A COMPARISON OF TWO MODELS TO PREDICT SNOWMELT IN MUSKOKA-HALIBURTON, ONTARIO

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ABSTRACT

Two models (MOEHYDR and WINTER) which simulate the accumulation and melt of a snowpack are described. The MOEHYDR model is based on energy balance and aerodynamic principles whereas the simpler WINTER model uses air temperature and precipitation as indices of heat exchange between the snowpack and the environment. The models were compared on the basis of their ability to predict the water equivalent content of the snowpack and on their ease of operation. The WINTER model provided results which agreed more closely to observed data obtained from a snow survey taken in Muskoka-Haliburton during 1981-82. Because of its simplicity, it was also concluded that the WINTER model was more readily applicable in areas with limited meteorological data.

INTRODUCTION

Acidic deposition has been reported over much of eastern North America (Likens et al. 1979). In the Muskoka-Haliburton area of Ontario, mean annual precipitation pH values of 4.0-4.2 have been observed (Scheider et al. 1979). Much of the acidic input entering lakes and streams in Muskoka-Haliburton does so during snowmelt and spring runoff (Jeffries et al. 1979) resulting in short term pH depressions. Damage to aquatic biota during the spring has been reported (Harvey 1979).

The ability to predict such changes in stream chemistry would be of use to environmental planners and managers. Several models have been developed which predict the chemistry of stream water occurring under a given deposition scenario (Christophersen et al. 1982, Chen et al. 1982, Schnoor et al. 1982). These models depend critically on an adequate hydrologic submodel because most of the chemicals entering and leaving the watershed are in aqueous form. A continuous daily streamflow model (Tennessee Valley Authority 1972) is being modified and tested for use in the Muskoka-Haliburton area as an integral part of a stream chemistry model. An important modification to the TVA model is the addition of a snow accumulation and melt routine. This paper describes two such snowmelt models and compares them on the basis of their ability to predict the water equivalent content of a snowpack and on their applicability to areas with limited meteorological data.

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Snowmelt is a function of the net heat exchange between the snowpack and its surroundings. The important processes influencing heat transfer are absorbed short-wave radiation, net longwave radiation, latent heat of vaporization derived from condensation, heat transferred from the air by convection, heat transferred from the ground by conduction and heat transferred by rainwater. Of the many approaches available for modelling snowmelt (see review in Gray 1970, Viessman et al. 1977), we have chosen a simple, empirical technique based on air temperature and precipitation (U.S. Army Corps of Engineers 1956) and a more complex approach (Logan 1976, 1977) based on energy balance and aerodynamic principles. Both methods have been modified for application in the Muskoka-Haliburton study area and the results compared to snow survey data collected at Harp Lake during 1981-82.

DESCRIPTION OF STUDY AREA

A map of the study area showing the location of Harp Lake is shown in Figure 1. Thirty-year averages of meteorological data taken from the Hydrological Atlas of Canada (1978) indicate that mean annual precipitation depth in the area ranges from 90-110 cm yr^{-1}, with 240-300 cm of snow falling per year generally between December 1 and April 10. Mean January air temperature is -10°C. Annual net radiation averages 40 Kcal cm^{-2}yr^{-1}. Further information on the general hydrologic and hydrometeorologic characteristics of the area are given by Scheider et al. (1983).

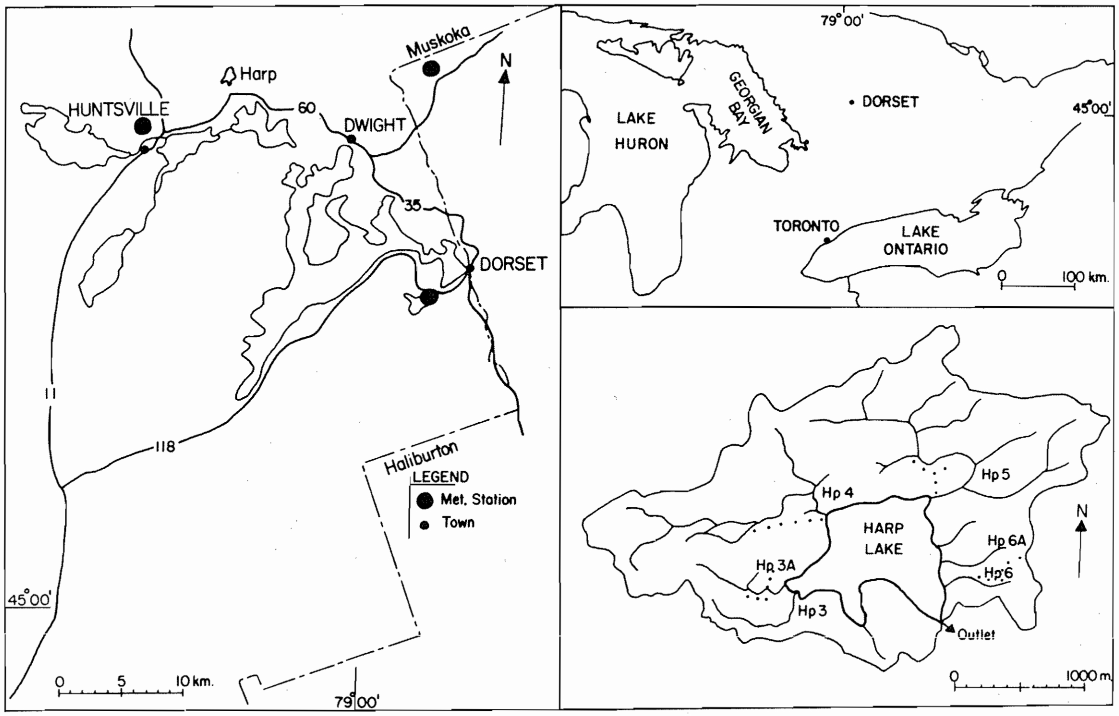

Figure 1. Location of study area, showing closest meteorological stations. Location of 4 snow courses (six sites per course, denoted by •) around Harp Lake.

The location of the four snow courses in the Harp Lake watershed are also shown in Figure 1. Harp Lake (surface area 66.9 ha) is at an elevation of 325 m above sea level. The topography is hilly and the basin is forested with the exception of small logging operations and clearings near the shore of the lake for houses.

METHODS OF DATA COLLECTION

Four snow courses were chosen (Figure 1) at Harp Lake, each consisting of six sampling sites spaced about 50 m apart extending from the lake up into the watershed. Sampling sites (approximately 2 m by 2 m in size) were located in small clearings where possible. The snow survey was carried out with a spring balance Utah snow corer (43" high with ID 3.5") on a weekly basis from January 7, 1982 - March 11, 1982 (initial sampling on Harp 4 was done January 12, 1982 but thereafter all courses were sampled on the same day). After March 11, the survey was carried out every 3-4 days until the snowpack had disappeared at all sites (April 30, 1982). Data on snow depth, water equivalent content and density were obtained for each of the 24 sampling sites (reported by Goebel (1983) in full).

Air temperature and precipitation data for Harp Lake were interpolated from data collected at the closest surrounding two meteorologic stations at Huntsville ($\simeq$8 km southwest) and Dwight ($\simeq$17 km east). Data from the stations were weighted according to the inverse square of the distance between the station and Harp Lake. Other necessary data to operate one of the snowmelt models included wind velocity (obtained from Dorset), dew point temperature (Dorset), vapour pressure (Dorset), net radiation (Ottawa) and potential evaporation (calculated from Morton et al. 1980 using data from Dwight and Huntsville).

DESCRIPTION OF SNOWMELT MODELS

Winter Model

A model (WINTER) was developed to simulate snow accumulation and melt based on mean daily air temperature and daily precipitation. The method, based on equations reported by the U.S. Army Corps of Engineers (1956), is a simple one and uses air temperature and precipitation as indices of heat exchange between the snowpack and the environment. A threshold temperature (mean daily) below which all precipitation was considered to be snow was chosen at 1.5°C based on observed data. If the mean daily temperature remained below 1.5°C all precipitation accumulated in the snowpack. Otherwise, the melting of the pack was simulated using the following two equations for dry weather (equation 1) and rain conditions (equation 2).

$$\text{melt} = 1.3\ T \tag{1}$$

$$\text{melt} = (3.5 + 0.012\ P)\ T + 1.2 \tag{2}$$

where:

melt = daily amount of snowmelt (mm day^{-1})
T = mean daily air temperature ($^{\circ}$C)
P = total daily precipitation (mm day^{-1})

The coefficients in these equations were chosen to provide the best agreement between the observed and simulated water equivalent content of the snowpack. The model also incorporated the retention of a small amount of liquid water (3%) in the snowpack to account for the ripening of the pack toward the end of the winter. The algorithm for the model is shown in Figure 2.

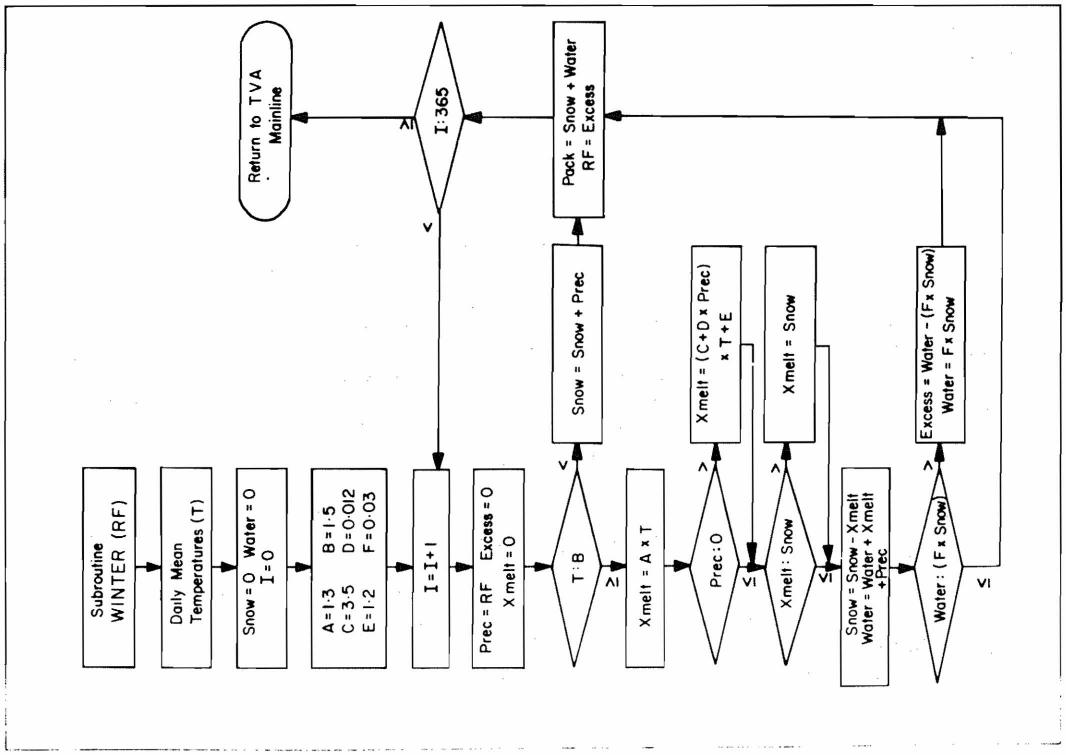

Figure 2. Algorithm for WINTER snowmelt model.

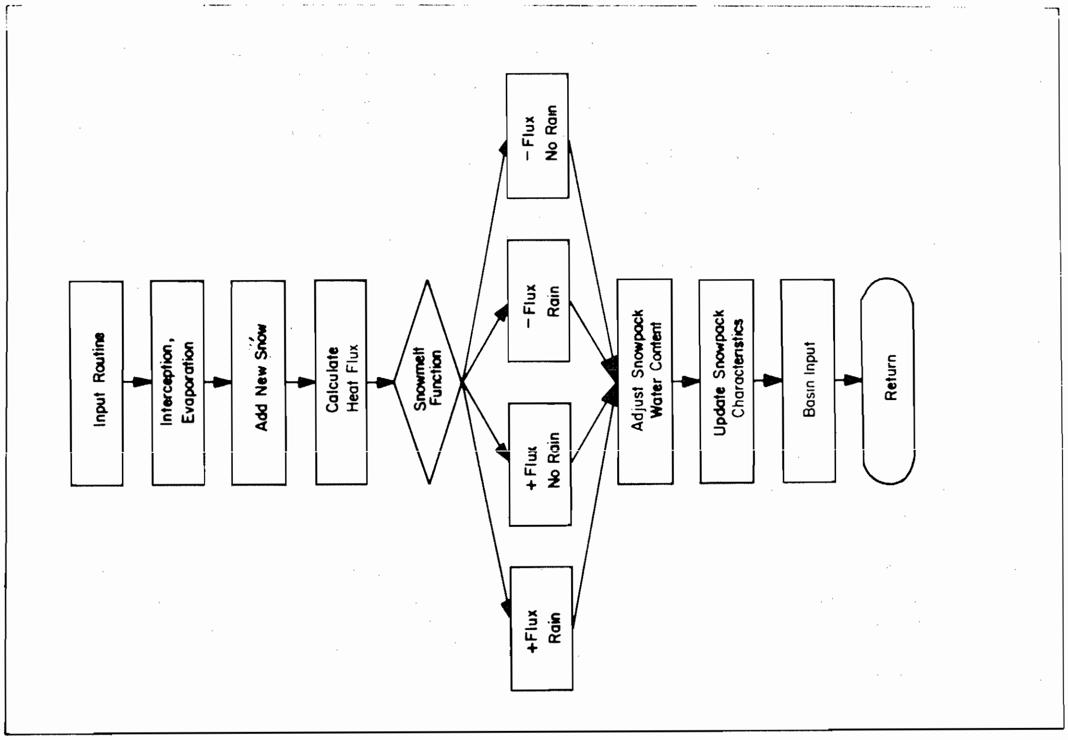

Figure 3. Flow chart for MOEHYDR snowmelt model.

MOEHYDR Model

The MOEHYDR model was described by Logan (1976, 1977) and only a brief review will be given here. Input data requirements for the operation of MOEHYDR are extensive. While various options exist for allowing flexibility in these requirements, the data actually used in this study were daily rainfall, daily snowfall, mean daily air temperature, wind velocity, dew point temperature, vapour pressure, net radiation and potential evapotranspiration.

The first step taken in the model (Figure 3) is to add any new snow to the old snowpack. If there was no previous snow then the new snowpack density is set at 0.1 and the initial snowpack temperature is set equal to the air temperature. The new depth, density and water equivalent content of the snowpack are calculated and the new potential water holding capacity is estimated based on an empirically derived function of the snowpack density. Allowance is also made for interception storage at this point. After verifying that there is still some snowpack left in the system, the model proceeds to reduce the snowpack by an amount reflecting the evaporation from the snow.

The net energy balance of the snowpack is described by the following equation:

$$H = -h_c + h_r + h_{cd} + h_{cv} + h_{cg} + h_{rn} \qquad (3)$$

where:

H = heat equivalent of melt
h_c = heat capacity of the snowpack
h_r = net radiation energy
h_{cd} = heat of condensation/sublimation
h_{cv} = heat of convection
h_{cg} = heat of conduction (ground melt)
h_{rn} = heat of advection in rainfall

The potential melt (M) of the snowpack is calculated as:

$$M = (H + h_c)/T_gL_f) \qquad (4)$$

where

T_g = thermal quality of the snowpack
L_f = latent heat of fusion of ice at 0^oC

Having estimated the net energy flux there are eight different possibilities for proceeding further. There can be either a positive or a negative heat flux, rain or no rain, and the antecedent snowpack condition (thermal quality) may be less than or greater than one. For each case the physical situation calls for a different treatment of the snowpack.

In the situation of a negative energy flux, any liquid water present in the snowpack may be frozen. This process reduces the heat deficit of the snowpack by releasing a proportional amount of latent heat of fusion. With no liquid water present, the negative energy flux causes a reduction in the snowpack temperature. If the energy flux is negative and rain occurs, then some or all of the rain may also freeze. Any unfrozen water is added to the liquid water present and any excess may be drained.

If the energy flux is positive, the simplest case is that the snowpack heat deficit is increased. Only when the snowpack temperature reaches the melting point and the heat deficit is satisfied, can liquid water exist in the snowpack. Any meltwater that is produced first fills the water holding capacity of the snowpack and then becomes excess water. In the presence of rain any heat deficit may cause freezing of some of the precipitation, in the process releasing latent heat of fusion and thereby increasing the snowpack temperature. Once the heat deficit is satisfied, any further liquid precipitation

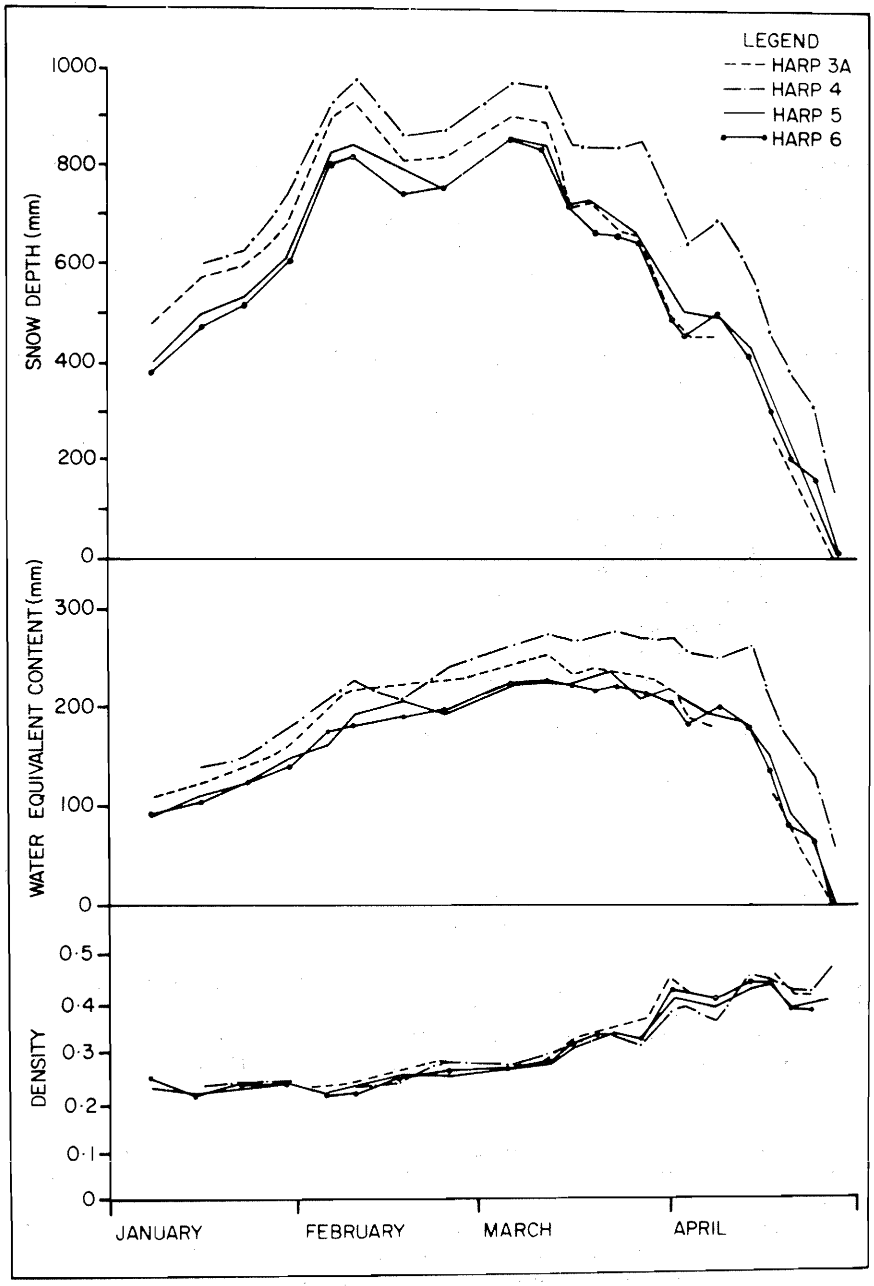

Figure 4. Snow depth (mm), water equivalent content (mm) and density for four snow courses at Harp Lake, 1981-82.

is added to any liquid water present in the snowpack and excess water can be released after the holding capacity of the snowpack is satisfied.

The final stage in MOEHYDR is to adjust the snowpack density and thereby the depth of the snowpack if warranted. This part of the model is based on regression equations obtained using the observations from the Harp Lake snow survey. The regression equations are as follows:

Accumulation period and no rain -

$$DENS = 0.0998 + 0.0341 (\ln depth) \tag{5}$$

Accumulation period with rain -

$$DENS = 0.0248 + 0.512 (\ln depth) + 0.0095 (rain) \tag{6}$$

Melt period and no rain -

$$DENS = 0.5324 - 0.0397 (\ln depth) \tag{7}$$

Melt period with rain -

$$DENS = 0.5338 - 0.0390 (\ln depth) - 0.0047 (rain) \tag{8}$$

where:

DENS = estimated snowpack density (g/cc)
depth = observed depth of snow (cm)
rain = total daily rainfall (cm)

RESULTS AND DISCUSSION

Replicability of Snow Survey Data

The temporal trends of mean snow depth, water equivalent content and snowpack density are shown in Figure 4. Although the results were similar for all four snow courses, the depth and water equivalent content of the snow at the Harp 4 snow course was consistently greater than that observed at the other snow courses, reflecting the difference observed on the initial sampling date. The hypothesis that there was no significant variation in the mean values of snow depth or water equivalent content between the four snow courses was tested using ANOVA. The replicates for each course were data from the six sampling sites. The results showed that for each observation date except one, there were significant differences (at 0.05 level) in snow depth and water equivalent content between the snow courses. Because the sampling methodology was such that the measurements were cumulative and as the difference in snow depth between the Harp 4 snow course and the other snow courses was observed on the first sampling date (when snow depth was already ≃0.5 m), the ANOVA tests were repeated using data on the difference or change in observed snow depth and water equivalent content between two consecutive sampling dates starting January 15 (Table 1). The results showed that on only one sampling date was there a significant difference in snow depth between the courses and on only four of twenty dates were there significant differences in the value of water equivalent depths between the four snow courses. For this reason, and because of the geographical proximity of the snow courses, we have pooled the results of the 24 sampling sites to obtain single mean values of snow depth, water equivalent content and density for use in the snowmelt modelling.

WINTER Simulation Results

The snowpack water equivalent contents as simulated by the WINTER model are compared to the observed data in Figure 5. Initially, the model underestimated the water equivalent but this trend reversed itself by early February. On almost all sampling

Table 1: Results of ANOVA for changes in snowpack depth and water equivalent content between consecutive sampling dates. Data obtained from snow survey at Harp Lake 1981-82. Critical value for F(3, 20; 0.05) = 3.098.

Dates	F-Ratio for Change In Snow Depth	F-Ratio for Change In Water Equivalent
Initial	5.418	5.667
January 15-22	1.053	0.769
January 22-29	2.226	1.229
January 29 - February 5	1.517	3.299
February 5-11	0.672	2.772
February 11-19	2.960	5.297
February 19-26	3.088	6.749
February 26 - March 5	0.409	0.922
March 5-11	0.278	0.454
March 11-15	2.342	1.361
March 15-19	2.562	0.946
March 19-22	1.930	0.247
March 22-26	0.609	1.317
March 26-31	0.584	2.275
March 31 - April 2	0.946	0.350
April 2-7	1.128	1.767
April 7-16	2.103	1.230
April 16-19	0.193	0.565
April 19-23	1.347	1.048
April 23-26	1.563	1.336

dates, the simulated water equivalent content was within one standard deviation of the mean observed snowpack water equivalent content. The model results also agreed with the observed data with respect to the date of the disappearance of the snowpack (April 30). Based on 24 observations, the model was able to explain 97.7% ($r^2 = 0.977$) of the variance in the observed data and was capable of estimating the snowpack water equivalent content to within 5.4 mm on average (mean value of observed-estimated = 5.4 mm).

MOEHYDR Simulation Results

The results of the MOEHYDR model in simulating the water equivalent content of the Harp Lake snowpack are shown in Figure 6. The MOEHYDR model also simulates snow depth, density, temperature and thermal quality but as these are not required by the TVA streamflow model they are not reported here. The model initially underestimated the water equivalent content of the snowpack and did so continuously until early April. The simulated water equivalent content lay outside one standard deviation of the mean of the observed on half of the dates. The model was able to explain 88.0% ($r^2 = 0.880$) of the variance in the observed data, and was capable of estimating the water equivalent content to within -20.6 mm on average (mean value of observed-estimated = -20.6 mm).

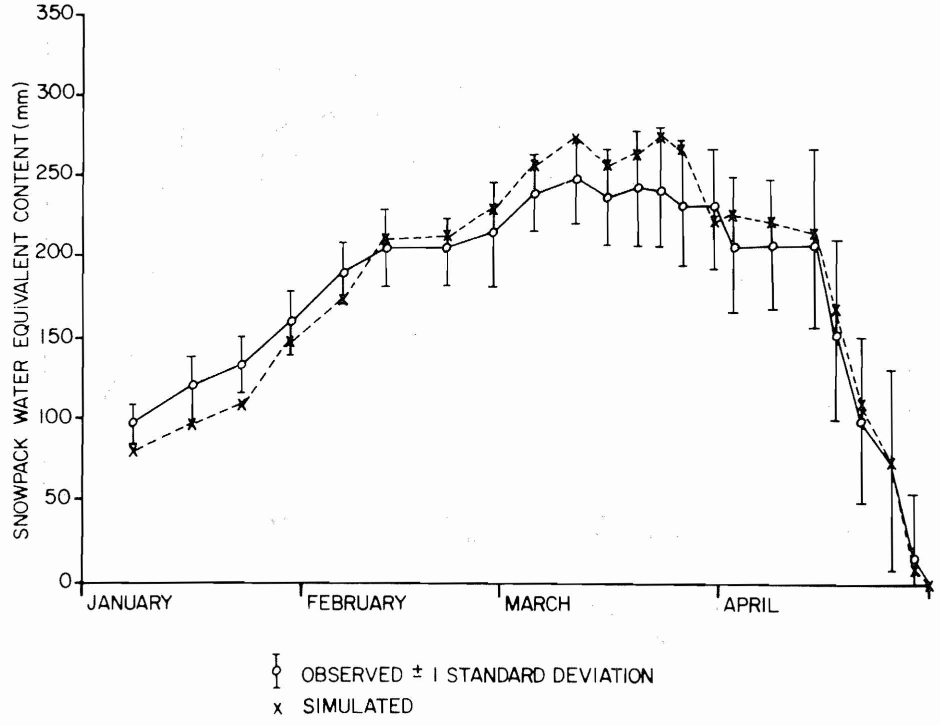

Figure 5. Comparison of simulated (WINTER) and observed water equivalent content (mm) at Harp Lake, 1981-82.

Comparison of Models

The ability of the two models to simulate the water equivalent content of the snowpack at Harp Lake was chosen as one criterion for model comparison. On this basis, the WINTER model was judged to be superior in that it explained a greater amount of the variance in the observed data than did the MOEHYDR model (r^2 between predicted and observed water equivalent = 0.977 and 0.880 respectively). The mean error of prediction for the WINTER model (5.4 mm) was lower than that for the MOEHYDR model (-20.6 mm). However, the TVA and other watershed models require excess melt as input data. The comparison

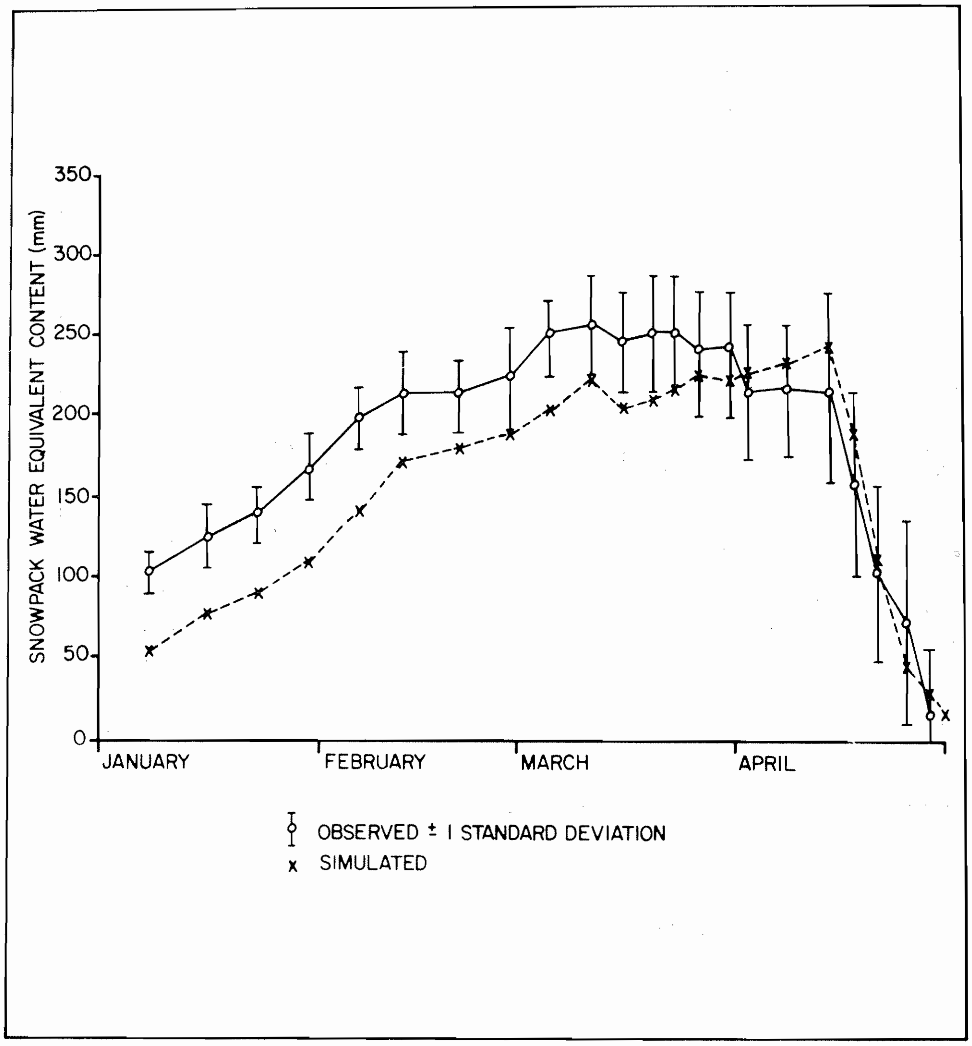

Figure 6. Comparison of simulated (MOEHYDR) and observed water equivalent content (mm) at Harp Lake, 1981-82.

of moisture release from the snowpack for the two models (Figure 7) shows that differences exist in the timing as well as the amount of excess melt product. A test of the models which would take this into account would be to compare the predicted and observed streamflow volume in the period of snowmelt. These data were not available for this study and will be presented elsewhere.

The ease of operation and the applicability of the models to areas with limited meteorological data were other criteria on which the models were compared. Because of its simplicity and the fact that only a few readily available meteorological data are required for its application, the WINTER model was judged to be better in this regard as well. However, as the melt coefficients used in the WINTER model were determined specifically for the Harp Lake study site, they may not be representative for other areas. The MOEHYDR model addresses most of the physical processes involved in snowmelt and may there-

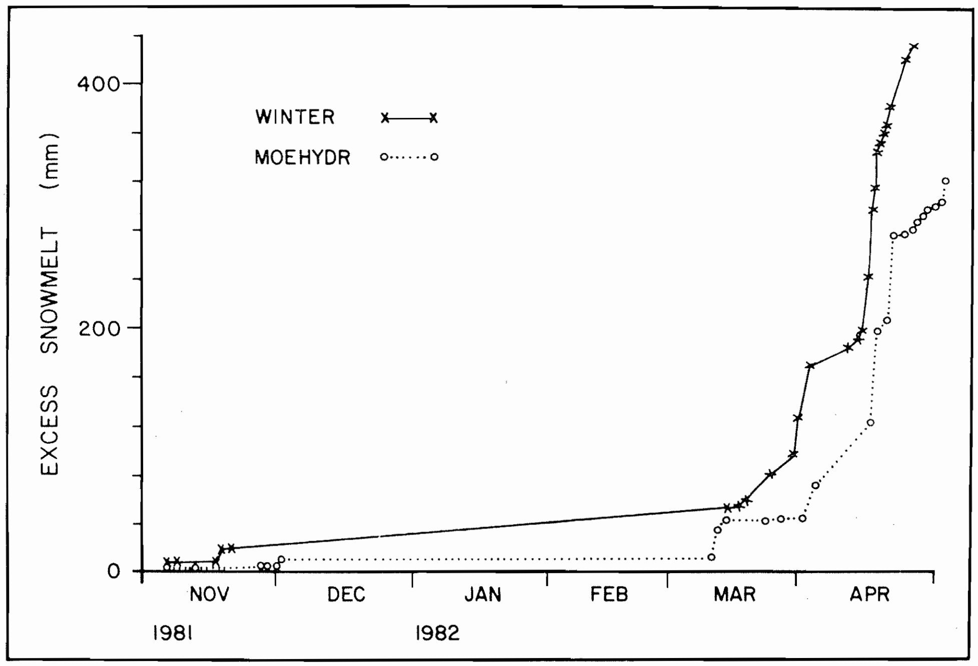

Figure 7. Comparison of excess snowmelt simulated by the WINTER and MOEHYDR models for Harp Lake, 1981-82.

fore be more widely applicable.

SUMMARY

Two snowmelt models, one based on air temperature and precipitation as indices of heat exchange between the snowpack and the environment (WINTER) and the other based on energy balance and aerodynamic principles (MOEHYDR), were modified for use in the Muskoka-Haliburton area of Ontario. The models were tested against snow survey data collected at Harp Lake in 1981-82. Data from four snow courses were combined into a single record of snowpack depth, density and water equivalent content after ANOVA showed there to be no significant differences between them.

Although both models were shown to be useful in simulating the water equivalent content of the snowpack, the WINTER model gave results which agreed more closely with the observed data. Because fewer and more readily available data were required to operate the WINTER model, it was judged to be more easily applicable to areas with limited meteorological data. However, as the model coefficients for WINTER were derived specifically for the Harp Lake site, the WINTER model may not be as widely applicable as the MOEHYDR model.

The ability of both models to provide acceptable estimates of moisture release from the snowpack makes them useful complements to models which simulate streamflow. On the basis of the comparisons in this study the WINTER model will be integrated with the

TVA streamflow model to predict runoff in the Muskoka-Haliburton area as a basis for modelling changes in stream chemistry.

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