Field testing of simulated soil freezing and thawing by the SHAW model

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Hayhoe, H.N. 1994. **Field testing of simulated soil freezing and thawing by the SHAW model.** Can. Agric. Eng. **36**:279-285. Winter conditions associated with freezing, thawing, and soil moisture changes are important factors for a number of agricultural applications. In this study, the SHAW (Simultaneous Heat And Water) model was evaluated on predicting winter conditions (i.e., soil temperature, moisture content, snow cover, and depth of frost penetration) at a natural snow covered site and a site with the snow removed for the winter season of 1983-1984. The model successfully estimated the observed snow depth, the temperature extremes, and changes in total and liquid water content. Observed maximum frost penetration was 1.02 m while the estimated was 1.04 m. The root mean square (RMS) difference between simulated and measured soil temperature was ≤ 1.5°C and between simulated and measured volumetric soil water content was ≤ 0.04 $m^3 \bullet m^{-3}$. The estimated last day with snow cover was within 2 days of the observed date. These results confirm the usefulness of the SHAW model to simulate these winter conditions.

Les conditions d'hiver associées au gel, au dégel et aux changements hydriques du sol sont des facteurs importants pour plusieurs applications agricoles. Dans cette étude, le modèle SHAW (Simultaneous Heat And Water) a été évalué pour sa capacité à prédire les conditions hivernales (i.e., température du sol, teneur en eau, couverture de neige, et profondeur du gel) à un site couvert de neige naturelle et à un site d'où la neige a été enlevée, durant la saison d'hiver 1983-1984. Le modèle a estimé avec succès l'épaisseur de la couverture de neige observée, les températures extrêmes, et les changements de la teneur en eau liquide et totale. La profondeur maximale du gel observée a été 1.02 m, alors que la valeur estimée était 1.04 m. La racine carrée de l'écart quadratique moyen entre la température du sol simulée et celle observée a été ≤ 1.5°C; la racine de l'écart quadratique moyen entre la teneur en eau volumétrique du sol mesurée et celle simulée a été ≤ 0.04 $m^3 \bullet m^{-3}$. L'erreur d'estimation du dernier jour avec couverture de neigé a été de 2 jours ou moins. Ces résultats confirment l'utilité du modèle SHAW pour simuler ces conditions hivernales.

INTRODUCTION

Winter conditions associated with snow cover and frozen soil are important in a wide range of agricultural areas. Extreme soil temperatures and soil ice affect winter survival of crops as well as pests (Larsen et al. 1988). Runoff and soil water transfer are important concerns for the analysis of soil erosion and for spring soil moisture reserves in dryland areas (Zuzel and Pikul 1990). Spring soil moisture conditions are often critical for pollution control to reduce contamination of ground water through infiltration and pollution of rivers and lakes by runoff and erosion. There is widespread interest in management practices which can be used to moderate the extreme conditions (Benoit et al. 1986).

A number of models have been developed to simulate winter soil moisture and temperature (Jame and Norum 1980). Most of these models focus primarily on winter soil temperature because of the complexity of water transfer in partially frozen soil (Goodrich 1982; Hayhoe and Tarnocai 1993). Technological advances have contributed to our ability to monitor processes which occur in the field during the winter as well as to our capacity to simulate a more comprehensive set of processes. The SHAW model is an example of a comprehensive, user-friendly system which quantifies a large number of processes occurring in the field (Flerchinger and Saxton 1989a, 1989b).

The SHAW model has been tested for a range of conditions (Flerchinger et al. 1990; Flerchinger and Pierson 1991) and compared with other models (Pierson et al. 1992). At the same time, because of the lack of data on winter soil moisture conditions, some of the winter components have not been extensively compared with field data. Data collected at Ottawa throughout the winter, which include measurements of total and unfrozen water content (Hayhoe et al. 1983; Hayhoe and Bailey 1985), provide insight into winter freezing and thawing processes and could contribute to the evaluation of the winter components of the model. This study is a contribution to validation of the SHAW model for winter conditions. Data collected during the winter of 1983-84 are compared with the SHAW model estimates of snow depth, total and liquid water contents, soil temperature, and freeze and thaw penetration starting before freeze up and continuing untill the spring thaw is complete.

METHOD

SHAW model

The SHAW model is a process-based model designed to simulate the physics of water and heat transfer in a plant-snow-residue-soil system (Flerchinger and Saxton 1989a, 1989b). It incorporates transport process models presented by Campbell (1985). The input data requirements for the SHAW model have been summarized by Pierson et al. (1992). It is designed to use hourly values of air temperature, wind speed, relative humidity, solar radiation, and precipitation to estimate surface boundary fluxes, although more recent versions can use daily values. Heat, liquid and vapour transfer through the snow, residue, and soil by convection, and conduction are estimated with one-dimensional heat and water flux equations. Since a detailed description of the process model has been given by Flerchinger and Saxton (1989a), only the equations for soil transfer processes are presented here. The heat flux equation for a layer of potentially freezing soil is specified by:

$$\frac{\partial}{\partial z}\left(k_s\frac{\partial T}{\partial z}\right)+\rho_l c_l\frac{\partial(q_l T)}{\partial z}+S = C_s\frac{\partial T}{\partial t}-\rho_i L_f\frac{\partial\theta_i}{\partial t}+L_v\left(\frac{\partial\rho_v}{\partial t}+\frac{\partial q_v}{\partial z}\right) \quad (1)$$

where:

k_s = thermal conductivity of soil ($W{\bullet}m^{-1}{\bullet}{}^oC^{-1}$),
T = temperature (^oC),
ρ_l = density of liquid water ($kg{\bullet}m^{-3}$),
c_l = specific heat capacity of water ($J{\bullet}kg^{-1}{\bullet}{}^oC^{-1}$),
q_l = downward liquid water flux ($m{\bullet}s^{-1}$),
S = source/sink term ($W{\bullet}m^{-3}$),
C_s = volumetric heat capacity of soil ($J{\bullet}m^{-3}{\bullet}{}^oC^{-1}$),
ρ_i = density of ice ($kg{\bullet}m^{-3}$),
L_f = latent heat of fusion ($J{\bullet}kg^{-1}$),
θ_i = volumetric ice content ($m^3{\bullet}m^{-3}$),
L_v = latent heat of vaporization ($J{\bullet}kg^{-1}$),
ρ_v = vapour density within snow, residue, or soil ($kg{\bullet}m^{-3}$),
q_v = downward water vapour flux ($m{\bullet}s^{-1}$),
t = time (s), and
z = depth from surface (m).

The equation for liquid and vapour flow through a frozen or unfrozen, unsaturated vertical soil profile is specified by:

$$\frac{\partial}{\partial z}\left[K\left(\frac{\partial\psi}{\partial z}+1\right)\right]+\frac{1}{\rho_l}\frac{\partial q_v}{\partial z}+U=\frac{\partial\theta_l}{\partial t}+\frac{\rho_i}{\rho_l}\frac{\partial\theta_i}{\partial t} \quad (2)$$

where:

K = unsaturated hydraulic conductivity ($m{\bullet}s^{-1}$),
ψ = soil matric potential (m),
U = source/sink term in water flux equation ($m^3{\bullet}m^{-3}{\bullet}s^{-1}$), and
θ_l = volumetric liquid water content ($m^3{\bullet}m^{-3}$).

Initial and boundary layer soil temperature and water content are required inputs. Soil data requirements include: layer thickness, bulk density/porosity, texture, saturated hydraulic conductivity, saturated water content, soil water characteristics, and soil albedo. In this study, the version of the SHAW model released in May, 1993 was used. It included a user-interface enhancement which provided menus designed for ease of data entry. The user-interface either suggests or estimates parameters for input into the simulation model. It is designed to run on an IBM PC or compatible microcomputer. The required input for soil properties can be derived from bulk density and texture (Saxton et al. 1986).

Observed data

Details of the experimental procedures and collection site layout have been reported previously (Hayhoe and Bailey 1985). The data were collected at Ottawa, Ontario from November 1983 through April 1984 on a sandy loam soil of the Uplands Association. The surface was of gently sloping topography (< 2%). The bulk density and particle size distribution are given in Table I. There were two test plots located 10 m apart. One plot was manually cleared of snow and the other was left with the snow cover undisturbed throughout the winter. Snow depth was monitored on the undisturbed site using a snow ruler. At both sites, time-domain reflectometry (TDR) transmission lines were installed in the soil for the measurement of unfrozen soil water content. Three pairs of stainless steel rods, 3 mm diameter, 50 mm apart, and 0.5 m long were installed at depths of 75, 150, and 225 mm. Four pairs of vertical stainless steel rods 6 mm diameter and 50 mm apart were installed to depths of 0.31, 0.51, 0.81, and 1.21 m (Hayhoe and Bailey 1985). A thin-wall aluminum tube with 48-mm inside diameter and 1.5 m length was inserted in the soil in the snow cleared site for neutron moderation measurements of total water content (frozen and unfrozen). It was within 2 m of the TDR lines. Starting in late November 1983, soil water contents at depths centred at 0.225, 0.32, 0.41, 0.54, 0.66, 0.84, and 1.0 m were taken with a Campbell Pacific Nuclear model 501 depth probe (Campbell Pacific Nuclear, Pacheco, CA). The TDR readings were taken using a portable TDR Tektronix model 1502 cable tester (Tektronix, Inc., Beaverton, OR). Temperature probes, consisting of thermocouples on a wooden dowel positioned every 50 mm down to 1.0 m and from there every 100 mm down to 1.4 m, were installed. Temperatures were recorded with a Campbell Scientific CR5 recorder (Campbell Scientific, Logan, UT). Frost-tubes (Hayhoe et al. 1983) were used to measure frost depth. Daily maximum and minimum air

Table I. Soil profile characteristics.

Horizon	Thickness (m)	Bulk density ($Mg{\bullet}m^{-3}$)	Particle size distribution Sand (%)	Silt (%)	Clay (%)
A	0.24	1.34	81	15	4
B_1B_2	0.65	1.63	92	7	1
B_3	0.35	1.69	97	2	1

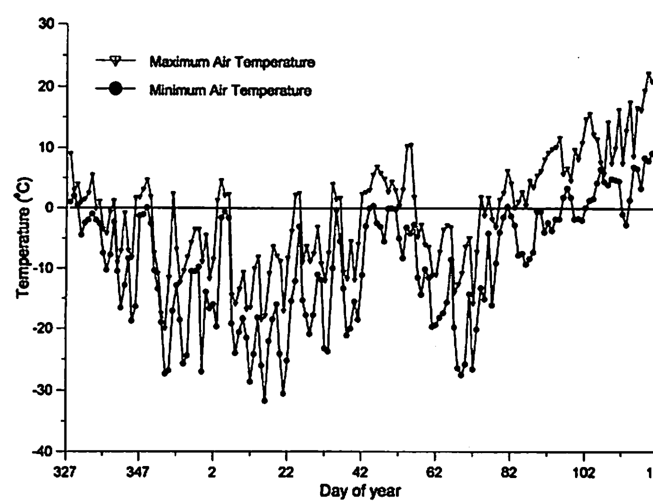

Fig. 1. Daily maximum and minimum air temperature from the climatological station.

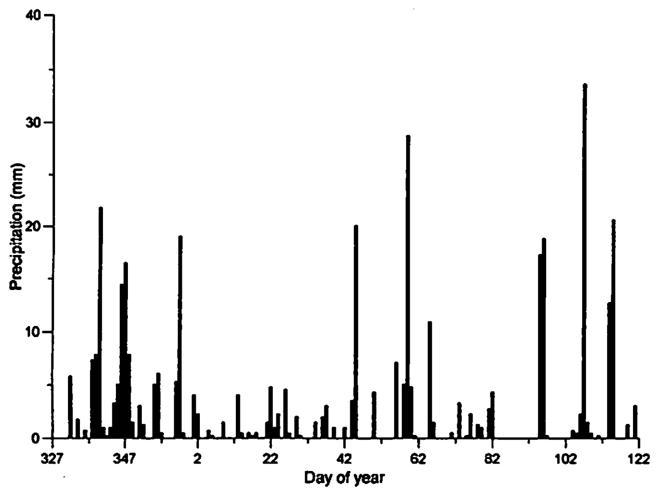

Fig. 2. Daily total precipitation including rainfall and the water equivalent of snowfall from the climatological station.

temperature (Fig. 1), dew-point, total wind run for the day, and precipitation (Fig. 2) were obtained from a climatological station located less than 1 km away. Daily solar radiation was measured at the experimental site.

Model setup

The new SHAW interface provided a user friendly shell to organize the simulation runs for the test sites. Any adjustments to the input data files created by the model shell could easily be made by using an editor or by running the model shell again. The saturated conductivity, air entry potential, and pore-size distribution parameter had a significant impact on water movement during freezing (Flerchinger 1991) and may require that the spatial and temporal grid be refined to avoid convergence problems and to obtain accurate estimates. A time step of 2 h was used. A soil profile of 1.4 m was simulated using 14 grid intervals. Grid intervals were 50 mm at the surface and increased to 0.2 m below 1.0 m. Linear interpolation and extrapolation were used to determine the initial soil temperature and soil water profile from measured values. Similarly, the bottom boundary conditions for the simulation were determined from measured soil temperatures and by extrapolation from measured soil water contents.

Thermal conductivities and volumetric heat capacities were estimated by the model as described by Flerchinger and Saxton (1989a). Soil thermal conductivity was calculated using the theory presented by De Vries (1963) and volumetric heat capacity was the sum of the volumetric heat capacities of the soil constituents. Soil water matric potential in the SHAW model is calculated with a power function of soil wetness and unsaturated hydraulic conductivity is determined from a power function of matric potential (Clapp and Hornberger 1978; Flerchinger and Saxton 1989a). The soil hydraulic parameters are specified in Table II. The horizon thickness (Table I) was adjusted so that the layer thickness in the model (Table II) matched the grid subintervals. The saturated hydraulic conductivities were determined using core samples. The saturated water content was based on the value for sand given by Clapp and Hornberger (1978). Permanent wilting points and field capacities were empirically estimated from the observed range in soil moisture. These values were used to calculate the pore-size distribution index and the air entry potential values in Table II by solving the power function equations relating matric potential to water content (Clapp and Hornberger 1978; Flerchinger and Saxton 1989a). The parameters in Table II are comparable to published values for sandy loam soils (Clapp and Hornberger 1978).

Simulations were run for the entire winter season starting on November 24, 1983 (day 328) and ending April 25, 1984 (day 115) at the site with snow removed and starting November 23, 1983 (day 327) and ending April 24, 1984 (day 114) at the snow covered site. The conditions at the site with snow removed were simulated by assuming the snowfall equalled zero. The two sites provide a good test over a wide range of temperature extremes which could occur. Simulated and measured results were compared using the mean difference (*MD*) defined as:

$$MD = \frac{\sum_{i=1}^{n} (X_i - Y_i)}{n} \tag{3}$$

and the root mean square (*RMS*) difference defined as:

$$RMS = \left\{ \frac{\sum_{i=1}^{n} (X_i - Y_i)^2}{n} \right\}^{1/2} \tag{4}$$

where:

X_i = measured value,
Y_i = estimated value, and
n = number of cases.

The *MD* is useful because it provides an indication of any systematic deviations in the model estimates while the *RMS* value provides a better indication of the scatter of the estimated values in relation to measured values. Bidlake et al. (1992) used *MD* and *RMS* values to assess the correspondence between observed and simulated soil temperatures and moisture values.

Table II. Soil hydraulic properties

Layer thickness (m)	Saturated water content ($m^3 \bullet m^{-3}$)	Pore-size distribution index	Air entry potential (m)	Saturated hydraulic conductivity ($m \bullet s^{-1}$)
0 - 0.30	0.395	5.53	-0.075	5.33×10^{-5}
0.30 - 0.88	0.395	5.87	-0.017	4.89×10^{-5}
0.88 - 1.40	0.395	4.70	-0.022	9.36×10^{-5}

RESULTS AND DISCUSSION

The correspondence between the observed and estimated parameters was comparable to previous studies (Clemente et al. 1994). Estimated snow depths are plotted with observed values for the snow covered site in Fig. 3. The results are consistent with previous estimates of snow depth by the SHAW model (Flerchinger et al. 1990). The *RMS* difference was 0.13 m and the *MD* was -0.09 m. The discrepancy between the measured and simulated snow depth results in part from limitations in the input data and from the variability in depth caused by drifting snow. The simulation model may not correctly estimate the mix of snowfall and rainfall from daily precipitation data on days with the minimum air temperature below 0°C and the maximum above 0°C. This limitation affected the estimates in December (days 346 through 363). For example, on day 346 the precipitation included snow, ice pellets, and freezing rain but it was treated as snowfall by the model (Figs. 1 and 2). This contributed to a large difference between the observed and estimated snow depth on day 346 (Fig. 3). By early January (day 3) the differences between observed and estimated values decreased considerably. The model accurately predicted thawing in February (days 42 through 56) and the increase in snow depth after the thaw (Fig. 3). The rate of snow melting in the spring corresponded well with the observed rate. The first day in the spring when no snow was observed on the ground was day 93. The model estimated that the snow was all melted 2 days later.

For the snow covered site, soil temperatures estimated at the 0.10 m depth by the SHAW model were generally slightly higher than observed (Fig. 4). The observed soil temperatures remained at 0°C throughout most of the winter, while simulated values remained slightly above 0°C. Measured data indicated that if any freezing or thawing was occurring, the temperature at that depth remained close to 0°C. The *RMS* difference was 0.58°C and the *MD* was -0.5°C. The over-estimation of the snow depth in December (days 346 through 363) could have contributed to the higher temperature estimates (Fig. 3). The fit compared favourably with other published soil temperature model evaluations. Pierson et al. (1992) reported *MD* as high as 1.6°C and mean absolute differences of 1.6°C for winter conditions at the 10 mm depth. Bidlake et al. (1992) found that simulated and measured soil temperatures at the 60 mm depth had a *MD* as high as 0.7°C and an *RMS* difference as high as 1.4°C. This model clearly accounts for the thermal insulation provided by snow cover and could be a useful tool for studies of winter survival. Observed soil temperatures were not available for the thaw period.

At the snow covered site, since soil temperatures generally remained at or above 0°C (Fig. 4), there was little or no ice in the soil. Under these conditions, the TDR, which measures unfrozen water content (Hayhoe and Bailey 1985), gave an indication of total water content throughout most of the winter. Observed and estimated soil moisture at the 0.15 m depth show how the simulated soil water content follows the measured pattern (Fig. 5). The *RMS* difference was 0.03 $m^3 \bullet m^{-3}$ and the *MD* was -0.01 $m^3 \bullet m^{-3}$. These differences are comparable to other published differences (Clemente et al. 1994). The observed soil water content was lower in early winter but increased to correspond with the estimate during the February thaw (days 42 through 56). The lack of fit in early winter may have resulted in part from the presence of frozen water (Fig. 4) which was not measured by the TDR. The model indicated the soil water was unfrozen because simulated soil temperatures were above 0°C (Fig. 4). The estimated and observed soil water content (Fig. 5) increased in response to the snow melt and the 20 mm of rain which fell on day 45 (Figs. 2 and 3). Another peak in observed and estimated water content occurred at the end of the spring snow melt (Figs. 3 and 4).

In contrast to the snow covered site, the site where the snow was removed experienced sub-zero temperatures and deep frost penetration. Soil temperatures below -9°C were observed and estimated at a depth of 0.5 m (Fig. 6). The model estimates generally followed the pattern of observed soil temperatures both in terms of the magnitude and the rates of cooling and warming. The *RMS* difference was 1.5°C and the *MD* was 0.7°C. The positive *MD* value indicates that the observed temperatures were on average slightly larger than the estimated values. A factor contributing to this could be

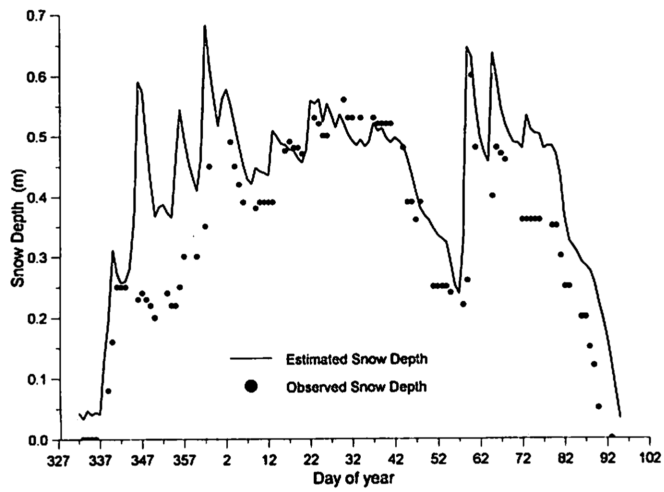

Fig. 3. Model estimates and observed values of snow depth.

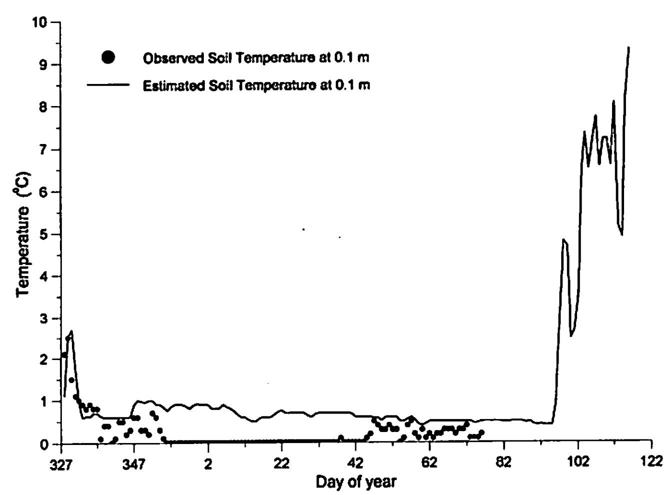

Fig. 4. Model estimates of daily average soil temperature at the 0.1 m soil depth as compared to observed temperatures at the snow covered site.

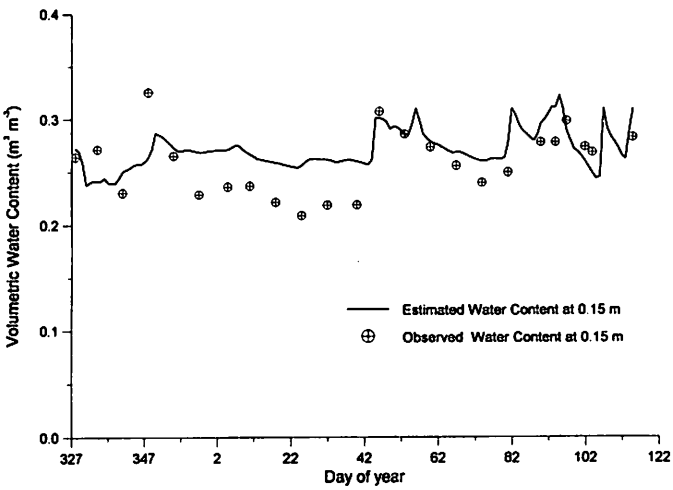

Fig. 5. Model estimates of volumetric water content at the 0.15 m depth as compared to observed values measured with the TDR at the snow covered site.

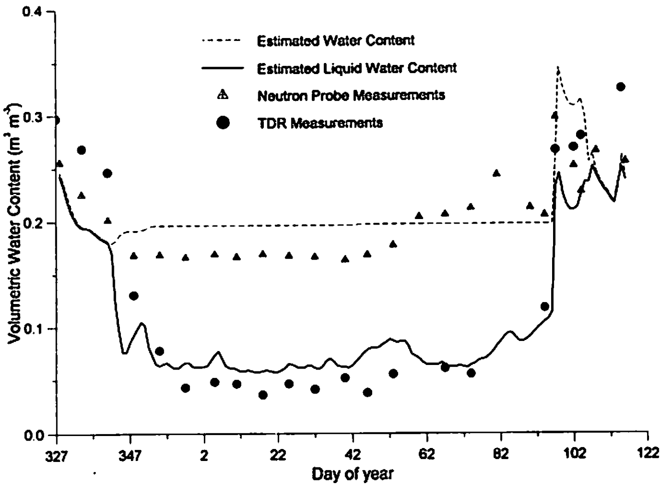

Fig. 7. Model estimates of total volumetric water content and unfrozen water content at the 0.4 m depth as compared to observed values measured with the neutron probe and the TDR at the snow cleared site.

the difficulty in maintaining the site snow free, particularly during snowfall or drifting conditions. In December (days 341 through 350) and February (days 58 through 67) the observed soil temperatures remained above the simulated values. Both these periods had snowfall and significant snow accumulation (Figs. 2 and 3).

The SHAW model simulates liquid water content as well as total water content. The data collected on the site with snow removed are uniquely suited to test the model. Neutron probe measurements provide a measure of the total water content (frozen and unfrozen). The observed values are plotted with the estimated values at the 0.4 m depth in Fig. 7. Frozen soil is indicated when the liquid water content is less than the total water content. The model showed a small increase in water content at 0.4 m as the soil froze and then the estimate remained almost constant until thawing began in the spring. The observed total water content generally agreed with the estimate but decreased slightly over the period that the soil froze and increased in February (days 42 through 56) in response to surface thawing conditions and precipitation (Fig. 7). These differences may result from the difference between observed and estimated soil temperatures (Fig. 6). The model indicated the soil froze earlier than observed and that it remained frozen at the 0.50 m depth throughout the winter. The observed soil moisture is consistent with observed soil temperature (Fig. 6) which indicated some thawing occurred during the winter to a depth of 0.50 m. The *RMS* difference of the soil water content was 0.04 $m^3 \bullet m^{-3}$ and the *MD* was -0.01 $m^3 \bullet m^{-3}$. TDR measurements provided a measure of the unfrozen water content and correspond to the model estimates of liquid water (Fig. 7). The *RMS* difference of liquid water was 0.04 $m^3 \bullet m^{-3}$ and the *MD* was 0.01 $m^3 \bullet m^{-3}$. These values are comparable to other published model evaluations (Clemente et al. 1994). Liquid water content dropped quickly when the soil froze and then rose rapidly with the spring thaw. A comparison of Figs. 6 and 7 shows that variations in estimated and predicted liquid water contents are sensitive to changes in soil temperature.

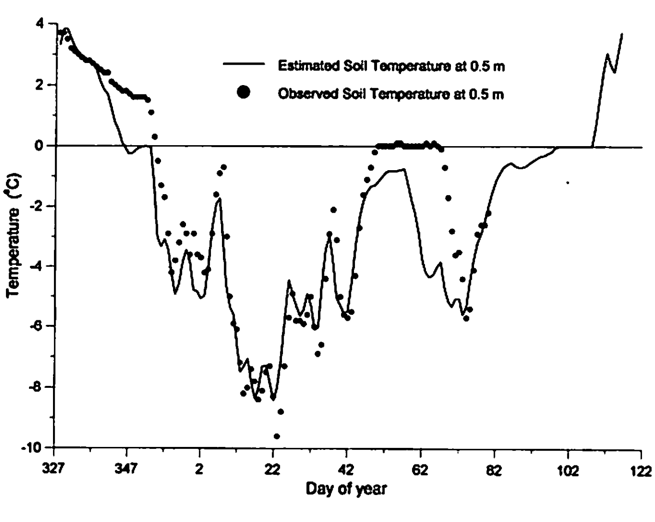

Fig. 6. Model estimates of daily average soil temperature at the 0.5 m soil depth as compared to observed temperatures at the snow cleared site.

Both simulated and measured water contents agreed on the rapid increase in spring. Observed liquid water content increased from 0.12 $m^3 \bullet m^{-3}$ on day 94 to 0.27 $m^3 \bullet m^{-3}$ on day 97 and estimated liquid water content increased from 0.11 $m^3 \bullet m^{-3}$ on day 96 to 0.23 $m^3 \bullet m^{-3}$ on day 97. Observed water content increased from 0.21 $m^3 \bullet m^{-3}$ on day 94 to 0.30 $m^3 \bullet m^{-3}$ on day 97 while estimated water content increased from 0.20 $m^3 \bullet m^{-3}$ on day 94 to 0.34 $m^3 \bullet m^{-3}$ on day 98. The SHAW model indicated that all the ice had melted at the 0.4 m depth by day 106. Observations with the TDR were higher than the neutron probe measurements when the soil was not frozen. We assume that this is largely due to site variability which made it difficult to determine when all the ice was melted. The first day in spring when the TDR measurement was greater than the neutron probe was 102. The difference in-

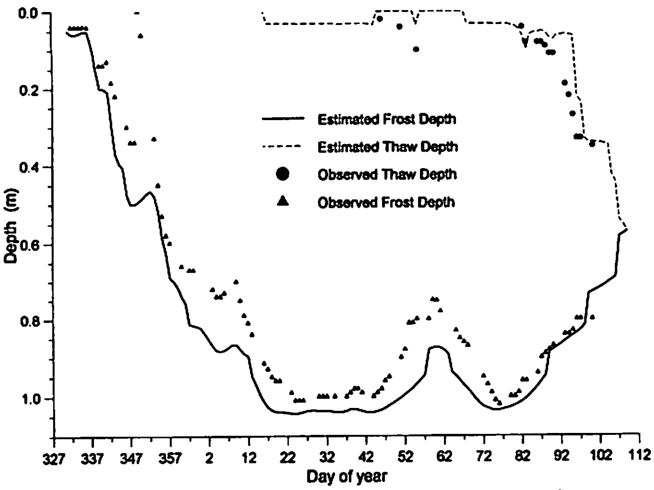

Fig. 8. Model estimates and observed values of freeze and thaw depth for the snow cleared site.

creased on day 104 and was comparable to the difference prior to freezing which suggests that most of the ice had melted by that date (Fig. 7).

The SHAW model also provides estimates of frost and thaw depth. These are plotted with the observed depth determined using the frost probe for the site with snow removed (Fig. 8). Observed frost penetration was slightly less than predicted early in the winter. The *RMS* difference was 0.11 m and the *MD* was -0.08 m. The maximum measured frost penetration occurred on day 76 and equalled 1.02 m. This agreed with the observed value. Thaw penetration from the soil surface was determined by probing the soil with a steel rod. The estimated thaw penetration both from below the frozen zone and from the surface agreed with the observed. The *RMS* difference of surface thaw penetration was 0.09 m and the *MD* was -0.06 m. During freezing and thawing, multiple freezing and thawing fronts can occur in the profile. The current version of the SHAW model takes the thawing front closest to the surface as the thaw depth. This lead to rapid changes in thaw depth resulting from overnight freezing of the soil surface. These brief shifts in thaw depth were ignored in plotting Fig. 8. On day 101, the frost probe did not indicate the presence of frozen soil. The SHAW model estimated that the soil was completely thawed on day 108. On this day, the soil was probed with a steel rod and, to a depth of 0.75 m, no ice was encountered. The SHAW model indicates the soil is frozen at a grid point if any ice is present. This may give higher estimates of frost depth and lower estimates of thaw penetration than measurements which are related closely to soil temperature.

CONCLUSIONS

The current version of the SHAW model is easy to set up and run. The agreement between observed and estimated values compared favourably with previous field testing of simulation models. Using limited information on soil properties and daily weather data, required inputs are automatically generated. The soil hydraulic properties estimated based on bulk density and texture by the SHAW model (Saxton et al. 1986) are useful, but may increase differences between observed and simulated soil water content. The model provided excellent estimates of snow depth and the timing and rate of snow melt for our site. Although some lack of agreement between observed and estimated snow depth occurred, this was attributed to the inherent limitations in the model in dealing with other forms of precipitation. Other factors include the effect of wind as well as the distance from the climatological station. Also, it was noted that observed soil temperatures were generally closer to 0°C during initial freezing or thawing than the simulated values.

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