A COMPARISON OF THREE SNOWMELT PREDICTION MODELS 1/ 646-78

By

Bruce A. Haverly 2/, Ross A. Wolford, and Kenneth N. Brooks 3/

Accurate and timely predictions of snowmelt are important for spring-flood forecasts in the Upper Midwest. Forecasters are continually seeking models which can accurately simulate snowmelt yet can be easily and quickly applied. Data requirements, computer hardware needs, and the ease or difficulty of model application to a large extent dictate the model to be used. These constraints have tended to direct operational hydrologists and streamflow forecasters away from the newer and more complex simulation models. The trade-off between accuracy and applicability, however, has not been examined in many cases.

The Upper Midwest in general has shallower snowpacks and a shorter melt season than the mountainous regions in the West, where most of the snowmelt models have been developed. Maximum depths of snowpacks in many drainages seldom exceed 60 to 75 cm, but a high percentage of the snowpack typically becomes runoff. The prevalence of soil frost, particularly in the nonforested areas, accounts largely for the high runoff efficiency. Baker (1972) indicated that little of the winter precipitation infiltrates soils in agricultural areas of Minnesota. He found that spring runoff was highly correlated with the quantity of snow which fell on frozen soils. Likewise, based on plot studies in Saskatchewan, Steppuhn et al. (1975) observed that over 85 percent of the snowmelt became surface runoff. This year, a snowpack of about 45 cm depth[1] resulted in considerable flooding in northwestern Minnesota along the Red River of the North.

This study compared three snowmelt models of different levels of complexity on the basis of predicting snowmelt in east-central Minnesota. A degree-day or temperature index model, a model using the Corps of Engineers generalized snowmelt equations, and the SNOW-MELT model (Solomon et al., 1976) were examined. The accuracy of predictions, the level of effort needed to apply the models, and data requirements were the basis of comparisons.

Models

Most existing models can be categorized as either empirical or process oriented. Although most models differ only in their degree of empiricism, a wide range of modeling capabilities and complexity exists. The models compared in this study are representative of this range and were chosen in an attempt to answer the following questions: Do the more complex models do a better job of simulating snowmelt? If so, does the added work involved with parameter calibration and increased data handling merit their use?

Degree-Day Model

Perhaps the most widely used method of predicting snowmelt is the degree-day or temperature index method. This method is available in most operational streamflow models such as the SSARR, National Weather Service Model, HEC-1, and others (Chu and Bowers, 1977). Daily snowmelt (SM) is determined by:

$$SM = MR\ (T_a - T_b)$$

where:

MR = Melt rate coefficient in cm (inches) per degree-day
T_a = Maximum or mean daily air temperature in degrees C (°F)
T_b = Base temperature in degrees C (°F)

1 Estimated from snow-depth data, March 16, 1978, as prepared by the State Climatology Office, Minnesota Department of Natural Resources.

1/ This paper published as a Minnesota Agricultural Experiment Station Scientific Journal Series Paper No. 10304.

2/ Hydraulic Engineer, Edwards and Kelcey Inc., Minneapolis, Minnesota.

3/ Respectively, Research Assistant and Assistant Professor, College of Forestry, University of Minnesota.

This model is simple and its application requires only air temperature data. Melt rate coefficients can be readily determined from the slope of the regression line of daily snowmelt against degree-day values ($T_a - T_b$). In this study, melt rate coefficients were determined for maximum and mean daily temperatures with base temperatures of -1°C (30°F) and 0°C (32°F), respectively.

Generalized Snowmelt Equations

A computer model was developed for this study to expedite daily snowmelt computations using the Corps of Engineers generalized snowmelt equations (USACE, 1956). Although not necessarily designed for operational flood forecasting, these equations represent a more complete accounting of factors affecting the energy budget of a snowpack. This model is not process oriented, but can be used to predict snowmelt under different levels of forest canopy cover and either rain or rain-free periods. Snowpack condition is not simulated; the following equations assume a ripe snowpack that is isothermal at 0°C (32°F) with a 3 percent free water content:

Rain-free Periods

(1) Heavily forested areas - forest cover greater than 80 percent

$$SM = 0.074\ (0.53TA + 0.47\ TD)$$

(2) Forested areas - forest cover between 60 and 80 percent

$$SM = CMF\ (0.0084V)\ \ (0.22YA + 0.78TD)\ +\ 0.029YA$$

(3) Partly forested areas - forest cover between 10 and 60 percent

$$SM = SMF\ (1 - F)\ \ (0.004SI)\ \ (1 - A)\ +\ CMF\ (0.0084V)$$
$$(0.22TA + 0.78TD) + F\ (0.029TA)$$

(4) Open areas - forest cover less than 10 percent

$$SM = SMF\ (0.00508SI)\ \ (1 - A) + (1 - CC)\ (0.0212TA - 0.84)$$
$$+ CC\ (0.029TC) + CMF\ (0.0084V)\ (0.22TA + 0.78TD)$$

Periods with Rain (periods of precipitation when daily temperature was at least 1.7°C (35°F).)

(5) Open or partly forested area - rain melt (60 percent forest cover or less)

$$SM + (0.029 + 0.0084\ (CMF)V + 0.007P)\ (TA-32) + 0.09$$

(6) Heavily forested area = rain melt (over 60 percent forest cover)

$$SM = (0.074 + 0.007P)\ (TA - 32) + 0.05$$

where:

SM = snowmelt rate in inches per day
TA = difference between air temperature @ 10 ft and snow surface temperature, °F
TD = difference between dewpoint temperature @ 10 ft and snow surface temperature, °F
V = wind speed @ 50 ft above snow, MPH
SI = observed solar insolation, langleys/day
A = albedo of snow surface
SMF = basin shortwave radiation melt factor (range: 0.7 to 1.1)
F = basin forest canopy cover
TC = difference between cloud base temperature and snow surface temperature, °F
CC = cloud cover
CMF = basin convection-condensation melt factor (range: 0.05 - 0.3)

The costs in terms of data requirements and parameter calibration are greater than for the degree-day model (Table 1). The basin shortwave radiation melt factor and the basin convection-condensation melt factor must be estimated or fitted in the calibration process. Solar insolation is usually estimated from tables such as those presented by Frank and Lee (1966). Albedo is also usually estimated, but on a more subjective basis.

Table 1 - Comparison of Snowmelt Model Data Requirements

Parameter	Model		
	Degree Day	Generalized Equations	Snowmelt
I. Daily Input			
Air Temperature	X	X	X
Dewpoint Temperature		X	
Precipitation		X	X
Cloud Cover		X	
Solar Radiation		X	0
Wind Speed		X	
Snow Albedo		X	
II. Watershed Input			
Forest Cover Density		X	X
Solar Radiation Coefficients		X	X
Convection Coefficients		X	
Melt Threshold Temperature		X	X
Vegetation Type			X
Potential Evapotranspiration			X
Slope-Aspect Factors			X
Degree Day Coefficients	X		

X = Required Data
0 = Optional Data

SNOWMELT Model

SNOWMELT is a continuous simulation model which is actually a modification by Solomon et al. (1976) of a model developed for Colorado subalpine watersheds by Leaf and Brink (1973). Although not necessarily developed for operational forecasting, this model represents a more process oriented simulation of accumulation, ripening and melt. This was the only model of the three studied, which simulated snowpack condition.

Data input requirements are not excessive despite the internal complexity of the model (Table 1). Daily maximum and minimum air temperature, precipitation, and shortwave radiation or percent cloud cover are required. Two options are available to simulate potential incident solar radiation when such data are not available, as with operational forecasting. The first option uses potential insolation tables (Frank and Lee, 1966). The second option uses a degree-day differential to estimate potential solar radiation. Measured solar radiation was available for this study. Other input requirements include forest cover density, mean slope and aspect, latitude of the watershed and a radiation transmissivity coefficient. To start a simulation, the initial snowpack temperature, snow water equivalent and ground moisture recharge deficit must be specified.

Study Procedures

Snow depth and water equivalent were measured with a Mt. Rose snow sampler in 1976 on two experimental snow courses located about eight miles north of St. Paul, Minnesota. Thirty sample points approximately 15 meters apart were located along each course. One course was located in a mixed conifer stand of red pine (*Pinus resinosa*), Eastern white pine (*P. strobus*), and jack pine (*P. banksiana*). The canopy cover was estimated to be 63 percent. The second course was located in a nearby open field. These areas were considered to be typical of cover conditions in much of Minnesota.

Snow depth and water equivalent were collected for ten and twelve periods for the open and forested courses, respectively, between February 8 and March 24, 1976. These data were used to calibrate each of the three models.

In 1977 three new snow courses were measured, one in the same open field, and one each in conifer stands with 40 and 80 percent canopy coverages. Snow water equivalent data collected for six periods between January 29 and March 13 were then used to test or verify the models.

Daily meteorological data were obtained for a weather station approximately 10 miles southwest of the snow courses on the St. Paul Campus of the University of Minnesota.[1] Climatological data from the National Weather Service at the Minneapolis-St. Paul International Airport were also used to supplement the data base.

The computer simulations were performed with the University of Minnesota CYBER-74 computer (Control Data Corporation). The generalized snowmelt equations model required an octal core memory of 47600 and an average central processing time of two seconds. The SNOWMELT model required an octal core memory of 47200 and an average processing time of 10 seconds. These core memory requirements could be reduced with overlay procedures.

Results and Discussion

Based on both calibration and test data, all three models performed similarly in terms of snowmelt predictions (Figures 1 through 5). In general, predictions were better for the forested than open conditions.

Degree Day Model

For this model, daily maximum temperatures with a $0^{o}C$ ($32^{o}F$) base temperature provided better snowmelt predictions than other combinations of base temperatures and mean daily temperatures. Melt rate coefficients determined from calibration were .082 cm/^{o}C-day (.018 in/^{o}F-day) for the open area (Figure 1), and .068cm/^{o}C-day (.015 in/^{o}F-day) for the forested area (Figure 2).

Generalized Snowmelt Equations

Little difference was observed between snowmelt predictions of the generalized snowmelt equations and the degree-day model. During the calibration period, the forest cover factors were fixed and the shortwave radiation and convection-condensation melt factors were adjusted to obtain the best fit with observed data. These adjustments resulted in slightly better predictions for the forested sites (Figures 2, 4 and 5) than the open site (Figures 1 and 3).

Snowmelt Model

Output from SNOWMELT includes interception of precipitation, the energy balance components of the snowpack, final snowpack temperature and snow water equivalent. Melt values used in the comparison were taken as the difference in snow water equivalent plus precipitation for any given period. The effects of initial condition estimates were eliminated by starting the simulation three months before the evaluation period.

Several of the basic watershed parameters were varied during calibration in an effort to obtain the most accurate snowmelt simulation. For 1976, a forest canopy density of 0.63 was used and the best fit with observed data was obtained with a transmissivity coefficient of 0.5 and a melt threshold temperature of $0^{o}C$ ($32^{o}F$). For the open area a transmissivity coefficient of 1.0 and a threshold temperature of $-1^{o}C$ ($30^{o}F$) were best.

One problem encountered during simulation, was that calculated snowpack temperature was found to be unrealistically cold after a period of accumulation. This lasted for only one day after which snowpack temperature returned to normal. The effects of this anomaly did not appear to adversely affect snowmelt prediction.

Results using observed solar radiation data were compared with those using solar data synthesized by the model. Greater variability of simulations was noted when observed data were used.

---

1 Data were provided by Dr. Donald Baker, Dept. Soil Science, University of Minnesota.

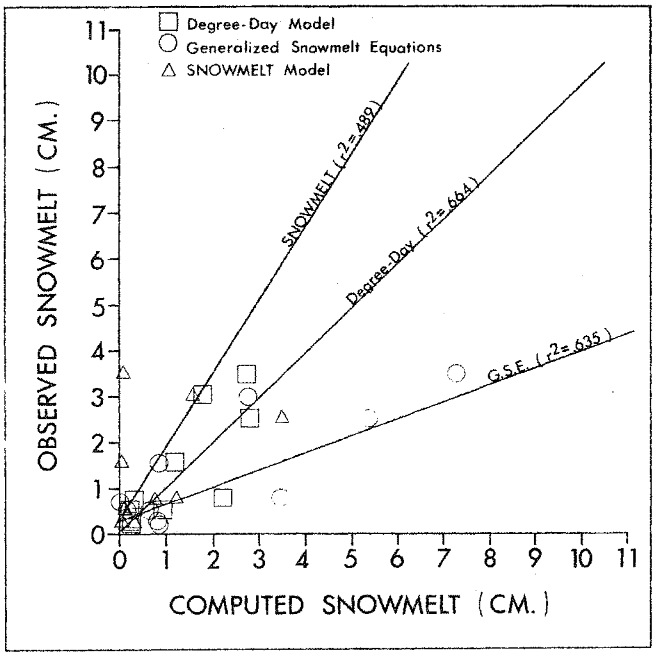

Figure 1. Model calibration results for the open sites, computer versus observed (1976) snowmelt.

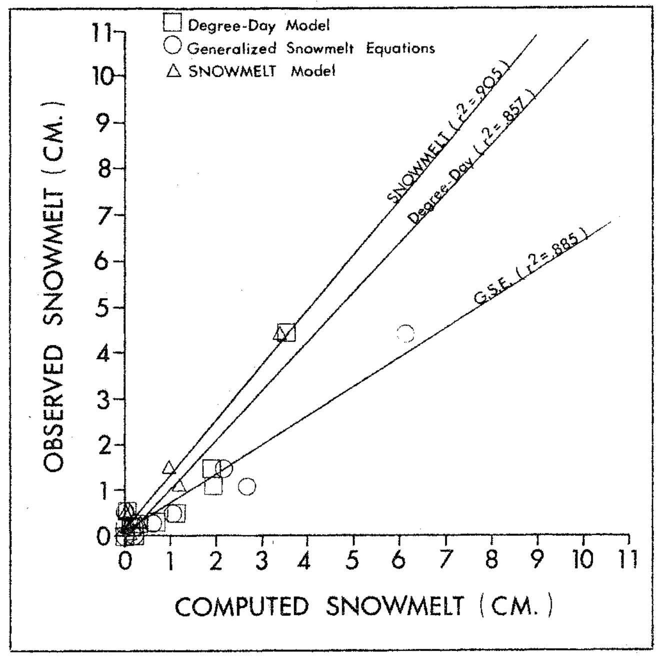

Figure 2. Model calibration results for the forested site, computed versus observed (1976) snowmelt.

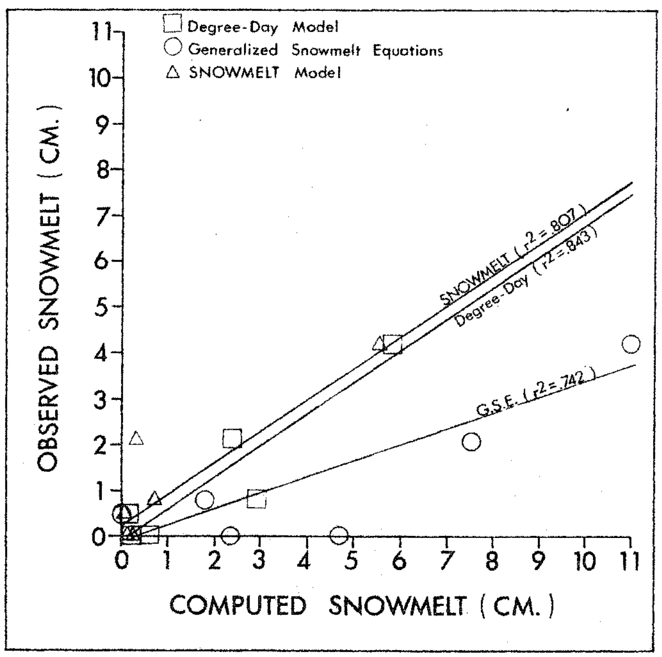

Figure 3. Model test results for the open site, computed versus observed (1977) snowmelt.

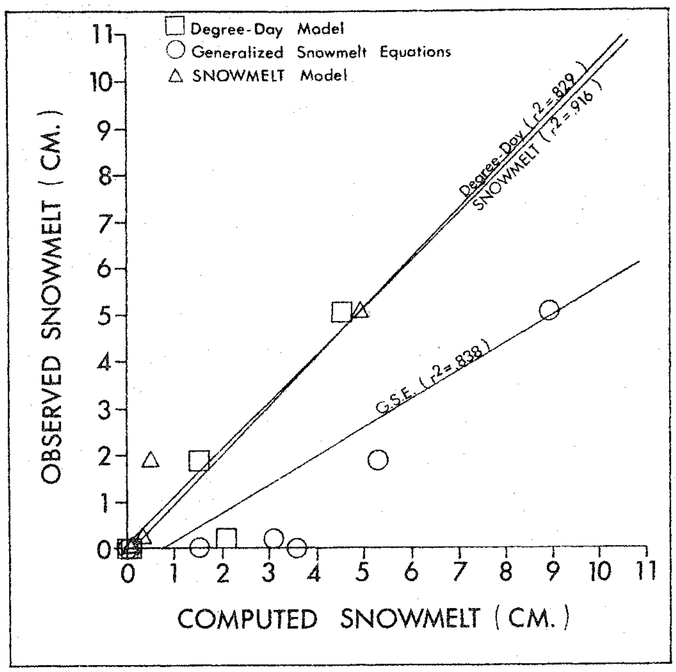

Figure 4. Model test results for the forest site with 40 percent canopy coverage, computed versus observed (1977) snowmelt.

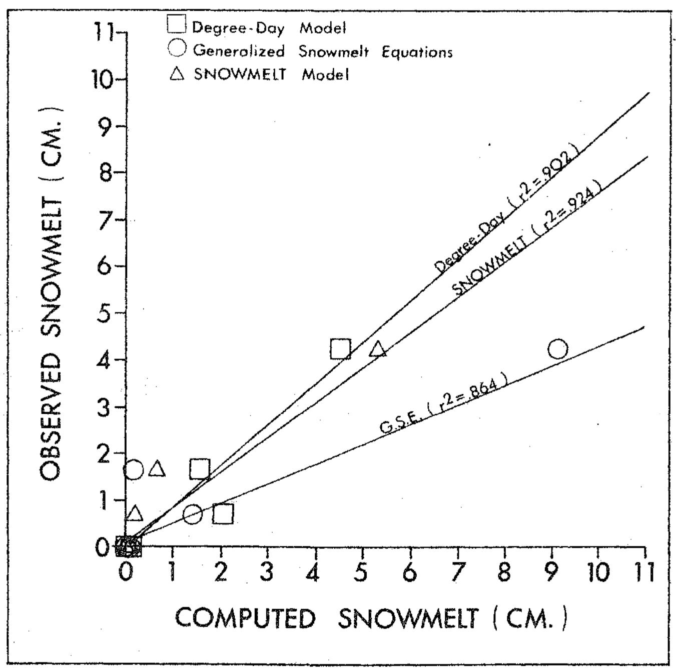

Figure 5. Model test results for the forest site with 80 percent canopy coverage, computed versus observed (1977) snowmelt.

A sensitivity analysis was performed on the model parameters, and as indicated by Baker and Carder (1977), the temperature adjustment factor greatly affected snowmelt computations. Selecting either the spruce-fir or the lodgepole pine types seemed to have little effect on snowmelt computations.

As with any continuous simulation model, a longer period of data may enhance model calibration and verification considerably. The computed melt, however, matched observed melt for the 1977 test data for both forest covers (Figutes 4 and 5). The accuracy of the open area simulation (Figure 3) was less than that of the forested areas (Figures 4 and 5).

Conclusions

Based on the cover conditions studied and data for two snowmelt seasons in Minnesota, the degree-day model, the generalized snowmelt equations and the SNOWMELT model were comparable in accuracy. In general, all three models more accurately predicted snowmelt for forested than nonforested sites. A greater accountability of energy budget components and snowpack condition did not appear to improve snowmelt predictions. For operational streamflow forecasting, therefore, the degree-day model is appropriate because it requires little calibration time and fewer data.

REFERENCES

Baker, D. G. 1972. Prediction of spring runoff. Water Resources Res. 8(4):966-972.

Baker, M. B., Jr. and D. R. Carder. 1977. Comparative evaluations of four snow models. Proceedings, 45th Western Snow Conference, Albuquerque, New Mexico, pp. 58-62.

Chu, C. S. and C. E. Bowers. 1977. Computer programs in water resources. WRRC Bull. 97, Water Resources Research Center, University of Minnesota, Minneapolis.

Frank, E. C. and R. Lee. 1966. Potential solar beam irradiation on slopes. Tables for 30^{o} to 50^{o} latitude. USDA For. Serv. Res. Pap. RM-18, 116 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Leaf, C. F. and G. E. Brink. 1973. Computer simulation of snowmelt within a Colorado subalpine watershed. USDA For. Serv. Res. Pap. RM-99, 22 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Solomon, R. M., P. F. Ffolliott, M. B. Baker, Jr., and J. R. Thompson. 1976. Computer simulation of snowmelt. USDA For. Serv. Res. Pap. RM-174, 8 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Steppuhn, H., H. R. Krouse and D. E. L. Erickson. 1975. Contributions to runoff from a melting prairie snow patch as traced by oxygen-18. Proceedings, 43rd Western Snow Conference, Coronado, California, pp. 28-34.

U.S. Army Corps of Engineers. 1956. Snow Hydrology. North Pacific Division, Portland, Oregon.