

## **Snowmelt Prediction in a Subarctic Drainage Area**

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Three prediction methods were tested against observed melt for their ability to predict snowmelt in a variety of subarctic environments. Four melt environments were defined according to vegetation cover. They are: Closed Lichen Woodland, Open Lichen Woodland, Regenerating Burn and Burn. The three methods tested are the physical energy balance method (with some data approximations), the U.S. Army Corps of Engineers method (empirical energy balance) and the temperature index method (using mean daily air temperature). It was found that the physical energy balance is most applicable in the Burn and Regenerating Burn while the U.S. Army Corps of Engineers and temperature index methods provide adequate prediction in all four melt environments.

### **Introduction**

In the arctic and subarctic the most significant event of the hydrologic year is the spring snowmelt. More than half of the total annual precipitation is stored in the snowpack and is released by the snowmelt. Thus, prediction of this event is of prime concern to the hydrologist.

Although considerable research has been conducted on the prediction of snowmelt, most of this effort has been concentrated in the midlatitudes rather than the arctic and subarctic. As a result, there is some question as to the applicability of the midlatitude methodologies to these northern areas. Further, most of the work carried out in the midlatitudes has been aimed at the prediction of snowmelt for a point. Prediction of snowmelt over a drainage basin with a range of slope orientations and vegetation cover is a problem which arises for hydrologists in all regions.

When dealing with a drainage basin, snowmelt prediction is usually accomplished using point meteorologic data. It is important to establish an accurate relationship of the point data to the area for which the prediction is being made.

The bulk of the energy available for snowmelt is derived from solar radiation and heat advected from other areas. Large scale variations in solar radiation are mainly due to latitudinal differences in receipt of solar radiation, while advection at this scale is a function of the movement of air masses of differing characteristics. Within a small drainage basin energy from the sun and atmosphere does not vary significantly from point to point. The characteristics of the surface upon which the solar energy is incident and with which the air masses interact cause small-scale variations in the receipt of energy. Thus within a small basin areal variation of snowmelt arises from the effects of surface characteristics. These generalizations have been recognized for some time as is illustrated by the inclusion of surface characteristic parameters in basin melt equations (U.S. Army Corps of Engineers 1960, Anderson 1968).

Hendrick et al. (1971) deal with the problem of areal prediction of snowmelt by dividing New England basins into a number of snowmelt environments, each having a specific combination of surface characteristics. Snowmelt is predicted for each environment and the results are integrated to provide an estimate of the basin melt. In large basins which have significant differences in available energy (due to their areal extent) sub-basins with uniform energy availability have to be defined. Melt is predicted for snowmelt environments within each sub-basin and integrated for that sub-basin and then the melt for each sub-basin is integrated for the large basin. The advantage of the Hendrick's approach is that the equations can be used (without redefinition) to predict snowmelt outside the original study basin where different areal combinations of the same melt environments exist.

Methods of snowmelt prediction can be classified into three broad groups; energy-balance models, simplified empirical energy-balance models, and empirical temperature-index models. The groups differ in physical sophistication and data requirements. Choosing a prediction model which will provide the best results with the available data is a problem particularly in the north where the terrain and weather conditions hamper the collection of large data sets.

This paper considers one formulation from each group of snowmelt models, and applies them to a small subarctic basin in which four melt environments are identified. The predicted results are compared with observed snowmelt to determine the applicability of the models to the subarctic environment.

## **The Study Area**

The study area is located near Schefferville, Quebec in the Knob Lake research basin (Fig. 1). In most respects the area is typical of the lowlands near the treeline of subarctic Canada. Relief is less than 120 m with most slopes less than 5°.

## Subarctic Snowmelt Prediction

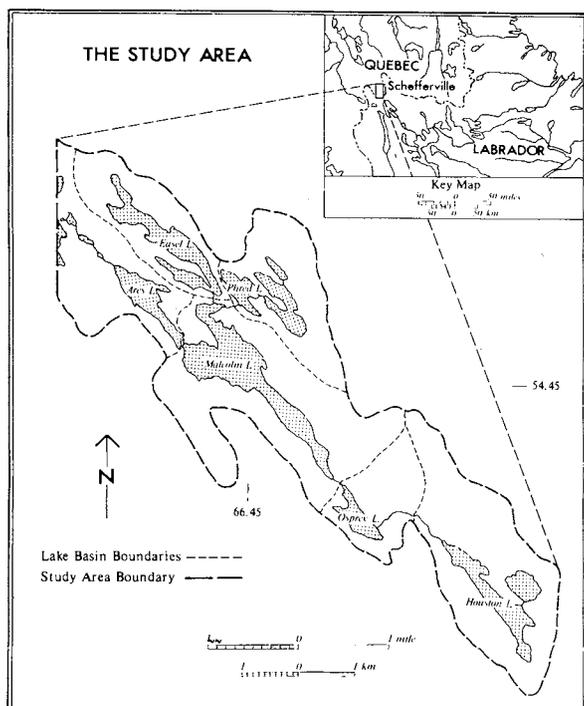


Fig. 1. Location of the study area.

Topography trends northwest to southeast with offsetting slope orientations. The climate is cold (mean annual temperature  $-4.7^{\circ}\text{C}$ ). Precipitation is heavier than in much of subarctic Canada (mean annual snowfall 330 mm with total precipitation of 740 mm, the average for subarctic Canada is 150 mm of snow fall and 400 mm total precipitation, Hydrological Atlas of Canada, 1978). The vegetation cover consists mainly of lichen woodland and burnt areas.

### Method

Due to the small scale of the study area, incoming energy from the atmosphere and the sun was considered to be uniform. The low slope angles, offsetting slope orientations and the small altitude range make topographic effects unimportant. Examination of the effects of other surface characteristics on snowmelt showed that vegetation cover is the single most important influence (FitzGibbon 1977). Thus four melt environments were defined according to vegetation cover. The melt environments are: Closed Lichen Woodland (25-50% crown cover), Open Lichen Woodland (15-25% crown cover), Regenerating Burn (5-15% crown cover), and Burn (0-5% crown cover) (see Fig. 2). The Open and Closed Lichen Woodland consist mainly of mature black and white spruce trees (averaging 6.8 m in height in the open forest and 7.5 m in the closed forest). The forest canopy is

Fig. 2. Vegetation cover in the study area.



a) Closed Lichen Woodland



b) Open Lichen Woodland



c) Regenerating Burn



d) Burn

rather uneven in the Open Lichen Woodland as compared to a more even cover in Closed Lichen Woodland. Since reproduction is mainly by root spread, the trees in the Open Lichen Woodland tend to occur in clumps thereby creating the uneven canopy. The bulk of the cover in the Regenerating Burn consists of young trees (larch and white spruce averaging about 2 m in height) while the Burn areas are characterized by scattered bushes (mainly dwarf birch and willow averaging 0.6 m in height).

A large quantity of data was required to apply and test the prediction models. Meteorologic sites were located in each of the melt environments and at a standard open site. Ten snow courses were distributed through the four melt environments. Snow depth and water equivalent were measured with an Adirondack snow sampler every three days. Data were collected through two snowmelt seasons.

### **The Energy Balance Formulation**

The energy balance formulation used here is as follows

$$M \equiv \frac{H_M}{\rho_w \delta_i \beta}$$

where

- $M$  = melt (cm/day)
- $\rho_w$  = density of water (g/cm<sup>3</sup>)
- $\delta_i$  = latent heat of fusion of ice (79.7 cal/g)
- $\beta$  = thermal quality of the snowpack = 0.97 (dimensionless)
- $H_M$  = total heat available for snowmelt  
=  $H_r + H_c + H_e + H_p$  (cal/cm<sup>2</sup>/day)
- $H_r$  = heat from net radiation  
=  $a + b(Q)$  (cal/cm<sup>2</sup>/day)
- $Q$  = incoming solar radiation total for the day (cal/cm<sup>2</sup>/day)
- $a$   $b$  = regression constants (from Petzold 1974)
- $H_c$  = sensible heat  
=  $C_I (T_a - T_s) u_a S$  (cal/cm<sup>2</sup>/day)
- $C_I$  =  $1.37 \times 10^{-6}$  (see Price 1975 for derivation)
- $T_a$  = air temperature average for the day (°C at 2 m above the snow surface)
- $T_s$  = snow surface temperature average for the day (°C)
- $u_a$  = wind speed average for the day at 2 m (cm/day)
- $s$  = dimensionless stability correction  
=  $1/(1+1ORi)$  for stable conditions
- $or$  =  $1/(1-1ORi)$  for unstable conditions
- $Ri$  = bulk Richardson number  
=  $(g\Delta T \Delta z)/(t_{ak} \Delta z)$  (dimensionless)
- $\Delta z$  = height difference over which  $Ri$  is calculated (cm)

## Subarctic Snowmelt Prediction

- $T_{ak}$  = air temperature ( $^{\circ}\text{K}$ )  
 $\Delta u$  = wind speed difference over height difference  $\Delta z$  (cm/day)  
 $H_e$  = latent heat  
           =  $C_2 (c_a - c_s) u_a S$  (cal/cm<sup>2</sup>/day)  
 $C_2$  =  $2.14 \times 10^{-6}$  (see Price 1975 for derivation)  
 $e_a$  = vapour pressure average for the day at 2 m (mb)  
 $e_s$  = snow surface vapour pressure average for the day (mb)  
 $H_p$  = heat from rain  
           =  $\rho_w C_w (T_p - T_s) P$  (cal/cm<sup>2</sup>/day)  
 $C_w$  = specific heat of water (cal/g $^{\circ}\text{C}$ )  
 $T_p$  = temperature of rainwater (taken to be the wet bulb temperature  $^{\circ}\text{C}$ )  
 $P$  = rain (cm/day)

The energy balance equations listed above were applied during the period after the snow had ripened sufficiently to release water and, when changes in heat storage in the snowpack could be ignored when daily averages were computed. Some data were not measured directly but were approximated. Snow surface temperature was taken to be  $0^{\circ}\text{C}$  for melt periods and equal to the wet bulb temperature during non-melt periods. The occurrence of melt and non-melt periods was determined from direct observation of water production on slopes as observed by Price (1975).

Snow surface vapour pressure was taken to be 6.11 mb for a melting snowpack and equal to the saturated vapour pressure over ice (for the appropriate snow surface temperature) during non-melt periods.

The coefficients  $C_1$  and  $C_2$  in the turbulent flux terms contain a surface roughness parameter and imply the occurrence of a logarithmic wind velocity profile even under woodland conditions. Price (1975) found that a logarithmic profile could be defined in the Open Lichen Woodland if measurements were averaged over the entire melt season. At present, it is not known to what extent the logarithmic profile is applicable in subarctic woodlands, but we have assumed its presence.

Negative calculated values of  $H_M$  (heat available for snowmelt) indicate a heat deficit (i.e., no melt on that day). When such a calculation was recorded the heat deficit was accumulated. Melting was considered to resume only after the accumulated deficits were eliminated by subsequent surpluses.

### The Simplified Empirical Energy-Balance Formulation

The simplified empirical energy-balance model tested here is the U.S. Army Corps of Engineers model (1960). The equations are as follows

For Periods of Bright Sunshine

$$M \equiv K(1-F)[0.01015(Q)(1-A)] + 0.1326(T_a - T_s)F + C(0.02134u_b)[0.22(T_a - T_s) + 0.78(T_{da} - T_{ds})]$$

where

- $M$  = snowmelt (cm/day)
- $K$  = a basin exposure factor for solar radiation  
(0.9 for north facing, 1.1 for south, 1.0 for flat)
- $F$  = forest canopy cover (%)
- $A$  = albedo of snow surface
- $u_p$  = wind speed at 15 m (km/hr)
- $C$  = condensation convection factor
- $T_{da}$  = dew point temperature of air (°C at 2m)
- $T_{ds}$  = dew point temperature of the snow surface (°C)

**For Periods of Rainfall**

$$M = 0.2286 + (0.326 + 0.02134Cu_b + 0.0125P) (T_a - T_s) \text{ (cm/day)}$$

Application of the U.S. Army Corps of Engineers equations for areal prediction of snowmelt requires that the empirical parameters be evaluated for each melt environment. This was done according to the guidelines set out by the U.S. Army Corps of Engineers (1973), (see Table 1 for calculated values for each melt environment).

Table 1 - U.S. Army Corps of Engineers Melt Parameters\*

Melt Environment	K	F	C
Burn.....	1.0	0.06	0.95
Regenerating Burn .....	1.0	0.1	0.91
Open Lichen Woodland .....	1.0	0.2	0.82
Closed Lichen Woodland .....	1.0	0.4	0.65

- K = basin exposure factor
- F = forest canopy cover (%)
- C = condensation convection factor

**The Temperature Index Formulation**

The empirical temp index model tested here used temperature index equations derived from linear regression of air temperature with observed snowmelt as follows

$$M = c + d(T_a - T_b)$$

where

- $M$  = observed melt (cm/day)
- $c$   $d$  = regression constants
- $T_a$  = air temperature (°C at 2 m above the snow surface)
- $T_b$  = base temperature = 0°C

## Subarctic Snowmelt Prediction

During one melt season water equivalent of the pack was measured every three days (in each melt environment) and an average daily melt rate was computed for each period. The melt rate was then regressed against mean daily air temperature (above 0°C) measured at the open meteorological site to yield an equation for each melt environment (see Table 2 for the regression statistics). The equations were then used to predict snowmelt during the following year.

Table 2 - Linear Regression Statistics for the Temperature Index Equations

Melt Environment	c	d	r	ste cm/day/°C	No. of Cases
Burn	0.90	0.31	0.94*	0.33	8
Regenerating Burn	0.87	0.32	0.75	0.92	8
Open Lichen Woodland	0.97	0.18	0.71	1.25	8
Closed Lichen Woodland	0.96	0.16	0.61	0.69	8

c and d = regression constants

r = correlation coefficient

ste = standard error of the estimate

\* correlation significant at 0.005 confidence level

## Results

Daily snowmelt was predicted for each of the melt environments using the three methods. The daily rates were then grouped and averaged for three-day periods and compared to the snow course measurements of melt (see Fig. 3). A summary of the average absolute errors of prediction is presented in Table 3. Generally speaking the accuracy of prediction is reasonable. In most cases the average absolute error is less than 20% of the observed melt and there is no general tendency for under or over prediction. In all cases the average absolute errors are smaller in value than the standard deviations of the mean observed melt rates. Indeed, some of the scatter seen in Fig. 3 is probably due to errors in the observed melt rates (which were used as the basis for comparison). For snow tube sampling, instrument and observer error is on an average 12% (Mc Kay and Blackwell, 1961).

The largest errors occurred when the physical energy balance method was used for the forested environments. This is probably due to the uncertainties and assumptions made in estimating the turbulent fluxes of heat. The uneven nature of the subarctic forest canopy makes accurate modeling of these fluxes extremely difficult.

The U.S. Army Corps of Engineers method was least successful in predicting the Open Lichen Woodland melt. This is not surprising since the empirical para-

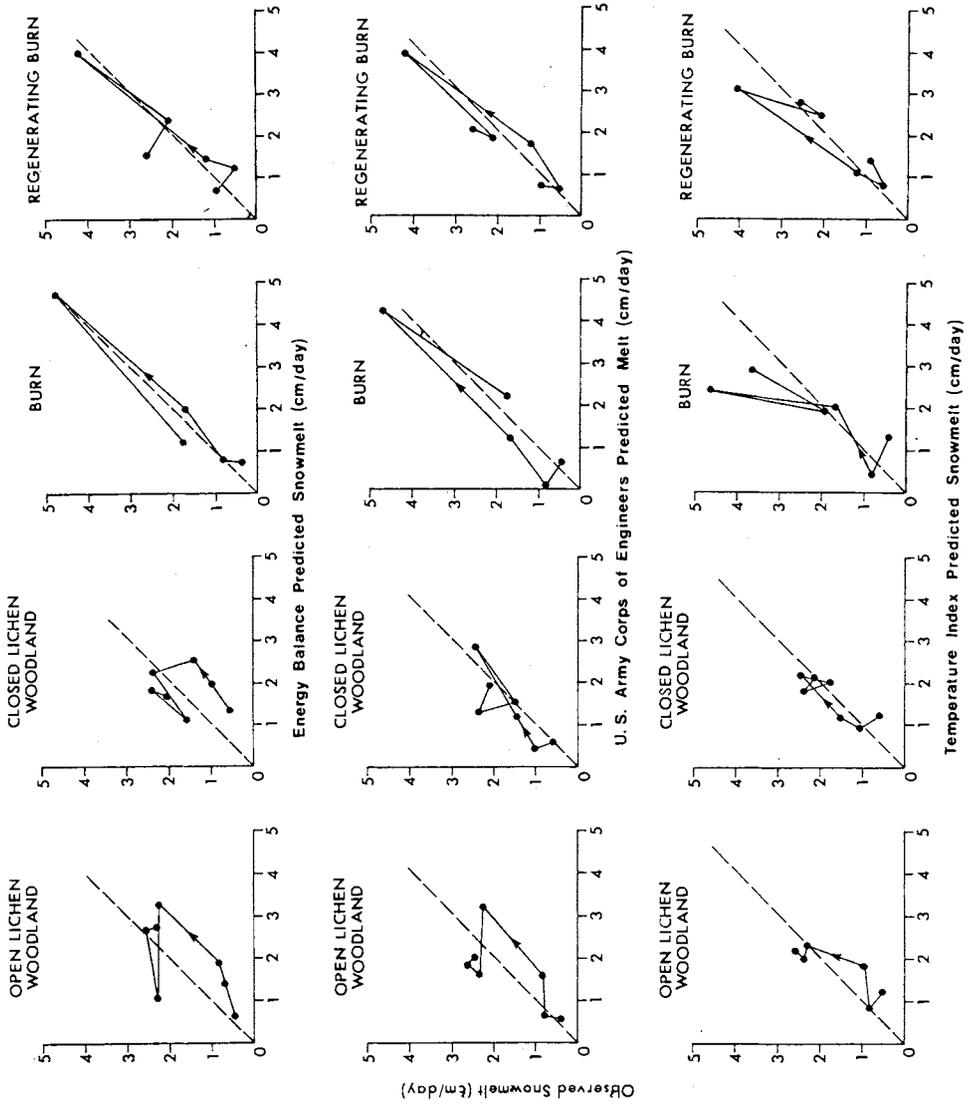


Fig. 3. Comparison of the observed and predicted snowmelt.

## Subarctic Snowmelt Prediction

Table 3 - Average Absolute Error of the Prediction Expressed in cm/day and as a Percentage of the Observed Melt

Melt Environment	Physical Energy Balance Method		U.S. Army Corps of Engineers Method		Temperature Index Method	
	Average Abs. Error (cm/day)	(% of observed)	Average Abs. Error (cm/day)	(% of observed)	Average Abs. Error (cm/day)	(% of observed)
Closed Lichen Woodland	0.49	32	0.27	15	0.25	14
Open Lichen Woodland	0.62	40	0.41	24	0.28	18
Regenerating Burn	0.36	18	0.28	14	0.33	19
Burn	0.19	9	0.35	18	0.61	26

meters in these equations were designed for midlatitudes where forest canopies are generally more dense and uniform. The Open Lichen Woodland is notably different in that the forest canopy is very uneven. Thus it is reasonable that the empirical melt factors would be least applicable in this environment and yield the poorer prediction of melt.

The poorest prediction obtained using the temperature index method, was for the Burn environment. The U.S. Army Corps of Engineers (1960) have noted that for essentially unforested areas in the midlatitudes the correlation between air temperature and daily snowmelt is poor, whereas for forested environments temperature indexes are fairly reliable estimators of snowmelt. The results of this study show a similar finding for subarctic environments.

### Conclusions

The three methods tested here may be used for subarctic snowmelt prediction. Each method however, has certain problem areas. The turbulent flux terms in the physical energy balance need to be improved for subarctic forests. This would probably involve better definition of the wind, temperature and vapour pressure profiles for the forest. However, these profiles may be very complicated and something other than the logarithmic profile approach for the turbulent flux terms may be required.

Definition of the U.S. Army Corps of Engineers empirical parameters needs to be improved for the Open Lichen Woodland environment. This would require an extensive snow lysimeter study of the melt in this environment.

The reliability of the temperature index method for open areas could be increased by adding further years of observed data to the regression used to define the prediction equations. This would not be a simple task since fieldwork in the subarctic is difficult and expensive because of the poor trafficability of the melting snow surface.

In spite of the deficiencies noted above, the comparison of the observed and predicted snowmelt indicate that the U.S. Army Corps of Engineers (1960) and the temperature index methods can be used to obtain melt predictions that are adequate for most hydrologic forecasting needs in the subarctic.

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