agree reasonably well considering the accuracy of both the snow survey on a shallow pack and the lysimeter arrangement.

It is interesting to note the close relation between the energy components and the actual melting of a "primed" snowpack as shown for mid-day 25 January (Figure 4). During this period rain ceased at 0600 hr, although the lysimeter continued to record runoff until the available energy became negative at 1800 hr.

Runoff from the forest for the 60-hr period is only 44% of that recorded by the lysimeter in the open. As explained previously, it is difficult to quantitatively analyse the energy balance and snowpack water balance in the forest. The 1 February snow survey in the forest is less accurate than usual because the pack had become discontinuous (Table 1). However, the evidence of snowmelt in the forest is indicated by the loss of about 30% of the snow cover on the lysimeter. The only quantitative values available are from the lysimeter, which show distinctly less runoff from the forest than from the open (Figure 4). The absence of turbulent energy, the almost zero net radiation, and the lower temperatures in the forest during both events in this period support the conclusion indicated by the lysimeter data, that of lower melt.

Event 3: 9-12 February, 1983 (Figure 5)

From 9 to 10 February, 40 mm w.e. of wet snow fell on the study site followed by increases in air temperature of 6°C and a two-day total rainfall of 194 mm. Concurrently a major flood occurred on Alberta Creek, in general vicinity of the study site, causing two deaths, the destruction of a highway bridge and many thousands of dollars of property damage. These events put into perspective the importance of problems associated with rain-on-snow events.

Unfortunately the lysimeter data for this time period are not reliable; both sites showed much less runoff than occurred. The open lysimeter developed a leak around the orifice of the outflow pipe, whereas twigs and needles that had collected on the snow during January were partially obstructing the free flow of water from the forest lysimeter. However, some very useful observations were made during the three site visits of this period, and the energy balance computations offer some interesting results.

After a prolonged wet snowfall, runoff has been frequently observed to be greater under the forest canopy than in the open site. The warm snow that gets trapped in the branches has no liquid requirement or cold content to be satisfied and any positive energy input will result in canopy drip. An excellent example of such an event is the night of 9 February to the afternoon of 10 February (Figure 5). Although the open site computations show no available energy for melt, it can be reasonably assumed that there was greater turbulent energy at the top of the canopy where the snow was caught. The available net radiation was in all likelihood greater than indicated by the instruments, as snow had accumulated on the domes filtering out a portion of shortwave energy. It should be noted that the sudden increase of net radiation at mid-day 10 January in the open is due to the removal of this snow from the radiometer domes.

The fact that the freshly fallen snow melted quickly in the forest, whereas it accumulated in the clearcut has some important consequences. When the intense rains started in the late afternoon of 10 February, a significant amount of the recent snowfall in the forest had already melted, thus giving a more even runoff distribution. However in the clearcut site, due to lack of available energy, very little melt occurred before the onset of the rains. This is the type of situation where it can be easily argued that extensive clearcutting may have negative effects by increasing peak flows.

The two previous analyses have suggested that our use of the Corps of Engineers' equations in determining the energy balance is valid. On this basis, results from a similar analysis of this event should provide useful information. A significant increase in total available energy occurred very early on 11 February in the open, with about two-thirds of the total energy supplied by transferred heat from rain and condensation. The period of maximum available energy, between midnight 10 February and midnight 11 February, theoretically melted 11.6 mm w.e. and saw a total rainfall of 118 mm. The cumulative runoff (snowmelt & rain) for the 24 hr would thus be 129.6 mm, an increase of 10% over the runoff that the precipitation alone would have produced. It

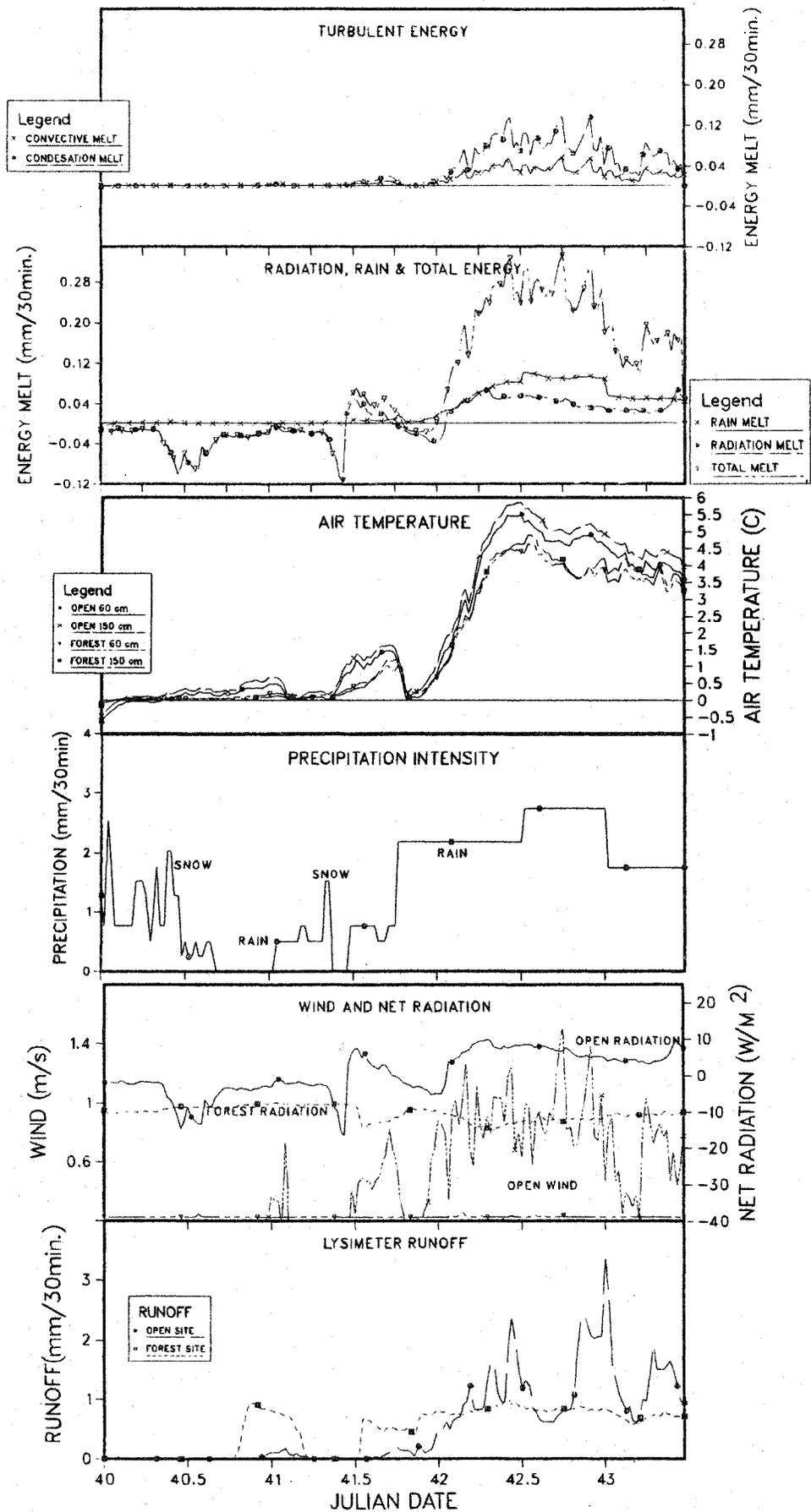


Figure 5. Calculated Energy Balance and Measured Variables, 9-12 February, 1983.

is important to recall that these results are for a small clearcut (16 ha) where wind speeds above snow surface were generally less than 2 m/sec.

The forest site experienced less runoff because of the absence of turbulent energy and also because of a lack of snow on the lysimeter. By February 12 many bare patches had begun to appear and the lysimeter had only a 50% cover of snow (Table 1). Unfortunately because of the lysimeter problems it is impossible to determine quantitatively the increase in total runoff that occurred due to the forest harvesting. It is clear however that a larger clearcut, where wind speeds and consequently turbulent energy would be greater, would cause higher melt rates.

SUMMARY

The energy balance over a melting snowpack in a 16-ha clearcut was determined with the U.S. Corps of Engineers point source melt equations for three rain-on-snow events during the winter of 1983. The results compared favorably with snow survey and lysimeter data. However, use of the equations was deemed infeasible for a second study site in an oldgrowth Coastal Western Hemlock forest because of the variability of precipitation under the canopy and the absence of wind.

One of the storms, that of 10 February, produced 194 mm of rain in one-and-a-half days. During that storm, snowmelt along with the rain increased the runoff rate from the lysimeter by only 10% over that which would have resulted from the rain alone. Runoff rates from the lysimeter were increased by 8% and 19% by snowmelt for the other two rain-on-snow events.

Runoff rates during the rain-on-snow events were generally less from the forest than from the open although the amount of the difference could not be assessed quantitatively.

Further research should include replication of forest plots to account for the variability of wind, net radiation, and precipitation intensity under the canopy. Ultimately, such studies should produce watershed management guidelines for rate of cut that are based on knowledge of the interactions between forest and the physical processes of melt during rain-on-snow.

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