RADIATION AND SNOWMELT ON A CLEARCUT WATERSHED

C. A. Federer
Meteorologist
Northeastern Forest Experiment Station
Forest Service, U. S. Dep. Agriculture
Durham, New Hampshire

ABSTRACT

Daily snowmelt on a clearcut watershed in central New Hampshire was estimated by using the energy balance. In melt periods, net solar radiation provided sufficient energy for melt and a small amount of evaporation; heat gain by convection was about equal to loss by net longwave radiation. Great spatial variation in slash density caused corresponding variation in net radiation and snowmelt.

At present, predicting the effects of various forest treatments on the timing of snowmelt runoff in the northeastern United States is practically impossible. The problem stems partly from lack of quantitative knowledge about the physical factors influencing snowmelt rates--especially under the second-growth hardwood forests that cover 45 percent of the land area.

The U. S. Forest Service is studying snowmelt under hardwoods on the Hubbard Brook Experimental Forest in New Hampshire. Snow cover at Hubbard Brook is continuous from December through April, and average peak snow water content is about 9 inches. The goal of these studies is to determine the efficiency of various forest treatments in reducing flooding from snowmelt runoff.

In December 1965, Hubbard Brook Watershed 2 was clearcut to determine the maximum increase in water yield when transpiration is eliminated and to determine the maximum speedup of snowmelt obtained by forest cutting (Hart, 1966). This report presents an initial analysis of the factors influencing snowmelt on this clearcut watershed.

DESCRIPTION OF AREA

The Hubbard Brook Experimental Forest is located near West Thornton, N.H., in the southwestern corner of the White Mountains. Nearly all the Forest is covered by second-growth northern hardwoods about 60 years old and 40 to 70 feet in height. Watershed 2, one of eight small gaged watersheds on the Forest, is a 38.6-acre area that faces south-southeast and has a slope of about 19 degrees. Its elevation ranges from about 1,650 to 2,350 feet.

The clearcutting operation consisted of cutting all woody vegetation and leaving it where it fell. The slash was lopped until it was no higher than 3 feet above the ground. Slash density varies from areas of no slash to areas where walking is almost impossible. Figure 1 shows the appearance of the watershed in winter.

Figure 1.--View of Hubbard Brook Watershed 2.

CUMULATIVE SNOWMELT RUNOFF

Figures 2 and 3 show differences in the timing of snowmelt runoff by plotting cumulative streamflow from Hubbard Brook Watersheds 1, 2, and 7 for the period March 1 to May 31 of 1966 and 1967. Arrows mark the approximate time snow cover disappeared from each watershed. Watershed 1 is an uncut area of 29.2 acres adjacent to and very similar to Watershed 2. Watersheds 1 and 2 had the same behavior before No. 2 was clearcut. Watershed 7, uncut, is a north-facing watershed of 191.2 acres having a slope of about 12 degrees. Its elevation ranges from 2,000 to 2,900 feet.

In 1966 Watersheds 1 and 2 had two distinct periods of high snowmelt runoff, centering around March 22 and April 13, while in 1967 most of the snowmelt runoff occurred in one short period around April 1. Differences between the clearcut and uncut watersheds were emphasized in 1966 by the long cold spell between the two melt periods. Cumulative streamflow by the end of March was about 25 percent higher from the clearcut area. In 1967 rapid snowmelt caused nearly complete disappearance of snow from both watersheds simultaneously and streamflow differences were minimized. Clearcutting the south-facing watershed apparently advanced snowmelt runoff only 3 to 6 days, as determined by the date on which 50 percent of the spring runoff had passed. This was in sharp contrast to a difference of 15 to 20 days between untreated north- and south-facing watersheds. Quantitative explanation of these differences and prediction of the effect of clearcutting a north-facing watershed are questions that cannot yet be answered.

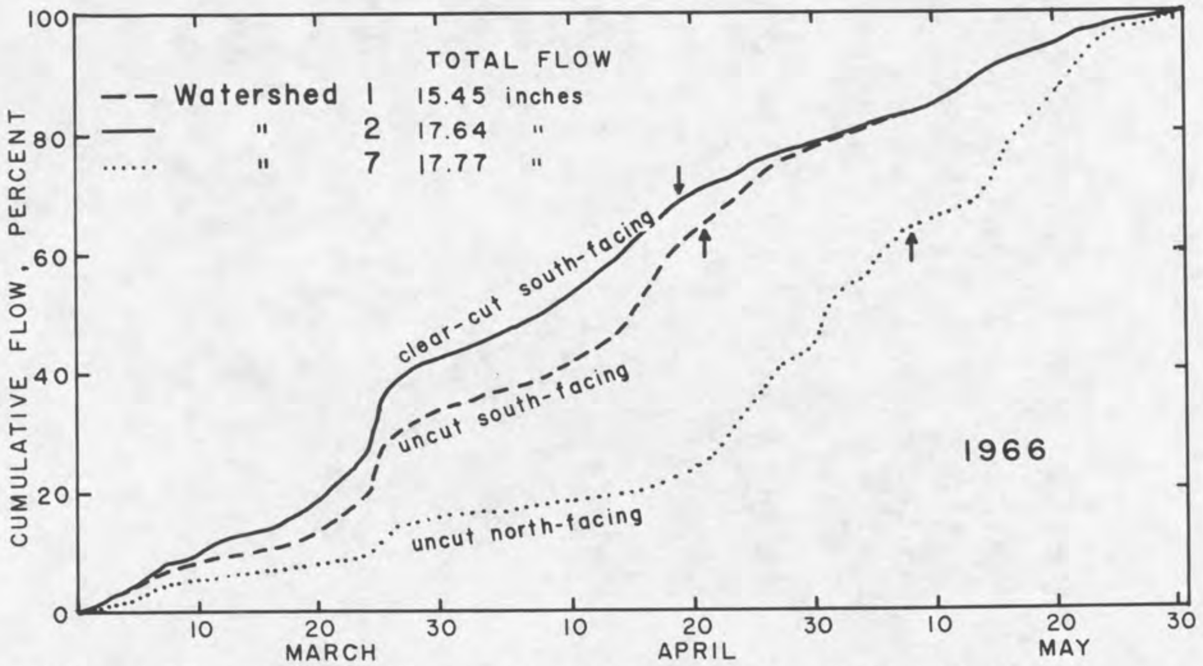


Figure 2.--Cumulative snowmelt runoff, Hubbard Brook Watersheds 1, 2, 7 for 1966. Arrows show approximate times of snow disappearance.

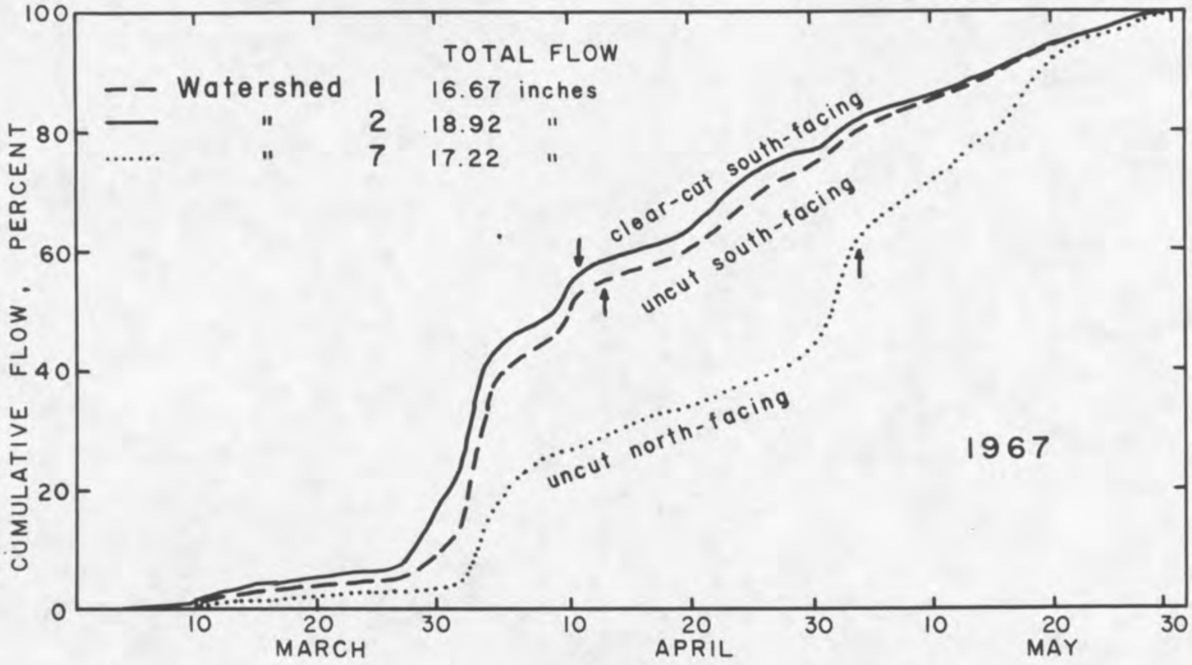


Figure 3.--Cumulative snowmelt runoff, Hubbard Brook Watersheds 1, 2, 7 for 1967. Arrows show approximate times of snow disappearance.

SNOWMELT ENERGY BALANCE ON WATERSHED 2

To understand the factors influencing snowmelt, we must use the energy balance approach. Eighty calories of heat are required to convert 1 gram of ice or snow into liquid water. The five possible sources of this energy are: radiation, condensation, convection, soil heat, and rain. Much important work on these factors is summarized in Snow Hydrology (U.S. Army, 1956), which is the fundamental reference on this subject. I have tried to predict snowmelt on Watershed 2 by using the energy balance approach.

The energy unit used is the calorie per square cm, or langley, abbreviated ly. If we assume that energy is distributed uniformly over the whole area, then it takes 80 cal/cm^2 or 80 ly to melt 1 cm of snow water content. This is equivalent to about 200 ly/inch of snow water content. Similarly, we find a requirement of 600 ly/cm or about 1,500 ly/inch to evaporate water.

Radiant energy is transferred in two forms: shortwave or solar radiation originating in the sun, and longwave radiation originating in the atmosphere or at the earth's surface. Shortwave radiation is directed downward from the sun, sky, and clouds. Some shortwave radiation is reflected by the surface; the remainder, which is absorbed by the surface, is the net shortwave radiation. The shortwave reflectivity is called the albedo. Longwave radiation coming down from the atmosphere is almost all absorbed at the surface, while the surface emits some longwave radiation upward. The difference is the net longwave radiation. Net radiation is the sum of net shortwave and net longwave radiation.

Daily shortwave radiation, R, was measured at Hubbard Brook Headquarters by a Belfort pyrheliograph. The headquarters' weather station is about 3 miles from Watershed 2. The measured radiation was corrected for the slope and aspect of Watershed 2 by

$$R_{sd} = \left[\frac{R_{pw}}{R_{ph}} f + (1 - f) \right] R$$

where R_{ph} is the potential insolation on a horizontal surface, R_{pw} is the potential insolation on the watershed (Lee, 1964), and the solar beam radiation fraction f is assumed to be R/R_{ph}. The albedo was obtained from curve V-2-3 in <u>Snow Hydrology</u>, which shows snow albedo vs. cumulated maximum temperature since the last snowfall. A snowfall was defined as at least 0.05 inch of new snow water content.

Downward longwave radiation, R_{ld}, was estimated by

$$\frac{R_{ld}}{\sigma T_a^4} = (0.58 + 0.05 \sqrt{e_a}) (2.08 \frac{R}{R_{ph}} - 0.58)$$

where T_a and e_a are absolute temperature and vapor pressure (mb) of the air, and σ is the Stefan-Boltzmann constant. R/R_{ph} is not allowed to be less than 0.37. This is developed from the work of Fitzpatrick and Stern (1965). The constant 0.58 is based on my own data for New Hampshire.

Estimation of the upward longwave radiation requires an estimate of the surface temperature, which is also used in convection and evaporation calculations. When the snow is melting, the snow surface must be at 0° C. At other times it will be less. For these calculations I assumed a surface temperature of 0° C. for all daytime periods and for night periods when the air temperature was greater than 0° C. At night with air temperature below 0° C., the surface temperature was set equal to the air temperature. Upward longwave radiation was then found from the Stefan-Boltzmann Law

$$R_{lu} = \sigma T_s^4$$

where T_s is the absolute temperature of the surface.

Calculations were made separately for each 12-hour period, so that day and night conditions were separated at 6 o'clock. All solar radiation was included in the daytime period. Net shortwave radiation was then obtained for daytime 12-hour periods as

$$R_{sn} = (1 - a) R_{sd}$$

where a is the albedo. Net longwave radiation for day and night periods was

$$R_{ln} = R_{ld} - R_{lu}.$$

Water condenses on the snow surface when the water vapor concentration of the air is greater than that at the surface. Dew is formed on the snow when the snow surface is at 0° C., releasing 600 ly/cm of dew. This heat may melt snow. When the surface is below freezing frost is formed, releasing 680 ly/cm that may be lost by radiation or convection but cannot cause melt because the snow is too cold. Evaporation, the opposite of condensation, occurs when the air is drier than the snow surface. It removes 600 ly/cm from the surface when the snow is melting and 680 ly/cm when the snow is below 0° C. (sublimation). This heat is carried away by the evaporated water vapor. Evaporation-condensation for Watershed 2 was estimated from a bulk aerodynamic equation

$$H_e = 0.238 u (e_a - e_s)$$

Here H_e is evaporation or condensation in ly, u is wind movement 6 feet above the ground in miles for the 12-hour period, e_a is the vapor pressure in mb at 4 feet, and e_s is the surface vapor pressure, assumed to be the saturated vapor pressure at the surface temperature. The transfer coefficient is that obtained in the Snow Hydrology investigations, modified for the units used here and for the sensor height.

Air temperature and relative humidity were measured by a hygrothermograph located somewhat below the center of the watershed. Total wind movement was measured weekly at the same location and a recording anemometer at headquarters was used to prorate wind movement into 12-hour values.

Convection heat transfer depends on the relative temperatures of the air and the snow surface and on wind movement. If the air is warmer than the surface, heat is transferred from the air to the snow and can be used in melting. If the air is colder than the snow, heat is lost from the snow surface to the air. Convection was determined by the equation

$$H_c = 0.156 u (T_a - T_s)$$

The transfer coefficient used here is obtained by multiplying the evaporation transfer coefficient used in the previous equation by the psychrometer constant, $0.654 \text{ mb } C^{-1}$. This theoretically correct coefficient is about three times larger than the value determined empirically in Snow Hydrology.

Since the unfrozen soil underlying the snowpack is warmer than the snow, heat is continually being transferred from the soil to the snow, thus melting the snow in contact with the ground. Federer (1965) studied this groundmelt at Hubbard Brook and found it to be 0.015 inch per day or less through the winter. This is negligible with respect to spring snowmelt rates so it will be ignored in the rest of this paper.

The heat content of rainwater is also a source of heat for melting snow. Warm rain landing on the snow surface is cooled to 0° C., releasing 1 calorie of heat for every cubic centimeter of rain and every degree C. above zero. On Watershed 2, rain heat caused only 0.04 inch of melt in 1966 and 0.10 inch in 1967. These are negligible amounts compared with the melt due to other sources so rain melt will not be considered further.

Since the snow surface is only two-dimensional, it cannot store heat; the gain of heat by the surface must therefore always equal the loss. The energy balance is then expressed as the equation for net melt for a 12-hour period

$$H_m = R_{sn} + R_{ln} + H_e + H_c$$

The terms on the right side are positive when they supply heat to the surface and negative when they remove heat from the surface.

When the energy supply is not great enough to maintain snowmelt, i.e. when H_m is negative, the snow surface cools below 0° C. and the snowpack becomes cooler. Heat is removed from the liquid water in the snowpack, causing it to refreeze, and from the snow itself, lowering its temperature. This amount of heat must be replaced before melting of additional snow can resume; it is called the cold content of the snow or, sometimes, negative melt. Negative H_m was accumulated over time and was reduced again to zero by positive H_m before actual melt was predicted. Because of assumptions made here--especially about surface temperature--a limit had to be placed on negative melt, although this is theoretically incorrect. For a snowpack water content of W inches, I assumed that refrozen water could reach a maximum of 0.05 W, which at 200 ly per inch gives a cold content of 10 W ly. I also assumed that cooling of the snowpack could produce a minimum temperature of -20° C. For a heat capacity of 1.25 ly/inch/°C, this gives a cold content of 25 W ly. Combining the two gave a maximum allowable negative melt of 35 W ly.

Snow accumulation was added to the snowpack when it occurred. Precipitation was measured weekly by a standard rain gage near the middle of Watershed 2. A nearby recording gage was used to prorate precipitation to daily values. If the air temperature during precipitation was 2° C or below, the precipitation was assumed to be snow.

Snow water content on Watershed 2 was measured by Mt. Rose snow tube on several days during the melt period. This snow course value was the average of about 60 points spaced along three paths that cross the watershed. Difficulties of sampling in slash biased the results toward a slash-free condition. In 1966, snow depth was measured at 49 points across the middle of the watershed with snow stakes. The average depth was converted to snow water content by assuming an average density of 0.32.

The snow water content as predicted by the energy balance is compared with the snow course measured values in Figures 4 and 5 for the snowmelt periods of 1966 and 1967, respectively. The snow course values for March 18, 1966, and March 9, 1967, were used as initial values for the energy balance prediction. The agreement in the first melt period of 1966 is excellent. At the onset of the second melt period, April 7-8, there was 0.71 inch of precipitation, which was called snow by the air temperature criterion, but was noted as rain at the headquarters' weather station. If this was snow, the prediction fits the April 12 and 14 snow surveys, but not the April 8 survey. Changing it to rain would fit April 8, but then give too high a rate of melt after that date.

In 1967 the major part of the snowpack melted very fast, almost 6 inches in 3 or 4 days. The predicted melt rate in this period agrees well with the snow-course data. However,

Figure 4.--Predicted and measured snow water content on Watershed 2, 1966.

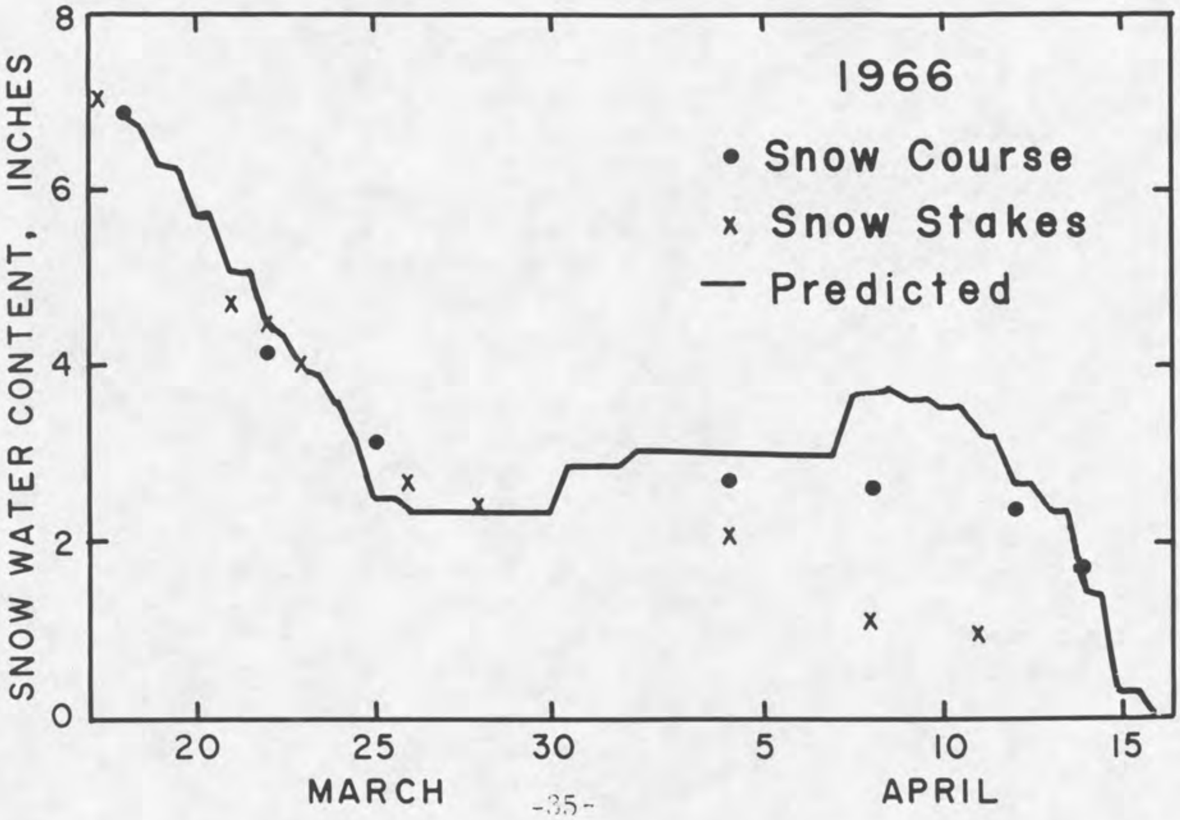
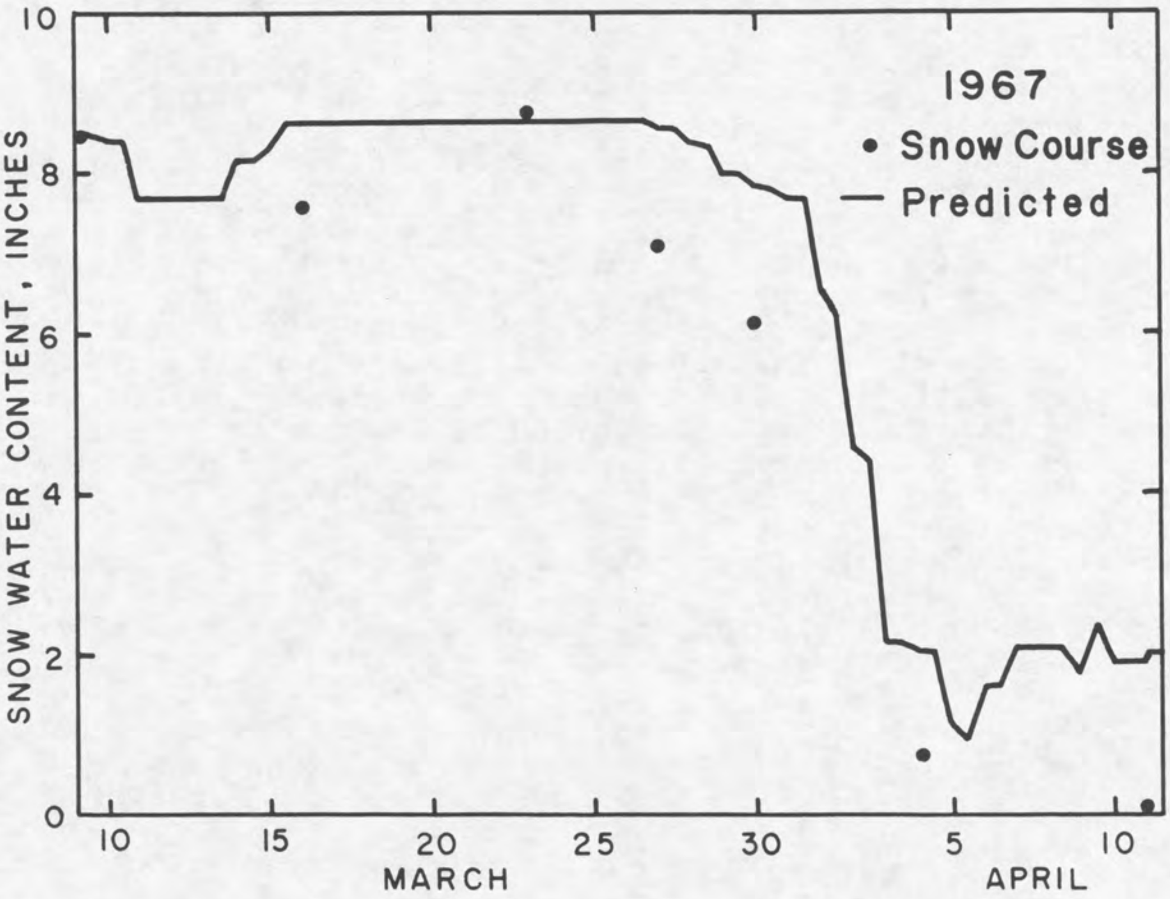


Figure 5.--Predicted and measured snow water content on Watershed 2, 1967.



the predicted snow water content is about 1.5 inches greater than the measured, indicating that melt actually began sooner than predicted. Predicted melt after snowfall on April 6 did not proceed as fast as it should have, probably because the albedo estimate was too high. Between March 16 and 23, measured snow water content increased by 1.1 inches although there was no precipitation. On March 16 the mean value of 65 points was 7.39 inches and the variance was 2.535. On March 23 the 61 points gave a mean of 8.46 and a variance of 3.327. The difference is highly significant by t-test. The anomaly is unexplained.

The heat budget for two high melt periods in 1966 and one in 1967 is shown in Table 1. Data of Ambach (1965) from much more detailed measurements at Obergurgl, Austria, are shown for comparison. Except for Ambach's early melt period, net solar radiation supplies about 10 percent more heat to the surface than is actually used in melt. Heat supplied by convection is about equal to that removed by net longwave radiation, and evaporation removes the extra 10 percent. However, with so many variables being involved this mean situation obviously varies a lot.

Table 1.-- Heat Budget of Snowmelt

Date	R_{sn}	R_{ln}	H_c	H_e	Melt
	- - - - % of melt			- - - -	ly
	Hubbard Brook Watershed 2				
3/17-3/26/66	104	-27	28	-5	1027
4/10-4/15/66	115	-41	41	-15	661
3/27-4/5/67	109	-47	50	-14	1350
	Obergurgl (Ambach, 1965)				
4/17-4/29/62	171	-84	40	-27	1493
5/3-5/11/62	108	-20	14	-2	1810

The 2 days of greatest melt, April 2 and 3, 1967, and their preceding nights have a total melt of 975 ly or 4.9 inches. The energy for this melt is divided among the heat sources as follows: R_{sn} 42%, R_{ln} 0%, H_c 41%, H_e 17%. These were partly cloudy days of mean temperature about 15° C., vapor pressure about 10 mb, and moderate wind averaging 4 mi/hr. High rates of snowmelt due to warm, moist air masses involve large heat contributions from convection and condensation and little or no net longwave loss.

EFFECT OF SLASH ON RADIATION AND SNOWMELT

Slash distribution on Watershed 2 is very uneven, ranging from areas of bare ground to areas of 3-foot-thick, dense slash piles. Slash density commonly varies from none to heavy within a distance of 15 feet. Thus I anticipated quite different rates of snowmelt from point to point. The slash, with its lower albedo, should become warmer and thus the snow around it should melt faster than in areas with a continuous snow surface.

I measured snowmelt rates with snow stakes in 1966 and again in 1967 to try to determine the influence of the slash. Snow depths were measured to the nearest half inch on stakes marked every inch. A simple slash rating was developed to describe slash density above the snow surface within a 3-foot radius of each stake: 0--no slash; 1--light slash; 2--moderate slash; and 3--heavy slash. The rating was recorded each time a stake was read. The slash rating is admittedly subjective, but comparison on 1 day between the two observers showed agreement on 36 out of 49 points and the other 13 differed by one unit.

In 1966, 49 stakes were placed 10 feet apart along a line across the watershed about one-third of the distance up the watershed. The slash rating at a given point generally increased as the snow depth decreased so interpretation of the results was somewhat difficult. To overcome this difficulty, slash was piled artificially in 1967 to provide two areas for each of the four slash ratings. Five stakes were placed in each area.

Slash influenced the snow depth at peak accumulation; deeper snow was found in denser slash. Table 2 shows data for both years. The 1966 slash rating is that for a snow depth of 12 inches, which is about half the maximum snow depth. The slash effect is due to wind redistribution of the snow during and after snowfall and to bridging, which leaves air holes in the snowpack.

Table 2.--Average Peak Snowpack Depth for Different Slash Ratings Hubbard Brook Watershed 2

Slash rating at 12-inch snow depth	March 14, 1966		March 9, 1967	
	Number of stakes	Ave. depth inches	Number of stakes	Ave. depth inches
0	5	21.3	10	29.4
1	10	22.8	10	43.9
2	14	24.9	10	42.6
3	19	25.4	10	46.6

Melting as a function of slash rating is shown in Table 3 as the change of snow depth in inches for the given period. During melt periods the snow density should be nearly constant. The 1966 slash ratings are for the beginning of the period. It is evident that a certain amount of slash above the snow increases the melt rate, but there is also some evidence that at times the melt rate for a snow surface in dense slash is less than in lighter slash. This probably comes from an insulating effect: the snow surface in the dense slash is shaded, and wind movement, which carries heat to the snow, is restricted. The range of melt amounts increases with slash rating, showing that conditions become much more variable. This variation may have three sources: actual variation in melt rates, uncovering of air pockets, and difficulty in measuring due to extreme unevenness of the snow surface.

Table 3.--Snowmelt for Different Slash Ratings, As Change of Snow Depth in Inches

Hubbard Brook Watershed 2

Slash rating on beginning date	3/17-3/22/66		3/22-3/28/66		3/23-3/27/67		3/27-3/30/67	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
0	6.5	5.5-7.5	5.3	4.3-6.5	4.6	4.0-6.0	5.7	5.0-7.0
1	7.0	6.0-8.5	6.8	5.0-9.0	6.4	5.0-9.0	7.5	6.5-10.0
2	9.2	6.0-16.0	7.0	4.5-11.0	5.8	5.0-6.5	8.0	6.0-11.5
3	8.0	6.0-12.5	6.6	2.0-16.0	5.6	-1.0-8.0	11.0	8.0-14.0

The effect of slash on net radiation was studied on 2 days in 1966. Radiation was measured by six economical radiometers (Swan, Federer, and Tanner, 1961) on March 9 and 22, 1966. The radiometers were mounted about 4 feet above the snow surface. Table 4 shows noontime values for undisturbed hardwood forest (mean of two radiometers), for one radiometer over snow (0 slash rating), and for one over heavy slash (3 slash rating). The other two radiometers (over areas of slash ratings 1 and 2) gave intermediate values. On March 9, sun elevation was about 41 degrees and the sky was clear. On March 22, sun elevation was 46 degrees with a complete cirrostratus cloud cover.

The effect of albedo on the resulting net radiation is obvious, both spatially due to slash variation and temporally with aging of the snow surface. The slash itself probably has an albedo of about 0.15, so the surface albedo of slash is a weighted average of this and the snow albedo. Similarly, the surface temperature is an average of snow at 0° C. and slash at some higher temperature. An attempt to correct estimated albedo and surface temperature for slash was made in the initial energy balance computations. It was based on a slash rating vs. snow depth relation obtained from 1966 snow stake data, but it produced too rapid melt, especially later in the season. However, this type of correction should be applicable and necessary.

The snow albedo (0 slash rating) compared favorably with the estimated albedo used in the energy balance: March 9--0.73 estimated, 0.72 measured; March 22--0.54 estimated, 0.51 measured. Similarly, comparing measured and estimated downward longwave radiation gave: March 9--0.32 ly/min estimated, 0.31 ly/min measured; March 22--0.43 ly/min estimated, 0.42 ly/min measured.

The radiation absorbed by the slash cannot be dissipated by evaporation or melting. The slash temperature rises, and emitted longwave radiation and convection loss are increased. The radiation is partly emitted downward to the snow beneath, making

Table 4.--Radiation Components over Melting Snow
Hubbard Brook Experimental Forest

Date and condition	R_{sd}	R_{su}	R_{ld}	R_{lu}	R_n	Albedo	T_s
	ly/min	ly/min	ly/min	ly/min	ly/min	%	°C.
March 9, 1966							
Snow	1.11	0.80	0.31	0.46	0.16	72	0
Slash	1.11	.34	.31	.48	.60	31	4
Woods	.64	.51	.40	.44	.09	80	-2
March 22, 1966							
Snow	.96	.49	.42	.46	.43	51	0
Slash	.96	.16	.42	.52	.70	17	9
Woods	.65	.34	.46	.46	.31	52	0

up in part for the shading produced by the slash. This effect also occurs in the hardwood forest where a higher downward longwave radiation is observed at the surface. The convection loss from the slash, which must be quite large because of its high temperature and exposure to wind, heats the air locally. When this air moves over an area of clear snow or light slash with a cool surface there can be heat transfer to the snow. This type of local advection also may occur in the hardwood forest, with vertical transfer downward from the crowns to the snow.

CONCLUSIONS

The energy balance approach gave moderately good results in predicting snowmelt from a clearcut mountainous watershed--in spite of some rather gross estimates of some of the variables involved. The calculated energy balance for melt periods showed that net solar radiation contributed sufficient energy for melting and that convection heat gain balanced net longwave radiation loss. Latent heat transfer as evaporation or condensation was relatively small. However, in high melt periods the relative heat contribution of solar radiation is decreased, while contributions due to convection and condensation become large. Net longwave loss may also diminish to zero or even contribute heat to melting. Later in the snowmelt season, and thus especially for north slopes, the relative influences of convection and condensation may become of equal or greater importance than radiation.

Clearcutting of a south-facing slope did not advance snowmelt runoff very much in spite of large quantities of slash. Apparently the slash-covered watershed behaves quite similarly to the forested watershed in terms of melt rate. However the energy balance components must be somewhat different. Solar radiation is reduced and downward longwave radiation is increased in the forest. Wind movement in the forest is reduced an unknown amount below that in the open.

This study has indicated that further research is necessary on a number of aspects of the problem. Methods are needed for estimating albedo and surface temperature for clearcut and partly cut areas with heavy slash cover, and for uncut hardwood forests. Surface temperature is an important variable in determining upward longwave radiation, convection, and surface vapor pressure. The value of the transfer coefficient is a subject for further research. The convection estimates made here may be up to three times too large. Tied to this is the need for greater understanding of the magnitude of local advection, horizontal in slash and vertical in hardwood forest. We also require information on wind movement within a hardwood forest compared with that in the open. At present the energy balance method used here cannot be applied to uncut hardwood forests. And we are still far from being able to predict accurately the effects of various cutting practices on snowmelt.

LITERATURE CITED

Ambach, W.
1965. Untersuchungen des Energiehaushaltes und des freien Wassergehaltes beim Abbau der winterlichen Schneedecke. Arch. Meteorol. Geophys. Bioklimatol., B 14: 148-160.

Federer, C. Anthony.
1965. Sustained winter streamflow from groundmelt. U.S. Forest Serv. Res. Note NE-41, 4 pp. NE. Forest Exp. Sta., Upper Darby, Pa.

Fitzpatrick, E. A. and W. R. Stern.
1965. Components of the radiation balance of irrigated plots in a dry monsoonal environment. J. Applied Meteorol. 4: 649-660.

Hart, George.
1966. Forest cutting to increase streamflow in the White Mountains. N.H. Forest Notes (89): 6-9.

Lee, Richard.
1964. Potential insolation as a topoclimatic characteristic of drainage basins. Bull. Int. Assoc. Sci. Hydrology 9(1): 27-41.

Swan, J. B., C. A. Federer, and C. B. Tanner.
1961. Economical radiometer, performance, construction and theory. Soils Bull. 4, 91 pp. Dep. Soils, Univ. of Wisconsin, Madison.

United States Army Corps of Engineers.
1956. Snow Hydrology. North Pacific Div., C. of E., U.S.A., Portland, Oregon. 437 pp.