DOCUMENTATION OF A HEAT AND WATER TRANSFER MODEL FOR SEASONALLY FROZEN SOILS
WITH APPLICATION TO A PRECIPITATION-RUNOFF MODEL

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### CONVERSION FACTORS

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To convert degrees Celsius (°C) to degrees Fahrenheit (°F), use the following formula:

\[°F = 1.8×(°C)+32\]
ABSTRACT

A model that simulates heat and water transfer in soils during freezing and thawing periods was developed and incorporated into the U.S. Geological Survey's Precipitation-Runoff Modeling System. The transfer of heat is based on an equation developed from Fourier's equation for heat flux. Field capacity and infiltration rate can vary throughout the freezing and thawing period, depending on soil conditions and rate and timing of snowmelt. The transfer of water within the soil profile is based on the concept of capillary forces. The model can be used to determine the effects of seasonally frozen soils on ground-water recharge and surface-water runoff.

Data collected for two winters, 1985-86 and 1986-87, on three runoff plots were used to calibrate and verify the model. The winter of 1985-86 was colder than normal and snow cover was continuous throughout the winter. The winter of 1986-87 was warmer than normal and snow accumulated for only short periods of several days.

Runoff, snowmelt, and frost depths were used as the criteria for determining the degree of agreement between simulated and measured data. The model was calibrated using the 1985-86 data for plot 2. The calibration simulation agreed closely with the measured data. The verification simulations for plots 1 and 3 using the 1985-86 data and for plots 1 and 2 using the 1986-87 data agreed closely with the measured data. The verification simulation for plot 3 using the 1986-87 data did not agree closely. The recalibration simulations for plots 1 and 3 using the 1985-86 data indicated small improvement because the verification simulations for plots 1 and 3 already agreed closely with the measured data.

INTRODUCTION

Until the 1940's, American hydrologists generally believed that frozen soil was completely impermeable (Dingman, 1975, p. 28). It has been determined, however, that saturated soils can transmit water at temperatures substantially below freezing (Dingman, 1975). Freezing and thawing can have significant effects on the permeability and structure of soils (Chamberlain and Gow, 1979). Hinman and Bisal (1973) found that infiltration rate during freezing and thawing depends on the initial water content of the soil. Water transfer through frozen soils has been studied by several other investigators, including Haupt (1967), Gray and others (1970), Harlan (1973), Bresler and Miller (1975), and Kane (1980, 1981a, 1981b).
Heat and mass transfer models for unsaturated soils, such as those developed by Harlan (1973), Kennedy and Liezems (1973), Guymon and Luthin (1974), and others, are based on the one-dimensional Richard's equation. The Richard's equation is solved by either finite-difference or finite-element methods. Because of the complexity of both the process and numerical solution, these heat- and mass-transfer models have not been adopted for use in snowmelt-runoff or ground-water models.

Most ground-water models require a recharge flux as part of the time-series data. Only a few ground-water models use infiltration as time-series data, and the effects of frozen soils are not considered in any ground-water models.

Snowmelt-runoff models have been developed and used as tools for solving watershed hydrology problems in cold climates. Snowmelt has been studied and modeled by many researchers, including the U.S. Army Corps of Engineers (1956), Anderson and Crawford (1964), Rockwood (1964), Eggleston and others (1971), Colbeck (1972), Leavesley (1973), Gray and Male (1981), and Peaco (1981). The effects of frozen soils on snowmelt infiltration have been emphasized by several investigators, including Haupt (1967), Gray and others (1970), Harlan (1973), Bresler and Miller (1975), Dlngman (1975), and Kane (1980, 1981b).

The National Weather Service (Eric Anderson, written commun., 1983) is developing a frozen-soil component for their National Weather Service River Forecast System. The preliminary model consists of modifying their Sacramento Soil Accounting Model (Burnash and others, 1973) to incorporate frost index equations. The forecast model is used for large river systems, and the frozen-soil component is being tested on the Minnesota River basin (43,770 km²). The modification has not been fully developed or tested.

Peaco (1981), in cooperation with the U.S. Army Corps of Engineers Cold Region Research and Engineering Laboratory, has developed and tested the inclusion of frozen-ground simulations in a lumped-parameter watershed model. Peaco used the Streamflow Synthesis and Reservoir Regulation (SSAR) model (Speers and others, 1978) developed by the U.S. Army Corps of Engineers. Peaco's approach uses the relation between the areal extent of frost and a freezing index. The approaches used by the National Weather Service and Peaco are quasi-physical, and neither is based on mass and energy laws.

The U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983) is a modular-design, distributed-parameter model that uses mathematical relations to represent the hydrologic system. In PRMS each component of the hydrologic cycle is defined by a model module (one or more subroutines). All modules can be linked and are maintained as a single computer system library. The library also contains modules for parameter optimization, data handling, and model output analysis. The distributed parameter approach is designed around the concept of partitioning a watershed into subunits on the basis of slope, aspect, altitude, vegetation type, soil type, and snow distribution. Partitioning is designed to account for temporal and spatial variations of the watershed's physical and hydrologic characteristics, climatic variables, and system response. PRMS has been
applied in many states, including Alabama, Colorado, Montana, New Mexico, North Dakota, Oklahoma, and West Virginia. Watersheds have ranged in size from 2,300 km² in Colorado to 21.9 km² in North Dakota. U.S. Geological Survey hydrologists in North Dakota have found that PRMS does not adequately simulate seasonally frozen soils, thus the applicability of PRMS is limited in regions where frozen soils are an important component in the hydrologic cycle.

For areas such as North Dakota, the effects of frozen soils on groundwater recharge, infiltration, and surface-water runoff can be significant. The determination of the magnitude of these effects and the development of an operational model are needed to improve the understanding of the physical processes involved in the freezing and thawing phenomenon and to better predict the effects of these processes on groundwater recharge, infiltration, and surface-water runoff. Therefore, the U.S. Geological Survey, in cooperation with the North Dakota State Water Commission, began a study in 1985 of heat and water transfer in seasonally frozen soils (Emerson, 1985). This report documents the model development and the coupling of the model to PRMS and evaluates the simulations using data collected for this study.

DEVELOPMENT OF HEAT AND WATER TRANSFER MODEL

The basic components of the conceptual model of the heat and water transfer system are shown in figure 1. The model's time-series data are air temperature, evaporation, precipitation, and snowmelt. Air temperature and precipitation are model input, whereas evaporation and snowmelt are computed by PRMS. Air temperature is used to determine the freezing and thawing of soil. The model transfers heat to the soil only when the soil is already frozen and the air temperature is above freezing. The model transfers heat away from the soil only when the air temperature is below freezing.

As the soil is freezing, the depth that the soil is frozen is computed daily and retained for future reference (fig. 2A). During thawing, the depth that the soil is thawed is computed daily and retained for future reference (fig. 2B). If the soil is completely thawed, the maximum frost depth is set to zero. If the soil starts to refreeze before the soil profile is completely thawed, the frost depth for the second frost layer is computed and retained for future reference (fig. 2C). Likewise, if a second thaw occurs before the first thaw layer is refrozen, the second thaw depth is computed and retained for future reference (fig. 2D). A maximum of 10 freeze layers and 10 thaw layers can be simulated by the model.

Soil profiles are seldom uniform but typically consist of fairly distinct layers. Each layer can have varying thermal and physical properties. To account for these varying properties for each layer of a soil profile, the model can accommodate as many as 10 soil layers in a soil profile.

The type of frost that occurs when the ground is frozen can affect the properties of the soil layer along with the infiltration rate. Five types of frost have been recognized (Dingman, 1975)
Figure 1.--Flow chart of the conceptual model.
Figure 2.—Diagrammatic representation of a soil profile with different number of freezing and thawing layers.
concrete frost -- saturated or supersaturated ground that is completely frozen,
porous concrete frost -- frozen ground similar to concrete frost but is permeable to air,
granular frost -- small ice crystals are intermixed with and aggregated around soil particles,
honeycomb frost -- frozen ground similar to granular frost but has a greater degree of connection among ice crystals and has a lower porosity,
stalactite frost -- frozen ground that is characterized by small needlelike ice crystals that are vertically aligned.

Frost type is used by the model to govern changes in the storage capacity of each layer of the soil profile and the infiltration rate of the soil.

Heat Transfer

The penetration of frost and the thawing of a soil are complicated processes of heat transfer. A frost-penetration equation, which is used to calculate the depth of frost as a function of time, was developed by the U.S. Army Corps of Engineers (1949) and is expressed as

\[ X_f = \left( \frac{86,400 K_f I_f}{(L + C(T_a + I_f/2t))} \right)^{0.5} \]  

where
\( X_f \) is the depth of frost, in centimeters;
\( K_f \) is the thermal conductivity of the frozen soil in calories per centimeter per second per degree Celsius;
\( I_f \) is the frost index, in degree Celsius days;
\( L \) is the latent heat, in calories per cubic centimeter;
\( C \) is the volumetric heat capacity, in calories per cubic centimeter per degree Celsius;
\( T_a \) is the mean annual temperature of the soil layer, in degree Celsius; and
\( t \) is the duration of the freezing period, in days.

The depth of frost calculated by equation 1 is reduced by the heat that is stored in the soil below the frost. The reduction in depth of frost by the heat from the soil below the frost is expressed as

\[ X_r = 86,400 K_u \frac{T_a}{(X_a - X_f)} / L \]

where
\( X_r \) is the reduction in depth of frost, in centimeters;
\( K_u \) is the thermal conductivity of the unfrozen soil, in calories per centimeter per second per degree Celsius; and
\( X_a \) is the depth of stable soil temperature, in centimeters.

Because the derivations of equations 1 and 2 are difficult to find in the literature, the derivations are presented in supplement 1.

An equation similar to equation 1 is used to determine thawing after a freeze. The main conceptual difference is that for thawing, soil layers need only be brought to 0°C and enough additional heat must be available to maintain a thermal gradient. Latent heat is the primary energy source for thawing. Instead of a frost index, \( I_f \), a thaw index, \( I_t \), is used and is
defined as the sum of the daily mean temperatures above 0°C for the thaw period. The depth of thaw is expressed as

\[ X_t = \left[86,400K_yI_t/(L+CI_t)\right]^{0.5} \]  

(3)

where \( X_t \) is the depth of thaw, in centimeters; and
\( I_t \) is the thaw index, in degree Celsius day.

The different substances that constitute a profile (soil, water, snow, and litter) have widely different thermal properties. Thermal properties of soil materials vary only slightly with temperatures in the range of temperatures occurring in the field (de Vries, 1966).

Thermal conductivity is not independent of the temperature gradient. An increase in the thermal conductivity results in a decrease in the temperature gradient if all other variables are constant. The thermal conductivity varies with the composition, density, and water content of a layer. Heat is transferred by the combination of substances present. If one substance has a thermal conductivity much less than another, most of the heat will be transferred through the substance with the greater thermal conductivity. In soil, heat transferred through air is two orders of magnitude less than for soil particles. Soil particles commonly are in poor thermal contact with other soil particles. Water films tend to have their greatest thickness at the contact points between soil particles and are good conductors of the heat; therefore, water is considered to be the substance that conducts most of the heat.

Because soil consists of different substances, a method of defining a composite thermal conductivity is needed. A ratio of the average temperature gradient of a substance and the average temperature gradient of the main substance (water) that conducts heat is used to compensate for the different effects that substances have on conduction of heat (de Vries, 1966, p. 214-216). A composite value for thermal conductivity for the ith soil layer is expressed as

\[ K_i = (K_yV_yG_y + K_wV_wG_w + K_aV_aG_a)/(V_yG_y + V_wG_w + V_aG_a) \] 

(4)

where \( K_i \) is the composite thermal conductivity of the ith layer, in calories per centimeter per second per degree Celsius;
\( K_y \) is the thermal conductivity of soil in the ith layer, in calories per centimeter per second per degree Celsius;
\( V_y \) is the volumetric fraction of soil in the ith layer;
\( G_y \) is the ratio of the average temperature gradient of soil with respect to water;
\( K_w \) is the thermal conductivity of water in the ith layer, in calories per centimeter per second per degree Celsius;
\( V_w \) is the volumetric fraction of water in the ith layer;
\( G_w \) is the ratio of the average temperature gradient of water with respect to water;
\( K_a \) is the thermal conductivity of air in the ith layer, in calories per centimeter per second per degree Celsius;
\( V_a \) is the volumetric fraction of air in the ith layer; and
\( G_a \) is the ratio of the average temperature gradient of air with respect to water.
Empirically determined thermal conductivity of snow has been based on snow density, although thermal conductivity of snow does not depend on density alone. Anderson (1976) reviewed several equations for determining effective thermal conductivity of snow. The equation used in the model is

\[ K_{sn} = 0.0068D_s^2 \]  

where \( K_{sn} \) is the thermal conductivity of snow, in calories per centimeter per second per degree Celsius; and

\( D_s \) is the density of the snow, in grams per cubic centimeter.

The heat capacity per unit volume can be determined by adding the heat capacities of the different constituents in the volume. The volumetric heat capacity for the ith soil layer was given by de Vries (1966, p. 211) as

\[ C_j = V_jC_s + V_jC_w + V_jC_a \]  

where \( C_j \) is the volumetric heat capacity of the ith layer, in calories per cubic centimeter per degree Celsius;

\( C_s \) is the volumetric heat capacity of the soil in the ith layer, in calories per cubic centimeter per degree Celsius;

\( C_w \) is the volumetric heat capacity of the water in the ith layer, in calories per cubic centimeter per degree Celsius;

\( C_a \) is the volumetric heat capacity of the air in the ith layer, in calories per cubic centimeter per degree Celsius.

The specific heat capacity of most soil materials was found to vary linearly from 0.16 (cal/g)/°C at -18°C to 0.19 (cal/g)/°C at 60°C (Kersten, 1949, p. 69). Because the density of soil materials is about 2.7 g/cm³, the average value for heat capacity of the soil, \( C_s \), is 0.46 (cal/cm³)/°C. The heat capacity of water, \( C_w \), is 1.00 (cal/cm³)/°C for liquid water and 0.45 (cal/cm³)/°C for ice at 0°C. The heat capacity of air (0.00030 (cal/cm³)/°C) is negligible compared to the other heat capacities and can be neglected. The heat capacity, \( C_j \), in the case involving liquid water can be given as

\[ C_j = (1-P_j)0.46 + V_w(1.00) \]  

where \( P_j \) is the porosity of the ith layer, in volume fraction; and for the case involving ice can be given as

\[ C_j = (1-P_j)0.46 + V_w(0.45). \]

For a layer that consists of snow or litter, an equation in the same format as equation 6 can be used. The heat capacity for old snow is about 0.40 (cal/cm³)/°C; for new snow, 0.15 (cal/cm³)/°C; and for litter, 0.06 (cal/cm³)/°C (Van Wijk and Derksen, 1966, p. 204).

Effective thermal conductivity, heat capacity, and latent heat are needed for equation 1 when the soil profile consists of several layers of varying proportions of substances. The thermal resistance of the ith layer is defined as
where $R_i$ is the thermal resistance of the $i$th layer, in square centimeters
seconds degrees Celsius per calorie, and
$X_i$ is the thickness of the $i$th layer, in centimeters.

The total thermal resistance, $R_t$, for $n$ layers is

$$R_t = X_1/K_1 + X_2/K_2 + \ldots + X_n/K_n$$ (10)

and the effective thermal conductivity, $K_t$, for the $n$ layers is

$$K_t = (X_1 + X_2 + \ldots + X_n)/R_t.$$ (11)

The effective volumetric heat capacity and latent heat for several layers
are computed using the forms

$$C_t = (\Sigma C_iX_i)/(\Sigma X_i)$$ (12)

$$L_t = (\Sigma L_iX_i)/(\Sigma X_i)$$ (13)

where $C_t$ is the effective volumetric heat capacity for several layers, in
calories per cubic centimeter per degree Celsius;
$L_t$ is the effective latent heat for several layers, in calories per
cubic centimeter; and
$L_i$ is the latent heat of the $i$th layer, in calories per cubic
centimeter.

If litter or snow or both form a layer above the soil, then the heat capacity
and the latent heat for these layers are included in equations 12 and 13.

**Water Transfer**

Soil water is the most important variable affecting the thermal con­
ductivity, heat capacity, and latent heat of the soil. Therefore, soil
water content and soil water transfer are an intricate part in determining
heat transfer and vice versa. Field capacity, a measure of how much water can
be stored in the various soil layers, affects how much water may run off.
Field capacity and infiltration rate can be varied in the model throughout
freezing and thawing periods. The variation depends upon the soil conditions
and snowmelt.

Frost type can be classified by soil conditions. Dingman (1975) reviewed
literature on local variations of seasonal freezing in a number of geographic
areas and established certain generalizations: "***vegetative cover type is a
major determinant of soil freezing characteristics, with the depth and
rapidity of freezing increasing in the sequence: hardwood forests < conifer
forests < brush or field < bare ground." Many investigations indicate that
this sequence largely is a result of the combined insulating effects of litter
and snow depth. The type of frost that is formed appears to be determined
mostly by soil water content, length and rate of freezing, organic matter,
and soil type. Farnsworth (1976, p. 63, 64) made the following assumptions
concerning the conditions for formation of the different frost types:
"***(1) If the ground is very moist or has thawed and the minimum temperature drops to at least -3°C, it is assumed that porous stalactite frost will form. By 'very moist' is meant that light snow has melted, the upper layer is at least at field capacity, or rain has preceded the freeze.

(2) If the moisture conditions for stalactite frost are not present and the organic content of the soil is above some threshold value, it is assumed that granular or honeycomb frost will form. It is assumed that under any of the conditions given to this point the soil is still porous. If the rate of frost penetration exceeds an inch per day, it is assumed that the moisture is frozen in position into separate granules of ice leaving the soil porous.

(3) If slow freezing occurs, organic content is too low, or freezing exceeds 3.25 in. (83 mm) into the soil, it is assumed that concrete frost has formed and that infiltration rates for any but the forested areas are brought to near zero.

(4) Should thawing occur above concretely frozen soil and then freezing reoccur, the ground will likely be saturated and concrete frost will form in the thawed region.

(5) Finally, if the ground is initially warm, freezing temperatures must occur for 2 days in a row before sufficient ground will be frozen to materially change the basin infiltration capacity. These conditions are used to identify the type of frost that is formed."

After the frost type is determined, the field capacity or the infiltration rate, or both, are modified on the basis of the effect that the frost type imposes on water movement into and through the soil. Investigators have reported different effects of the frost types (Dingman, 1975). Most of these differences are due to the lack of knowledge of the complete frozen soil system. Better quantification of the effect of frost type is still needed. Granular, honeycomb, and stalactite frost generally have been found to have minimal effect on field capacity. However, when concrete frost has formed and a partial thaw occurs, the thawed layer can become supersaturated. For this condition, the field capacity of the first soil layer is triple, which allows for soil water contents as high as those observed by Post and Dreibelbis (1942).

Cooler soil temperatures increase soil moisture retention. To compensate for this increase, the field capacity of the first soil layer is assumed to increase by 12 percent when the maximum daily air temperature is less than 5.0°C. The increase in soil water retention corresponds to that found by Jensen and others (1970), Klock (1972), and Peck (1974).

If the first soil layer is at field capacity, 90 percent of water available after evapotranspiration is subtracted is assumed to infiltrate, and the remainder is assumed to run off. If the first and second soil layers are at field capacity, 80 percent of the water is assumed to infiltrate and the remainder is assumed to run off. If the first soil layer is less than field capacity, then all the water after evapotranspiration is subtracted is assumed
to be available for infiltration. Water is added to the first layer until the soil layer reaches field capacity. If more water is available, it is added to the second layer up to the field capacity of the second layer. If still more water is available, it is added to the next layer, and so on.

After the available water is added to the soil layer, the soil water is redistributed. The concept of capillary forces is incorporated into the redistribution of the soil water profile. Soil water is held at small tensions in layers that have a large water content. These soil layers are likely to release water at a greater rate than soil layers having smaller water-content that is held at greater tensions. The ratio for the soil water in the last layer to have water added \( D_f \) and the ratio for the next lower layer \( D_{f+1} \) are given as

\[
D_f = \frac{M_f}{M_{f1}} \quad \text{(14)}
\]

\[
D_{f+1} = \frac{M_{f+1}}{M_{f(f+1)}} \quad \text{(15)}
\]

where \( D_f \) is the ratio of soil water of the \( f \)th layer; \( M_f \) is the soil water content of the \( f \)th layer, in cubic centimeters per cubic centimeter; \( M_{f1} \) is the field capacity of the \( f \)th layer, in cubic centimeters per cubic centimeter; \( D_{f+1} \) is the ratio of soil water of the \( f+1 \) layer; \( M_{f+1} \) is the soil water content of the \( f+1 \) layer, in cubic centimeters per cubic centimeter; and \( M_{f(f+1)} \) is the field capacity of the \( f+1 \) layer, in cubic centimeters per cubic centimeter.

If the difference between the ratios, \( D_0 \), where \( D_0 = D_f - D_{f+1} \), is greater than 0.2, then water content of the \( f \)th layer, \( M_f \), is reduced by half the ratio difference and the water content of the \( f+1 \) layer is increased by half the ratio difference as

\[
M_f = M_f - D_0 / 2 \quad \text{(16)}
\]

\[
M_{f+1} = M_{f+1} + D_0 / 2 \quad \text{(17)}
\]

This process is repeated until the differences in the ratios, \( D_0 \), is less than or equal to 0.2. The process is repeated again for the \( f+1 \) and \( f+2 \) layers. This procedure is similar to the one used by Farnsworth (1976).

COUPLING OF MODEL TO THE PRECIPITATION-RUNOFF MODELING SYSTEM

The U.S. Geological Survey's PRMS model (Leavesley and others, 1983) serves as the basis for the development of the heat and water transfer model for seasonally frozen soils. Because PRMS is a modular-designed model, modifications were easily accomplished. PRMS has a data-management component for manipulating and storing hydrologic and meteorologic data in a model-compatible direct access file (Lumb and others, 1990). A library component consists of a source-module library and a load-module library for the storage of the compatible subroutines used to define and simulate the
physical process of the hydrologic cycle, and parameter-optimization and sensitivity-analysis subroutines for parameter fitting and analysis. The last component of PRMS is an output component that provides the model output handling and analysis capabilities. Names and descriptions of the subroutines in PRMS are listed in table 1 and provide a general overview of PRMS's capabilities.

Soil water accounting for daily computations in PRMS is performed in subroutine SMBAL (Leavesley and others, 1983). The depth of the active soil profile is considered to be the average rooting depth of the predominant vegetation. The maximum available water-holding capacity of the active soil profile is the difference between field capacity and wilting point of the profile. The active soil profile is divided into two layers. The upper layer is termed the recharge zone and the lower layer is termed the lower zone. The recharge zone is assumed to be the depth interval from which water can be lost by evaporation; its depth and maximum available water-holding capacity are defined by the user of the model. The maximum available water-holding capacity of the lower zone is the difference between the water-holding capacity of the active soil profile and of the recharge zone. Losses from the recharge zone occur from evaporation and transpiration. Losses from the lower zone occur only as transpiration. Evapotranspiration losses occur at a rate that is a function of available soil water storage. The attempt to satisfy potential evapotranspiration is made first from the recharge zone.

PRMS was modified by coupling two subroutines, FRZ and SMP. FRZ computes heat transfer and SMP computes water transfer. Heat is transferred through a combination of snow, litter, and soil layers whereas water is transferred through a combination of litter and soil layers. The computer codes for the two subroutines are listed in supplements 2 and 3. Variables used in the two subroutines are listed in supplement 4. Flow charts for the two subroutines are shown in figures 3 and 4. The subroutines FRZ and SMP are called from within the PRMS's subroutine SMBAL (fig. 5) when vegetation is dormant, that is during winter periods. The modification of PRMS allows the soil water accounting system in SMBAL to be bypassed when vegetation is dormant, and the accounting system in SMP is used. To go from a system in SMBAL, which consists of two zones, to a system in SMP, which can have a maximum of 10 layers, the model distributes the soil water evenly into the layer system of SMP when SMP is used for the first time during the dormant period; a similar procedure is used to convert back to a two-zone system when leaving the dormant period. An option is available to allow the distribution of soil water to be input at the beginning of the dormant period. Additional data that are required to run PRMS with FRZ and SMP are explained in supplement 5.

**MODEL APPLICATION**

**Site Description and Data**

Data from three runoff plots, each 7x7 m, were used in model simulations. The runoff plots are located 11.3 km southeast of Oakes, N. Dak. (fig. 6). The topography is flat. No surface drainage systems exist in the vicinity of the plots and runoff occurs as overland flow into local depressions that provide only temporary storage.
Table 1.--Listing of subroutines in the Precipitation-Runoff Modeling System

[Modified from Leavesley and others, 1983]

<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Daily components:</strong></td>
<td></td>
</tr>
<tr>
<td>BASFLW</td>
<td>Computes base flow and subsurface flow components of the streamflow hydrograph.</td>
</tr>
<tr>
<td>CALIN</td>
<td>Computes change in snowpack when a net gain in heat energy has occurred.</td>
</tr>
<tr>
<td>CALOSS</td>
<td>Computes change in snowpack when a net loss in heat energy has occurred.</td>
</tr>
<tr>
<td>INTLOS</td>
<td>Computes the evaporation and sublimation of intercepted rain and snow.</td>
</tr>
<tr>
<td>PETS</td>
<td>Computes daily estimate of potential evapotranspiration.</td>
</tr>
<tr>
<td>PKADJ</td>
<td>Adjusts snowpack water equivalent based on snow-course data.</td>
</tr>
<tr>
<td>PRECIP</td>
<td>Computes precipitation form, total precipitation depth, depth intercepted by vegetation, and the net precipitation.</td>
</tr>
<tr>
<td>RESVRD</td>
<td>Performs daily routing for surface-water detention reservoirs.</td>
</tr>
<tr>
<td>SMBAL</td>
<td>Performs daily soil water accounting.</td>
</tr>
<tr>
<td>SNOBAL</td>
<td>Computes snowpack energy balance.</td>
</tr>
<tr>
<td>SOLRAD</td>
<td>Computes daily incoming shortwave solar radiation for each hydrologic response unit.</td>
</tr>
<tr>
<td>SOLTAB</td>
<td>Computes potential solar radiation and daylight hours for radiation planes.</td>
</tr>
<tr>
<td>SRFRO</td>
<td>Computes daily storm runoff from rainfall.</td>
</tr>
<tr>
<td>SUMALL</td>
<td>Computes daily, monthly, and annual data summaries for total basin and individual hydrologic response units.</td>
</tr>
<tr>
<td>TEMP</td>
<td>Adjusts daily maximum and minimum air temperature to account for differences in elevation and aspect from point of measurement to each hydrologic response unit.</td>
</tr>
<tr>
<td>TIMEY</td>
<td>Performs initialization and maintenance of the time accounting variables.</td>
</tr>
<tr>
<td>Subroutine</td>
<td>Description</td>
</tr>
<tr>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>Storm components:</strong></td>
<td></td>
</tr>
<tr>
<td>AM</td>
<td>Computes kinematic routing parameters $a$ and $m$.</td>
</tr>
<tr>
<td>RESVRU</td>
<td>Performs storm-period routing for surface-water detention reservoirs.</td>
</tr>
<tr>
<td>ROUTE</td>
<td>Performs channel routing of water and sediment.</td>
</tr>
<tr>
<td>UNITD</td>
<td>Computes rainfall excess and performs overland flow routing of water and sediment.</td>
</tr>
<tr>
<td>UNSM</td>
<td>Performs subsurface and ground-water reservoir routing for storms.</td>
</tr>
<tr>
<td><strong>Optimization components:</strong></td>
<td></td>
</tr>
<tr>
<td>BDRY</td>
<td>Determines whether any of the parameters being optimized lie close to their boundaries and penalizes the objective function if they do.</td>
</tr>
<tr>
<td>COROPT</td>
<td>Performs a correlation analysis of the residuals in a daily optimization.</td>
</tr>
<tr>
<td>OPINIT</td>
<td>Reads input data and initializes variables for optimization.</td>
</tr>
<tr>
<td>PARAM</td>
<td>Adjusts selected model parameters at the beginning of each parameter fitting iteration.</td>
</tr>
<tr>
<td>ROSOPT</td>
<td>Initializes model variables and selected model parameters at the beginning of each parameter fitting iteration.</td>
</tr>
<tr>
<td>SCALE</td>
<td>Scales parameters and constraint values and unscales parameter and constraint values.</td>
</tr>
<tr>
<td>SNORT</td>
<td>Determines which of new search directions is most parallel to each of the old directions following an end of stage.</td>
</tr>
<tr>
<td>SUB1</td>
<td>Controls the main strategy of the Rosenbrock optimization procedure.</td>
</tr>
<tr>
<td>SUB3</td>
<td>Does Gram-Schmidt orthogonalization to establish new orthogonal search directions.</td>
</tr>
</tbody>
</table>
Table 1.--Listing of subroutines in the Precipitation-Runoff Modeling System--Continued

<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity analysis components:</strong></td>
<td></td>
</tr>
<tr>
<td>MATINV</td>
<td>Performs matrix inversion.</td>
</tr>
<tr>
<td>OPINIT</td>
<td>Reads input data and initializes variables for a sensitivity analysis.</td>
</tr>
<tr>
<td>PARAM</td>
<td>Adjusts selected model parameters for use in sensitivity analysis routines.</td>
</tr>
<tr>
<td>SENMAT</td>
<td>Computes the sensitivity matrix.</td>
</tr>
<tr>
<td>SENST</td>
<td>Controls the main strategy of the sensitivity analysis procedure.</td>
</tr>
<tr>
<td><strong>Statistical analysis components:</strong></td>
<td></td>
</tr>
<tr>
<td>STATS</td>
<td>Computes daily statistics.</td>
</tr>
<tr>
<td>SUMUNT</td>
<td>Computes summary statistics.</td>
</tr>
<tr>
<td><strong>Data handling components:</strong></td>
<td></td>
</tr>
<tr>
<td>BLKDAT</td>
<td>Initializes data for common areas.</td>
</tr>
<tr>
<td>DATIN</td>
<td>Reads input of model options, parameters, and variables.</td>
</tr>
<tr>
<td>DVPLLOT</td>
<td>Provides line printer plot of predicted and observed daily mean streamflow.</td>
</tr>
<tr>
<td>DVRETR</td>
<td>Selects required daily records from direct access file.</td>
</tr>
<tr>
<td>INVIN</td>
<td>Reads input data for storm periods and handles accounting for storms.</td>
</tr>
<tr>
<td>PRTHYD</td>
<td>Provides tabular output of stormflow hydrograph.</td>
</tr>
<tr>
<td>UVPLLOT</td>
<td>Provides line printer plot of predicted and observed stormflow hydrographs and sediment concentration graphs.</td>
</tr>
<tr>
<td>UVRETR</td>
<td>Selects required storm records from direct access file.</td>
</tr>
</tbody>
</table>
Figure 3.—Flow chart of the subroutine FRZ, which simulates heat transfer.
ADJUST WATER-HOLDING CAPACITY FOR THE SOIL PROFILE AND FOR EACH SOIL LAYER

DAILY MAXIMUM AIR TEMPERATURE IS LESS THAN FREEZING AND SNOWMELT IS LESS THAN 0.001 INCH

YES

RETURN

NO

AVAILABLE WATER IS GREATER THAN EVAPORATION

YES

SNOW PACK GREATER THAN ZERO

YES

RETURN

NO

AVAILABLE WATER IS LESS THAN FREEZING AND SNOWMELT IS LESS THAN 0.001 INCH

NO

AVAILABLE WATER IS ZERO OR EQUAL TO EVAPORATION

YES

COMPUTE THE LOSS OF SOIL WATER CONTENT TO EVAPORATION

NO

COMPUTE RUNOFF

NO

AVAILABLE WATER FOR INFILTRATION IS EQUAL TO OR GREATER THAN WATER-HOLDING CAPACITY OF THE SOIL

YES

COMPUTE RECHARGE

NO

SOIL PROFILE IS AT WATER-HOLDING CAPACITY

YES

COMPUTE SOIL WATER FOR THE SOIL LAYERS SUBJECT TO EVAPORATION AND THE TOTAL SOIL WATER FOR THE SOIL PROFILE

NO

Distribute soil water in the soil layers

RETURN

Figure 4.—Flow chart of the subroutine SMP, which simulates water transfer.
Figure 5.--Flow chart showing the coupling of the subroutine FRZ, which simulates heat transfer, and the subroutine SMP, which simulates water transfer, to the Precipitation-Runoff Modeling System. (Abbreviations correspond to those defined in table 1.)
Figure 6.--Location of the study area.
The soils in each of the three plots are classified as Hecla soil series (sandy, mixed Aquic Haploboroll; U.S. Department of Agriculture, 1975). These soils were formed in sandy sediments in glacial Lake Dakota and have been reworked by wind.

The Oakes aquifer, described by Armstrong (1980), underlies the plots. The primary source of recharge to the Oakes aquifer is direct infiltration of precipitation and snowmelt. The direction of ground-water flow in the vicinity of the study area is from east to west (Shaver and Schuh, 1990).

The climate of the area is semiarid to subhumid. The mean temperature for November through March is -8.3 °C (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982). January, the coldest month, has a mean temperature of -14.8°C. The mean number of days that the temperature is at or below freezing is 190 per year (Jensen, no date). Mean total precipitation for November through March is 87 mm. The mean seasonal maximum snow depth is 305 mm, and the mean seasonal number of days with snow depth of 152 mm or more is 40.

Data were collected during the winters of 1985-86 and 1986-87. Data collection started just prior to freezing of the soil and continued through the spring melting period. Soil temperatures were recorded continuously for one soil profile in plots 1 and 3 and for three soil profiles in plot 2. Soil temperatures were measured periodically for two soil profiles in each of plots 1 and 3. Soil water content was measured periodically for three soil profiles in each plot. Periodic snow depth and density measurements were made, and the runoff from the plots was recorded. Air temperature, global and reflected solar radiation, ground-water level, and precipitation also were recorded at the site of the plots.

On October 30, 1985, 86 mm of water was applied to plot 1, and 43 mm of water was applied to plot 3. No water was applied to plot 2. The application of water to the plots was followed by freezing weather conditions that produced the desired condition of a large soil water content during the fall season. The first snow fell November 10, 1985, and a continuous snow cover existed throughout the winter. Total recorded snowfall for the 1985-86 winter period had a snow water equivalent of 79 mm. The snowpack varied among the three plots due to the redistribution of the snow by wind.

No water was applied to the plots in the fall of 1986. The fall of 1986 had greater-than-normal precipitation, and soil water content on all plots was greater than after the application of water in the fall of 1985. The 1986-87 winter was quite mild and mostly snow free. Snow accumulated on the plots for periods of only a few days. On February 26, 1987, a rare event occurred in North Dakota. Rain fell on snow-free frozen soil and produced runoff and infiltration into the frozen soil.

**Model Calibration**

Calibration of a model involves adjusting parameters to improve agreement between measured and simulated values. The PRMS's optimization procedure automatically adjusts a specified set of parameters to improve agreement between measured and simulated runoff values. PRMS was modified to allow
optimization and sensitivity analysis with respect to frost depths. An absolute difference form of the objective function was used to measure the agreement between measured and simulated data. Descriptions of the optimization and sensitivity procedures used in PRMS are given in Leavesley and others (1983). PRMS's optimization procedure was not very useful in optimizing parameters associated with runoff because very little runoff occurred. Instead, a calibration procedure for runoff-related parameters involved numerous model runs in which parameters were adjusted until acceptable agreement between measured and simulated snow cover was obtained. Next, an optimization analysis and a sensitivity analysis with respect to frost depths were performed using PRMS's subroutines.

PRMS with the added subroutines FRZ and SMP was calibrated using the 1985-86 data for plot 2. The time-series data used for model input are given in Emerson and others (1990). A listing of the input used for the calibration is shown in supplement 6. An example of the output for the calibration is shown in supplement 7. The only parameters that were adjusted during the calibration were emissivity of air on days without precipitation (EAIR), depth of stable soil temperature (DEPTH_STABLE_TEMP), freeze and thaw adjustment coefficient (ADJUST_COEF), and mean annual air temperature (MEAN_Ann_AIR_TEMP). These are the only parameters that will be discussed.

Initially, the model could not be calibrated adequately because the modeled snowpack melted too early and runoff or infiltration or both were simulated days before they occurred. Snow ablation is an integral part of the heat and water transfer in frozen soils. A complete description of the energy balance used in the model is presented by Leavesley and others (1983, p. 39-46). In general, the energy at the air-snow interface is computed for each 12-hour period by summing the net shortwave radiation, net longwave radiation, and the convection-condensation energy. EAIR is a parameter used to compute net longwave radiation and can be adjusted to fit the modeled snowmelt to the measured snowmelt. A value of 0.757 generally is accepted for EAIR (U.S. Army Corps of Engineers, 1956, p. 159). Investigators have determined values of EAIR ranging from 0.546 to 0.877 (U.S. Army Corps of Engineers, 1956). Even when unrealistically small values of EAIR were tried, simulated snowmelt still was too early.

Further analysis revealed that the modeled albedo did not agree closely with the measured albedo. PRMS uses two mathematical equations that define the relation between albedo and time. One equation is for the snow accumulation period, and the other equation is for the snowmelt period (fig. 7). The equations used in PRMS were developed for deep mountain snowpacks (U.S. Army Corps of Engineers, 1956). Albedo values collected at the site of the plots were substantially greater than the values obtained from the equations developed for deep mountain snowpacks. Therefore, two new equations for a prairie environment (fig. 7) were developed. When the model was modified to incorporate the two new albedo equations, the modeled albedo agreed closely with the measured albedo. Calibration was accomplished when a value of 0.715 was used for EAIR. The snowpack for plot 2 was completely melted by the end of the day, March 22, 1986, which is 1 day before the modeled snowpack was completely melted.
DEPTH_STABLE_TEMP is the depth at which daily and seasonal soil temperatures do not change measurable, and is the term \( X_d \) in equation 2. At this depth, the soil temperature remains near the annual mean air temperature. Van Wijk and de Vries (1966) presented the following equation to estimate DEPTH_STABLE_TEMP:

\[
DEPTH_{\text{STABLE TEMP}} = \left[0.0002K/(CW)\right]^{0.5}
\]  

(18)

where DEPTH_STABLE_TEMP, is the depth of stable soil temperature, in meters;
- \( K \) is the thermal conductivity, in calories per centimeter per second per degree Celsius;
- \( C \) is the volumetric heat capacity, in calories per cubic centimeter per degree Celsius; and
- \( W \) is the angular frequency and is equal to 1.99x10\(^{-7}\) per second for annual variation.

Van Wijk and de Vries (1966) presented some calculated values of DEPTH_STABLE_TEMP based on average thermal soil properties (table 2). Increased values of DEPTH_STABLE_TEMP have the effect of allowing frost to penetrate deeper. Equation 18 was used to obtain an estimate for DEPTH_STABLE_TEMP to start optimization. The final optimized value for DEPTH_STABLE_TEMP as the result of calibration was 2.41 m.

ADJUST_COEF is an adjustment factor that modifies the square-root term within the penetration equation (eq. 1). Aldrich and Paynter (1953) used a similar adjustment factor and indicated that the adjustment factor is a

![Graph of albedo decay with age of snow](image)

Figure 7.--Decay of albedo with the age of snow.
Table 2.--Average thermal properties of soils
[Modified from Van Wijk and de Vries, 1966]

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Porosity (decimal fraction)</th>
<th>Volumetric water content (decimal fraction)</th>
<th>Thermal conductivity (10⁻³ calories per centimeter per second per degree Celsius)</th>
<th>Volumetric heat capacity (calories per cubic centimeter per degree Celsius)</th>
<th>Depth of stable soil temperature (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>.4</td>
<td>.0</td>
<td>.7</td>
<td>.3</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>.4</td>
<td>.2</td>
<td>4.2</td>
<td>.5</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>.4</td>
<td>.4</td>
<td>5.2</td>
<td>.7</td>
<td>2.73</td>
</tr>
<tr>
<td>Clay</td>
<td>.4</td>
<td>.0</td>
<td>.6</td>
<td>.3</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>.4</td>
<td>.2</td>
<td>2.8</td>
<td>.5</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td>.4</td>
<td>.4</td>
<td>3.8</td>
<td>.7</td>
<td>2.33</td>
</tr>
<tr>
<td>Peat</td>
<td>.8</td>
<td>.0</td>
<td>.14</td>
<td>.12</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>.8</td>
<td>.4</td>
<td>.7</td>
<td>.52</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>.8</td>
<td>.8</td>
<td>1.2</td>
<td>.92</td>
<td>1.14</td>
</tr>
</tbody>
</table>

A complicated function of thermal ratio, fusion parameter, and root diffusivity ratio. They indicated that values are greater for areas such as Alaska than for areas such as Kansas, and that values for North Dakota should be similar to those expected for Alaska. Increasing values of ADJUST_COEF have the effect of allowing the rate of frost penetration and thaw to increase. The final adjusted value for ADJUST_COEF as the result of calibration was 2.62.

MEAN ANN AIR TEMP is the mean annual air temperature. The mean annual air temperature for Oakes, N. Dak., is 5°C (U.S. Department of Commerce, 1982). The annual mean air temperature for 1984-87 ranged from 4 to 8°C. The final optimized value for MEAN ANN AIR TEMP as the result of calibration was 7.4°C.

The sensitivity analysis determines the extent to which uncertainty in the parameters results in uncertainty in the predicted frost depths and assesses the magnitude of parameter error and parameter intercorrelations when optimization is performed. Parameter error propagation summary of the sensitivity analysis for plot 2 for 1985-86 indicates that none of the parameters that were evaluated contribute significant prediction error (table 3). "Relative" sensitivities are computed rather than "absolute" sensitivities. Comparison of "absolute" values for different parameters is difficult because the magnitude is highly dependent on the magnitude of the parameter value itself. The values in table 3 are in square millimeters and need to be compared to the mean square error of prediction. DEPTH_STABLE_TEMP had the largest value of 3,200. A value of 3,200 means that a 10-percent error in the given parameter results in an increase of 3,200 in the mean squared error of prediction of 33,500. Parameter correlations give an
Table 3.—Ten-percent parameter error propagation summary

[DEPTH_STABLE TEMP; value of 3,200 given for the parameter for plot 2, 1985-86, would mean that a 10-percent error in the given parameter results in an increase of 3,200 in the mean squared error of prediction of 33,500]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plot 1, 1985-86</th>
<th>Plot 2, 1985-86</th>
<th>Plot 3, 1985-86</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEPTH_STABLE_TEMP (depth of stable soil temperature)</td>
<td>1,900 (4 percent)</td>
<td>3,200 (10 percent)</td>
<td>1,700 (5 percent)</td>
</tr>
<tr>
<td>ADJUST_COEF (freeze and thaw adjustment coefficient)</td>
<td>4,400 (10 percent)</td>
<td>2,500 (8 percent)</td>
<td>4,300 (13 percent)</td>
</tr>
<tr>
<td>MEAN_ANNUAL_AIR_TEMP (mean annual air temperature)</td>
<td>2,500 (5 percent)</td>
<td>2,200 (7 percent)</td>
<td>500 (2 percent)</td>
</tr>
<tr>
<td>Mean squared error of prediction</td>
<td>45,900</td>
<td>33,500</td>
<td>33,700</td>
</tr>
</tbody>
</table>

The calibration simulation of frost and thaw depths using 1985-86 data for plot 2 agrees closely with the measured frost and thaw depths (fig. 8). The measured maximum frost depth occurred in plot 2 from February 22 to March 3, 1986, and the depth ranged from 1.24 to 1.36 m. The simulated maximum frost depth occurred February 12, 1986, and the depth was 1.01 m. The final thaw is when the soil profile is completely thawed for the spring and no more refreezing occurs. Final thaw for measured soil profiles in plot 2 varied from March 23 to 28, 1986. The simulated thaw occurred from the top by surface heating and from below by the heat from the soil below the frost (fig. 8). The final simulated thaw occurred March 31, 1986. The change in simulated soil water content from October 1, 1985, to March 24, 1986, was only 1.7 mm more than the measured (table 4). The model simulated the soil water profile for March 24, 1986, closely with the measured soil water profile (fig. 9).

Model Verification

Model verification is the process of using a calibrated model to produce simulations with time-series data and physical descriptors not previously used in the calibration procedure. Results of these simulations were then compared with the measured data to evaluate the performance of the model. Evaluation
Figure 8.--Measured frost depths and calibration simulation of frost depths for plot 2, October 1985 through April 1986.

Figure 9.--Measured soil water profile and calibration simulation of soil water profile for plot 2, March 24, 1986.
Table 4.--Summary of the results of model calibration for plot 2
using 1985-86 data

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in soil water, in millimeters</td>
<td>73.2</td>
<td>74.9</td>
</tr>
<tr>
<td>Recharge, in millimeters</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Runoff, in millimeters</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maximum frost depth, in meters</td>
<td>1.29</td>
<td>1.01</td>
</tr>
<tr>
<td>Date of final thaw</td>
<td>3/25/86</td>
<td>3/31/86</td>
</tr>
</tbody>
</table>

1 The change in soil water is from October 1, 1985, through March 24, 1986.
2 Recharge from October 1, 1985, through March 31, 1986.
3 Measured maximum frost depths ranged from 1.24 to 1.36 meters; the mean is 1.29 meters.

Simulations of heat and water transfer for plots 1 and 3 using 1985-86 data and plots 1, 2, and 3 using 1986-87 data were used for model verification. The measured and simulated frost depths are shown in figures 10-14. The results of the verification simulations are listed in table 5. The simulations agreed closely with the measured frost depths except for plot 3, 1986-87. The measured frost depths for plot 3, 1986-87, which were determined by recorded data, are much greater than those measured for plots 1 and 2 or for other periodic measurements taken in plot 3. The recorded data for plot 3 were reviewed carefully and no reason was found for dismissing the data. However, the recorded data for plot 3 do not appear to be representative of the plot when compared to other periodic measurements.

The verification simulations for 1985-86 did not simulate the date of final thaw as well as those for 1986-87, but several partial thaws were simulated during the winter of 1986-87. The date of the final thaw for the 1985-86 simulations were 16 and 18 days after the measured date, whereas the date of the final thaw for the 1986-87 simulations were from 2 to 4 days after the measured date.

Model Recalibration

Several years of data that represent a range of hydrologic conditions are preferred for model calibration. Model calibration with several years of data is not always possible, as in these simulations for which data are available
Figure 10.—Measured frost depths and verification and recalibration simulations of frost depths for plot 1, October 1985 through April 1986.

Figure 11.—Measured frost depths and verification and recalibration simulations of frost depths for plot 3, October 1985 through April 1986.
Figure 12.--Measured frost depths and verification simulation of frost depths for plot 1, October 1986 through April 1987.

Figure 13.--Measured frost depths and verification simulation of frost depths for plot 2, October 1986 through April 1987.
only for two winters and three plots. The model was initially calibrated using the 1985-86 data for plot 2. To determine what effect variable hydrologic conditions had on optimizing parameter values, the model was recalibrated for plots 1 and 3 using the 1985-86 data. The model was not recalibrated using the 1986-87 data because the optimization analysis would have provided incorrect parameter adjustments because of missing frost-depth data. Comparisons of the recalibration simulations of frost depths with measured frost depths are shown in figures 10 and 11 and table 5. The optimized parameters for various recalibration simulations are listed in table 6. Recall that if no adjustments were made to the parameters, their values would be that of plot 2, 1985-86 (original calibration, table 6). No changes or small changes between calibrated and recalibrated parameter values support the calibrated parameter as being a representative value. Large changes imply that the parameter value varies with changes in hydrologic conditions or is not a representative value for the parameter.

The EAIR value for plot 1 was the largest at 0.788, the value for plot 3 was the next largest at 0.747, and the value for plot 2 was the smallest at 0.715. The depth of the snowpack for each plot was in the same order—plot 1 had the deepest snowpack and plot 2 had the shallowest. The variation in EAIR probably is compensating for the variation that shallow prairie snowpack has on the heat transfer to and from the soil. For deep, ripe snowpacks, solar radiation, which is absorbed by the snow, results in the same quantity of melt, whether the radiation is all absorbed in the top surface or is penetrated to a depth of 0.3 m or so. For shallow snowpacks, a measurable
Table 5.--Summary of the results of model verification and recalibration

[---, no data]

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Verification</td>
<td>Measured</td>
<td>Verification</td>
<td>Measured</td>
</tr>
<tr>
<td>Change in soil water, in</td>
<td>100</td>
<td>45</td>
<td>102</td>
<td>256</td>
<td>276</td>
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<tr>
<td>millimeters</td>
<td></td>
<td></td>
<td></td>
<td>381</td>
<td>398</td>
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<tr>
<td>Ground-water recharge, in</td>
<td>--</td>
<td>0</td>
<td>--</td>
<td>0</td>
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<tr>
<td>millimeters</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Runoff, in millimeters</td>
<td>14.2</td>
<td>16.5</td>
<td>0</td>
<td>9.0</td>
<td>3.3</td>
</tr>
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<td></td>
<td></td>
<td>5.8</td>
<td>.3</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>6.5</td>
<td>0</td>
</tr>
<tr>
<td>Maximum frost depth, in meters</td>
<td>1.24</td>
<td>1.00</td>
<td>1.00</td>
<td>1.31</td>
<td>1.00</td>
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<td>.85</td>
<td>.59</td>
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<td>.56</td>
<td>1.06</td>
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<td>4/06/86</td>
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</tr>
</tbody>
</table>

1 The change in soil water is from November 1, 1985, through March 24, 1986.
2 The change in soil water is from November 1, 1985, through March 25, 1986.
3 The change in soil water is from October 1, 1986, through March 25, 1987.
4 Recharge from November 1, 1985, through March 31, 1986.
6 The mean date of final thaw of plot.
Table 6.--Model parameter values for original calibration and recalibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plot 1, 1985-86 (recalibration)</th>
<th>Plot 2, 1985-86 (original calibration)</th>
<th>Plot 3, 1985-86 (recalibration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAIR (emissivity of air on days without precipitation)</td>
<td>0.788</td>
<td>0.715</td>
<td>0.747</td>
</tr>
<tr>
<td>DEPTH_STABLE_TEMP (depth of stable soil temperature), in meters</td>
<td>2.37</td>
<td>2.41</td>
<td>2.79</td>
</tr>
<tr>
<td>ADJUST_COEF (freeze and thaw adjustment coefficient)</td>
<td>2.45</td>
<td>2.62</td>
<td>2.74</td>
</tr>
<tr>
<td>MEAN ANN_AIR_TEMP (mean annual air temperature), in degree Celsius</td>
<td>7.4</td>
<td>7.4</td>
<td>6.9</td>
</tr>
</tbody>
</table>

The quantity of solar radiation may penetrate through to the soil. Some of the heat energy from the soil may return to the snowpack by conducted or long-wave radiation, or both. In the case of frozen soil, some of the heat may be absorbed by the soil. A lower EAIR value than one used for a deep snowpack would compensate for the absorption of heat by the soil.

The values of the optimized parameters of the FRZ and SMP subroutines (DEPTH_STABLE_TEMP, ADJUST_COEF, AND MEAN ANN_AIR_TEMP) did not change significantly from the original calibration. The sensitivity analysis (table 3) indicates that the model is not very sensitive to these parameters. The optimized values of both DEPTH_STABLE_TEMP and MEAN ANN_AIR_TEMP are within their expected range.

**DISCUSSION**

The most common definition of frozen soil is earth material that has a temperature of less than 0°C. This definition, however, is independent of the state of water in the material. Algorithms based on the definition are incorporated into the model, but this definition does not necessarily mean that the soil water is frozen for temperatures at or below 0°C. Dingman (1975, p. 4) stated that "In many soils, ice does not form until the temperature falls considerably below 0°C. This 'freezing point depression' may be due to several causes: (1) The presence of dissolved ions in the water, (2) supercooling due to the absence of freezing nuclei, and (3) the existence of water that is tightly bound to soil particle surfaces, such that
its intermolecular structure, and hence its thermodynamic properties, are altered." Algorithms based on different definitions of frozen soil can affect the model's prediction of freezing and thawing and in turn affect the prediction of soil water movement. For example, if the definition of frozen soil is soil with temperatures less than \(-1^\circ C\), then the day soil began to freeze would be later, the day of complete thaw would be earlier, and the maximum frost depth would be less than if the definition is soil with temperatures less than \(0^\circ C\). All these changes, in turn, would affect rate and amount of soil water movement. Observed soil temperatures indicated a large thermal gradient occurred during the freezing period but, as the soil profile approached complete thaw, the thermal gradient was near zero. Soil temperatures between \(0\) and \(-1.0^\circ C\) were observed for the whole soil profile during thaw.

Dingman's (1975, p. 23) comprehensive literature review on hydrologic effects of frozen ground stated that "***a sufficient number of observation studies have been done in a number of geographical areas***." However, these observation studies vary in the type of data that were measured, which makes comparison of their conclusions difficult. A thorough analysis of the factors that result in the different types of frost formation and the effect that frost formation has on water movement is needed. Once these factors are better defined, the model algorithms can be modified to better simulate the physical processes.

Data for the 1985-86 winter for plot 2 were used for the original model calibration. Preferably, several years of data that would include a wide range of conditions should be used in model calibration. Results of the simulations have provided a limited test of the model's performance because the time-series data only consisted of two winters and the physical settings of the three plots were similar. Additional simulations that include different climatic conditions and physical settings are needed.

Although the simulations were limited to two winters and to three plots that had similar physical settings, the simulations do represent variability in some of the conditions. Because water was applied to plots 1 and 3 in the fall of 1985 and because the fall of 1986 was very wet, a full range of antecedent soil water conditions from moderate to wet was used in the simulations with successful results. A full range of snow-cover conditions commonly expected for cultivated fields in North Dakota also was used in the simulations with successful results. The winter of 1985-86 was colder than normal and the winter of 1986-87 was milder than normal. The model performed very well for both of these winters.

SUMMARY

A model that simulates heat and water transfer in seasonally frozen soils was developed and incorporated into the U.S. Geological Survey's watershed Precipitation-Runoff Modeling System (PRMS). Heat transfer is based on an equation that was derived from Fourier's equation for heat flux. The model allows as many as 10 soil layers to be defined by the user. Field capacity and infiltration rate can be varied throughout freezing and thawing periods, and the variation depends upon the soil conditions and snowmelt. The soil water is redistributed based on the concept of capillary forces.
PRMS is a modular-designed model and consists of three components: (1) Data-management component that is used for manipulating and storing data, (2) library component for storage of source code used in simulating physical processes and used for model fitting and analysis, and (3) output component that provides model output handling and analysis capabilities. PRMS was modified by coupling two subroutines, FRZ and SMP. FRZ computes heat transfer through a profile and SMP computes water transfer through a soil profile.

Data used in model simulations were collected for two winters, 1985-86 and 1986-87, from three runoff plots. The runoff plots are located 11.3 kilometers southeast of Oakes, N. Dak. Data collection started just prior to freezing of the soil and continued through the spring snowmelt period. Meteorologic conditions during the two winters were quite different. The winter of 1985-86 was fairly cold and there was continuous snow cover throughout the winter. The winter of 1986-87 was quite mild and snow accumulated only for short periods of several days.

Calibration consisted of optimizing runoff-related parameters and then optimizing frost-related parameters. The model was calibrated using the 1985-86 data for plot 2. The only parameters that were adjusted during calibration were EAIR, DEPTH_STABLE_TEMP, ADJUST_COEF, and MEAN_ANN_AIR_TEMP. EAIR is the emissivity of air on days without precipitation. DEPTH_STABLE_TEMP is the depth of stable soil temperatures. ADJUST_COEF is a freeze and thaw adjustment coefficient. MEAN_ANN_AIR_TEMP is the mean annual air temperature. Calibrated values were 0.715 for EAIR, 2.41 meters for DEPTH_STABLE_TEMP, 2.62 for ADJUST_COEF, and 7.4°C for MEAN_ANN_AIR_TEMP. The calibrated simulation agrees closely with the measured frost and thaw depths. The sensitivity analysis indicated that none of the frost-related parameters that were evaluated contributed significantly to prediction error. The simulated change in soil water content from October 1, 1985, through March 24, 1986, was predicted within 2 millimeters of that measured, and the simulated thaw occurred 6 days after the measured thaw.

Verification of the model was performed using the 1985-86 data for plots 1 and 3 and using 1986-87 data for plots 1, 2, and 3. The verification simulations agreed closely with the measured frost depths except for plot 3 for 1986-87 data, which did not agree closely. The model was recalibrated using each time-series data set that was used in the verification simulations for 1985-86. The optimized parameters used during the recalibration did not change substantially from the original calibration. The major improvements in the recalibration simulations were in the date of final thaw.

The results of the simulations have provided a limited test of the model's performance because the time-series data only consist of two winters and because the physical settings of the three plots were similar. However, a full range of antecedent soil water conditions from moderate to wet and a full range of snow-cover conditions for cultivated fields in North Dakota were simulated successfully. Additional simulations that include different climatic conditions and physical settings are needed.
REFERENCES


Jensen, R.E., (no date), Climate of North Dakota: Fargo, North Dakota State University, 48 p.


Kersten, M.S., 1949, Thermal properties of soils: Minneapolis, University of Minnesota, Institute of Technology, Engineering Experiment Station Bulletin No. 28, 227 p.


Supplement 1.---Formula for the determination of depth of freezing

Conduction is the main mechanism of heat transfer in soil. The heat flux is given by Fourier's equation as

\[ q = K \left( \frac{dT}{dX} \right) \]  

(19)

where \( q \) is specific heat flux, in calories per square centimeter per second;

\( K \) is thermal conductivity, in calories per centimeter per second per degree Celsius;

\( T \) is temperature, in degrees Celsius; and

\( X \) is depth, in centimeters.

Measurements of thermal gradient, \( dT/dX \), rarely are available. Thermal gradient over a day can be defined as \( IF/X \). \( IF \) is a frost index and commonly is referred to as degree-day. \( IF \) is summed over a number of days and is defined as

\[ IF = \sum (T_b - T_d) \]  

(20)

where \( T_b \), a base temperature, usually is set to 0°C but may need to be adjusted by a degree or two and \( T_d \) is the daily mean air temperature. The adjustment will vary from area to area and will have to be determined by calibration. The total of the degree-days, \( T_b - T_d \), is computed by adding the daily degree-days for the entire freezing period. The frost index, \( IF \), will be positive during freezing. Substituting \( IF/X \) into equation 19 gives

\[ q = 86,400IF/X \]  

(21)

where 86,400 converts heat flux per second to heat flux per day.

The energy transferred in the form of heat in time, \( dt \), is

\[ dq = 86,400IF/X \ dt \]  

(22)

or for \( dt \) equals 1 day

\[ Q = 86,400IF/X \]  

(23)

where \( Q \) is heat, in calories per square centimeter.

The required heat loss to freeze a soil layer of \( X \) thickness can be estimated by

\[ Q = XL+XCT_a \]  

(24)

where \( L \) is the latent heat, in calories per cubic centimeter;

\( C \) is the volumetric heat capacity, in calories per cubic centimeter per degree Celsius; and

\( T_a \) is the mean annual temperature of the soil layer, in degrees Celsius.
Soil temperature, $T_a$, represents the heat that must be lost during a season to bring the soil to a freezing temperature. Soil temperature fluctuates about some mean value during the year. At some seasonally stable depth, $X_a$, seasonal soil temperature changes are reduced to the fraction $1/e$, 0.368, of the surface variation during the year (Van Wijk and de Vries, 1966, p. 109). The temperature at this depth is close to the mean annual air temperature. At some time during the fall when the mean daily temperature at the surface layer cools to the mean annual temperature, heat begins to be conducted from the lower levels of the soil up to the surface rather than into the soil.

Heat must continue to be lost during freezing to maintain a thermal gradient and can be considered by the term $C t_f/(2t)$ where $t$ is the duration of the freezing period in days. Adding this term to equation 24 gives

$$Q = X L + X C T_a + X C t_f/(2t).$$ (25)

Setting equation 25 to 23 and solving for $X$ gives

$$X_f = [(86,400K_f t_f)/(L + C(T_a + t_f/(2t)))]^{0.5}$$ (26)

where $K_f$ is the thermal conductivity of the horizon layers, in calories per centimeter per second per degree Celsius.

Equation 26 was proposed by the U.S. Army Corps of Engineers (1949) to calculate the depth to which the soil freezes as a function of time.

The primary source of energy that is stored in the soil is radiation from the sun during the summer, and this stored energy is the source of heat that causes thawing of the soil from below the frost front. A similar derivation as used in frost penetration can be used to compute the heat from the layer between the frost front, $X_f$, and the seasonally stable depth, $X_a$. The thermal gradient for the depth interval, $X_a - X_f$, can be estimated by $T_a/(X_a - X_f)$ and substituted in equation 23 to give

$$Q = 86,400K_u(T_a/(X_a - X_f))$$ (27)

where $K_u$ is the thermal conductivity of the unfrozen layers, in calories per centimeter per second per degree Celsius.

Latent heat is the only energy transferred in the soil layer, $X_a - X_f$. The heat transferred in the soil depth that the frost is reduced can be estimated by

$$Q = LX_f$$ (28)

where $X_f$ is the depth that the frost is reduced, in centimeters.

Setting equation 27 to equation 28 and solving for $X_f$ gives

$$X_f = 86,400K_u(T_a/(X_a - X_f))/L.$$ (29)
Supplement 2. Computer code for subroutine FRZ

C Definitions of the variables that are used in FRZ are listed below.
C
C ACZONE  Distance between the depth of 0 degree Celsius isotherm of the soil and the depth of stable soil temperature (centimeters).
C ADJUST_COEF  Freeze and thaw adjustment coefficient.
C AVAIL_WATER  Daily available water in soil profile (inches).
C DAILY_MAX_TEMP  Daily maximum air temperature (degrees Celsius).
C DAILY_MEAN_TEMP  Daily mean air temperature (degrees Celsius).
C DAILY_MIN_TEMP  Daily minimum air temperature (degrees Celsius).
C DAYS_FREEZE  Number of days in the current freeze period.
C DAYS_THAW_PERIOD  Number of days in the current thaw period.
C DEN  Computational term used for density of snowpack (grams per cubic centimeter).
C DEPTHLEFT  Depth of soil profile that is not frozen. Used in computing thawing from below (inches).
C DEPTHREDUC_BELOW  Reduction in frost depth due to heating from below (centimeters).
C DEPTH_STABLE_TEMPS  Depth of stable soil temperatures. The point in the ground at which daily and seasonal temperatures cease to cause measureable change (inches).
C DEPTH2  Temporary value of depth of frost or thaw (centimeters).
C DIFF_DEPTH  Fractional part of an interval to be frozen or thawed (centimeters).
C FREEZECOUNT  Fractional part of an interval to be frozen or thawed (centimeters).
C FREEZECOUNT  Flag which indicates that some frost has occurred:
C FREEZEINDEX  Current freezing index--cumulative degree days for mean air temperatures below 0 degree Celsius.
C FREEZEINDEXARRAY  Array of freezing index for successive freezing cycles.
C FREEZING_DOMAIN  Array of frost penetration depths for successive freezing cycles--soil only (inches).
C FROZENFLAG  Flag which indicates that the watershed has been frozen imperviously:
C FROZENSOLIDFLAG  Array of volumetric heat capacity of soil profile for successive freezing cycles (calories per cubic centimeter per degree Celsius).
C HC  Computational term used in computing heat capacity of the profile.
C H C_SOIL

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Supplement 2.--Computer code for subroutine FRZ--Continued

C ***** HEAT_CAP_COMPOSITE Volumetric heat capacity of partial soil profile (calories per cubic centimeter per degree Celsius).
C ***** HEAT_CAP_ICE Heat capacity of ice (calories per cubic centimeter per degree Celsius).
C ***** HEAT_CAP_LITTER Heat capacity of litter (calories per cubic centimeter per degree Celsius).
C ***** HEAT_CAP_PROFILE Volumetric heat capacity of the profile--snow, litter, and soil--undergoing freezing or thawing (calories per cubic centimeter per degree Celsius).
C ***** HEAT_CAP_SNOW Heat capacity of snow (calories per cubic centimeter per degree Celsius).
C ***** HEAT_CAP_SOIL Heat capacity of dry soil (calories per cubic centimeter per degree Celsius).
C ***** HEAT_CAP_SOIL_SUM Volumetric heat capacity of soil and water in the profile (calories per cubic centimeter per degree Celsius).
C ***** INCR_SNOW_DEPTH Increase snow depth (inches).
C ***** IRU Hydrologic response unit.
C ***** JULIAN_DATE Julian date.
C ***** LATENTHEAT Composite latent heat of the profile--litter and soil--undergoing freezing or thawing (calories per cubic centimeter).
C ***** LAT_HT_LITTER Latent heat of the litter (calories per cubic centimeter).
C ***** LAT_HT_SOIL Latent heat of the soil profile undergoing freezing or thawing (calories per cubic centimeter).
C ***** LAT_HT_UNIT_CHG Latent heat of the soil profile below frost penetration (calories per cubic centimeter).
C ***** LAYERDEPTH Thickness of each soil layer (inches).
C ***** LAYER_MOIST Daily soil water content of each layer (inches).
C ***** LAYERPOROSITY Porosity of each layer (decimal fraction).
C ***** L_H Array of latent heat for successive freezing cycles (calories per cubic centimeter).
C ***** LITTERDEPTH Depth of the litter layer (inches).
C ***** MEAN ANN AIR TEMP Mean annual air temperature (degrees Celsius).
C ***** MEAN_ANN_TEMP_NUMTR Computational term involving the numerator of the frost penetration equation.
C ***** MIN_INFILTR Minimum infiltration rate when the soil is near field capacity and is under frozen conditions (inches per hour).
C ***** MOIST Soil water of layers below frost penetration (decimal fraction, volume).
C ***** MOIST_LITTER Water content of the litter layer (inches).
C ***** MOS Water content of a soil layer (decimal fraction, volume).
C ***** MOS_UNDFROZE Water content of the soil below frost penetration (inches).
C ***** NET_PRECIP Daily precipitation (inches).
**Supplement 2. Computer code for subroutine FRZ--Continued**

C ***** NEW_SNOW
C ***** NEW_SNOW_DENSITY
C ***** NUM_LAYERS
C ***** ORGANIC_MATTER
C ***** ORGANIC_MATTER1
C ***** ORGANIC_MATTER2
C ***** PEN_CTR
C ***** PENDEPTHARRAY
C ***** PENETRATION_DENOM
C ***** PENETRATION
C ***** PENETRATION_CODE
C ***** PENETRATION_MAX_SOIL
C ***** PENETRATION_NUMTR
C ***** PEN_S
C ***** PERC_DEPTH
C ***** POROSITY_LOWER
C ***** POTSATURATEDFLAG
C ***** PROFILE_MOIST_POT
C ***** RATIO_TC_AIR1
C ***** RATIO_TC_AIR2

Daily precipitation in the form of snow (inches).
Initial density of new-fallen snow (decimal percent).
Number of soil layers.
Organic material of the top soil layer (decimal fraction).
Threshold for organic material below which puddling of the soil is likely to occur (decimal fraction).
Threshold for organic material above which puddling of the soil is unlikely to occur (decimal fraction).
Counter to allow penetration to go centimeter by centimeter through soil layers.
Array of frost penetration depths for successive freezing cycles and includes snow and litter depths (inches).
Computational term involving the denominator of the frost penetration equation.
Current depth of frost penetration (inches).
The frost penetration code for the top soil layer:
0: No frost in the top layer,
1: Frost does exist in the top layer,
9999: Error—something is wrong.
Maximum frost penetration into the soil. Does not include penetration through snow or litter (inches).
Computational term involving the numerator of the frost penetration equation.
Computational term used in the frost penetration equation.
Depth of percolation of excess water to lower layers that might occur on a day when the mean temperature is above freezing and the minimum is below freezing (inches).
Porosity of soil layers below frost penetration (decimal fraction).
Flag which, when set to 1, allows the surface soil layer to collect more water than the normal field capacity and increases the likelihood that concrete frost will form if it has not already.
Maximum available water-holding capacity of a soil profile: Sum of the variables "LAYER_MOIST_POT" (inches).
Ratio of the thermal conductivities of mineral soil to air.
Ratio of the thermal conductivities of mineral soil to air.
C **** RATIO_TC_ICE Ratio of the thermal conductivities of mineral
C **** soil to ice.
C **** RATIO_TC_WAT_SOIL Ratio of the thermal conductivities of water to
C **** soil.
C **** SNOW Water equivalent of snowpack (inches).
C **** SNOW_DENSITY Density of the snowpack (grams per cubic
C **** centimeter).
C **** SNOWDEPTH Depth of snowpack (inches).
C **** SNOWDEPTH LOSS Loss in depth of snowpack (inches).
C **** SURLAYER_MOIST_POT Soil water between field capacity and wilting
C **** point for the surface layer that is subject to
direct evaporation (inches).
C **** SUR_STORE_OVER_WILT Soil water in the surface layers subject to
direct evaporation (inches).
C **** TC Array of thermal conductivity of the profile for
C **** successive freezing cycles (calories per
C **** centimeter per second per degree Celsius).
C **** TC_AIR Thermal conductivity of air (calories per
C **** centimeter per second per degree Celsius).
C **** TC_COMPOSITE Composite thermal conductivity of the soil
C **** (calories per centimeter per second per degree
C **** Celsius).
C **** TC_DENOM Computational term used in computing
C **** "TC_COMPOSITE."
C **** TC_DRYSOIL Thermal conductivity of dry soil (calories per
C **** centimeter per second per degree Celsius).
C **** TC_ICE Thermal conductivity of ice (calories per
C **** centimeter per second per degree Celsius).
C **** TC_LITTER Thermal conductivity of litter (calories per
C **** centimeter per second per degree Celsius).
C **** TC_NUM Computational term used in computing
C **** "TC_COMPOSITE."
C **** TC_SUM Current thermal conductivity of the profile
C **** (calories per centimeter per second per degree
C **** Celsius).
C **** TC_UNDFROZE_COMPOSITE Thermal conductivity of soil below frost
C **** penetration (calories per centimeter per second
C **** per degree Celsius).
C **** TC_UNDFROZE_DENOM Computational term used in computing
C **** "TC_UNDFROZE_COMPOSITE."
C **** TC_UNDFROZE_NUM Computational term used in computing
C **** "TC_UNDFROZE_COMPOSITE."
C **** TC_WATER Thermal conductivity of water (calories per
C **** centimeter per second per degree Celsius).
C **** THAW_DENOM Computational term involving the denominator of
C **** the thaw equation.
C **** THAWDEPTH Current depth of thaw (inches).
C **** THAWDEPTHARRAY Array of depths for successive thawing cycles
C **** (inches).
Supplement 2.--Computer code for subroutine FRZ--Continued

C **** THAW_FACTOR
Factor used in computing heat capacity during thaw.

C **** THAWFROSTCODE
Code indicating type of frost in the soil:

1: Generally a quick freeze--granular frost expected,
2: Very moist ground--needle ice and possible heaving expected,
3: Concrete frost expected with impervious soil,
4: Snow is melting and some thawing of soil from below is expected,
5: Some thawing has taken place but the soil is still partially frozen,
6: Soil is free of frost,
7: Soil is freezing but conditions make the type of frost indeterminant,
8: Frost did not penetrate the litter,
9: Error--something is wrong.

C **** THAW_NUMTR
Computational term involving the numerator of the thaw equation.

C **** THAW_SUM
Current thaw index--cumulative degree days for mean air temperatures above 0 degree Celsius.

C **** THAWSUMARRAY
Array of thaw indexes for successive thawing cycles (inches).

C **** THERMAL_RESIST_LITTER
Thermal resistance of litter (centimeters seconds degrees Celsius per calorie).

C **** THERMAL_RESIST_SNOW
Thermal resistance of snow (centimeters seconds degrees Celsius per calorie).

C **** THERMAL_RESIST_SOIL
Thermal resistance of soil (centimeters seconds degrees Celsius per calorie).

C **** TOTALDEPTH
Computational term used to determine the depth of frost or thaw (centimeters).

C **** T_R_SOIL
Array of thermal resistance of the soil for successive freezing cycles (centimeters seconds degrees Celsius per calorie).

C **** WATER_POT
Water available for runoff, infiltration, or evaporation (inches).

C **** WEIGHTED_POROS
Porosity of soil layer weighted by the thickness of each layer (decimal fraction).

C **** YESTERDAY
Yesterday used for testing whether days of thaw are consecutive.

C **** YEST_MEAN_AIR_TEMP
Yesterday's mean air temperature (degrees Celsius).

C **** YEST_TYPE_FROST
Yesterday's frost type.

C **** YEST_SNOW_DEPTH
Yesterday's depth of snowpack (inches).

C **** YEST_WATER_POT
Yesterday's "WATER_POT" (inches).

$INSERT ALL.COM

REAL
* ACZONE,
* ADJUST_COEF,
* AVAIL_WATER,
* DAILY_MAX_TEMP,
* DAILY_MEAN_TEMP,
* DAILY_MIN_TEMP,
* DEPTHLEFT,
* DEPTHREDUC BELOW,
* DEPTH_STABLE_TEMPS,
* DEPTHZ,
* DIFFDEPTH,
* FREEZESUM,
* FREEZESUM_ARRAY(10, 50),
* FROST (10, 50),
* HC,
* H_C_SOIL(10, 50),
* HEAT_CAP_COMPOSITE,
* HEAT_CAP_ICE,
* HEAT_CAP_LITTER,
* HEAT_CAP_PROFILE,
* HEAT_CAP_SNOW,
* HEAT_CAP_SOIL,
* HEAT_CAP_SOIL_SUM,
* INCR_SNOW_DEPTH,
* LATENTHEAT,
* LAT_HT_LITTER,
* LAT_HT_SOIL,
* LAT_HT_UNIT_chg,
* LAYERDEPTH(IO,50),
* LAYER_MOIST(10,50),
* LAYER_POROSITY(10,50),
* L_H(IO,50),
* LITTERDEPTH,
* MEAN_ANN_AIR_TEMP,
* MEAN_ANN_TEMP_NUMTR,
* MIN_INFGTR,
* MOIST,
* MOIST_LITTER,
* MOS(IO),
* MOS_UNDFROZE,
* NET_PRECIP,
* NEW_SNOW,
* NEW_SNOW_DENSITY
* ORGANIC_MATTER,
* ORGANIC_MATTER1,
* ORGANIC_MATTER2,
* PENDEPTHARRAY(IO,50),
* PENETRATION_DENOM,
* PENETRATION,
* PENETRATION_MAX_SOIL,
* PENETRATION_NUMTR,
* PEN_S,
* PERC_DEPTH,
* POROSITY_LOWER,
* PROFILE_MOIST_POT,
* RATIO_TC_AIR1,
* RATIO_TC_AIR2,
* RATIO_TC_ICE,
* RATIO_TC_WAT_SOIL,
* SNOW,
* SNOW_DENSITY,
* SNOWDEPTH,
* SNOWDEPTH_LOSS,
* SURLAYER_MOIST_POT,
* SUR_STORE_OVER_WILT,
* TC(IO,50),
Supplement 2.--Computer code for subroutine FRZ--Continued

* TC_AIR,
* TC_DENOM,
* TC_DRYSOIL,
* TC_ICE,
* TC_LITTER,
* TC_NUM,
* TC_SUM,
* TC_UNDFROZE_COMPOSITE,
* TC_UNDFROZE_DENOM,
* TC_UNDFROZE_NUM,
* TC_WATER,
* THAW_DENOM,
* THAWDEPTH,
* THAWDEPTHARRAY(10,50),
* THAW_FACTOR,
* THAW_NUMTR,
* THAW_SUM,
* THAWSUMARRAY(10,50),
* THERMAL_RESIST_LITTER,
* THERMAL_RESIST_SNOW,
* THERMAL_RESIST_SOIL,
* TOTALDEPTH,
* T_R_SOIL(10,50),
* WATER_POT,
* WEIGHTED_POROS,
* YEST_MEAN_AIR_TEMP,
* YEST_SNOW_DEPTH,
* YEST_WATER_POT

INTEGER
* DAYS_FREEZE(10,50),
* DAYS_THAW_PERIOD,
* DUMMY,
* DUMMY2,
* FREEZEFLAG,
* FROZENSOILFLAG,
* FRZ_THAW_FLAG,
* I,
* IRU,
* J_LEFT,
* JULIAN_DATE,
* K,
* NUM_LAYERS,
* PENCTR,
* PENETRATIONCODE,
* P_MAX,
* PUTSATURATEDFLAG,
* TEMPORARY,
* THAWFROSTCODE,
* T_MAX,
* YESTERDAY,
* YEST_TYPE_FROST

ACZONE = 0.0
DAILY_MEAN_TEMP = 0.0
DEPTHLEFT = 0.0
DEPTHREDUC_BELOW = 0.0
DEPTH2 = 0.0
DIFF_DEPTH = 0.0
DUMMY = 0
DUMMY2 = 0
HC = 0.0
HEAT_CAP_COMPOSITE = 0.0
HEAT_CAP_ICE = 0.45
HEAT_CAP_PROFILE = 0.0
HEAT_CAP_SOIL = 0.46
HEAT_CAP_SOIL_SUM = 0.0
I = 0
J_LEFT = 0
K = 0
LATENHEAT = 0.0
LAT_HT_LITTER = 0.0
LAT_HT_SOIL = 0.0
LAT_HT_UNIT_CHG = 0.0
MEAN_ANN_TEMP_NUMTR = 0.0
MOIST = 0.0
MOS_UNDFROZE = 0.0
MOS(1) = 0.0
MOS(2) = 0.0
MOS(3) = 0.0
MOS(4) = 0.0
MOS(5) = 0.0
PEN_CTR = 0
PENETRATION_DENOM = 0.0
PENETRATION_NUMTR = 0.0
PEN_S = 0.0
PERC_DEPTH = 0.0
POROSITY_LOWER = 0.0
RATIO_TC_AIR1 = 0.0253
RATIO_TC_AIR2 = 1.4678
RATIO_TC_ICE = 0.9
RATIO_TC_WAT_SOIL = 0.332
TC_AIR = 0.00006
TC_COMPOSITE = 0.0
TC_DENOM = 0.0
TC_DRYSOIL = 0.0007
Supplement 2.--Computer code for subroutine FRZ--Continued

TC_ICE = 0.00052
TC_LITTER = 0.00008
TC_NUM = 0.0
TC_SUM = 0.0
TC_UNDFROZE_COMPOSITE = 0.0
TC_UNDFROZE_DENOM = 0.0
TC_UNDFROZE_NUM = 0.0
THAW_DENOM = 0.0
THAW_FACTOR = 0.0
THAW_NUMTR = 0.0
THERMAL_RESIST_LITTER = 0.0
THERMAL_RESIST_SNOW = 0.0
THERMAL_RESIST_SOIL = 0.0
TOTALDEPTH = 0.0
WEIGHTED_POROS = 0.0

TEMPORARY = TEMPORARY + 1
WRITE(1,7000) TEMPORARY
7000 FORMAT(' ************ INSIDE FRZ ********** DAY # ',I3)

IF (YEST_SNOW_DEPTH .GT. SNOWDEPTH) THEN
   SNOWDEPTHLOSS = YEST_SNOW_DEPTH - SNOWDEPTH
ELSE
   SNOWDEPTHLOSS = 0.0
END IF
DAILY_MEAN_TEMP = (DAILY_MAX_TEMP + DAILY_MIN_TEMP) * 0.5

DO 5 J = 1,NUM_LAYERS
   MOS(J) = LAYER_MOIST(J,IRU) / LAYERDEPTH(J,IRU)
5

IF (FREEZEFLAG .EQ. 1 .AND. DAILY_MEAN_TEMP .GT. 0.0) GO TO 1300

IF (FREEZEFLAG .EQ. 1 .AND. DAILY_MEAN_TEMP .GT. 0.0) GO TO 1300

C

49
Supplement 2.--Computer code for subroutine FRZ--Continued

C  ****
   >%%%%%%% BETA %%%%%%%>
   ****
   ********************************************
   IF (DAILY_MEAN_TEMP .GT. -1.0 .AND. PENETRATIONCODE .NE. 1)
      *  GO TO 115
C  ********************************************
C  ****
C  If frost already exists and daily mean air temperature is below freezing, go to # 45.
C  ****
C  ********************************************
C  ****
C  >%%%%%%% GAMMA %%%%%%%>
C  ****
C  ********************************************
C  IF (FREEZEFLAG .EQ. 1) GO TO 45
C  ********************************************
C  If no frost exists and daily mean air temperature is less than or equal to -1.0, continue and set initial values.
C  ********************************************
C  >%%%%%%% DELTA %%%%%%%>
C  ****
C  % DELTA % DELTA % DELTA % DELTA % DELTA % DELTA % DELTA %
C  ****
C  Initialize values for "gamma"
C  ********************************************
DAYS_FREEZE(P_MAX, IRU) = 0
DAYS_THAW_PERIOD = 0
DEPTH2 = 0.0
FREEZESUM = 0.0
FROZEN_SOLID_FLAG = 0
POT_SATURATED_FLAG = 0
THAW_SUM = 0.0
TOTAL_DEPTH = 0.0
YESTYPE_FROST = 0
DO 11 DUMMY2 = 1,50
   DO 10 DUMMY = 1,10
      FREEZESUMARRAY(DUMMY,DUMMY2) = 0.0
10    CONTINUE
11    CONTINUE
C  ******************************************************
C  ****
C  Just came from initializing values (frost does not exist and daily mean air temperature is below
freezing) or came from main branch (frost already exists and daily mean air temperature is below freezing).
Compute the frost penetration parameters.
Check if snow loss is greater than 0.0.

% GAMMA % GAMMA % GAMMA % GAMMA % GAMMA % GAMMA % GAMMA %

45 IF (SNOWDEPTHLOSS .GT. 0.0) THEN
   IF ( (PENETRATION_MAX_SOIL .LT. 0.0) .OR. 
       (TC_SUM .LT. 0.0)) THEN
      FREEZESUMARRAY(P_MAX,IRU) = 0.0
      SNOWDEPTHLOSS = -0.001
   END IF
   SNOWDEPTHLOSS = 0.0
END IF

Remember old thaw depth.

IF (THAWDEPTH .GT. 0.0) THEN
   P_MAX = P_MAX + 1
   DAYS_FREEZE(P_MAX, IRU) = 0
   THAWDEPTH = 0.0
   FREEZESUM = 0.0
END IF

DAYS_FREEZE(P_MAX, IRU) = DAYS_FREEZE(P_MAX, IRU) + 1
FREEZESUM = FREEZESUMARRAY(P_MAX,IRU) - DAILY_MEAN_TEMP 
           MEAN_ANN_TEMP_NUMTR = MEAN_ANN_AIR_TEMP + 
           (FREEZESUM / (2.0 * DAYS_FREEZE(P_MAX, IRU)))

If snow exists, go to # 69.

IF (SNOW .GT. 0.0) GO TO 69
THERMAL_RESIST_SNOW = 0.0
HEAT_CAP_SNOW = 0.0
DO 48 I = 1,P_MAX
   PENDEPTHARRAY(I,IRU) = PENDEPTHARRAY(I,IRU) - SNOWDEPTHLOSS
48 CONTINUE
THERMAL_RESIST_SNOW = 0.0

If litter exists, go to # 120.

51
Supplement 2.--Computer code for subroutine FRZ--Continued

IF (LITTERDEPTH .GT. 0.0) GO TO 120

TOTALDEPTH = 0.0

C ***************************************************************
C **** Compute the frost penetration equation centimeter by
C **** centimeter through the soil profile.
C ***************************************************************

49 LAT_HT_SOIL = 0.0
TC_SUM = 0.0
HEAT_CAP_SOIL_SUM = 0.0
THERMAL_RESIST_SOIL = 0.0

J = 0
51 J = J + 1
PEN_CTR = 0
501 PEN_CTR = PEN_CTR + 1
IF (PEN_CTR * 0.394 .LE. LAYERDEPTH(J,IRU)) GO TO 502
IF (J .LT. NUM_LAYERS) GO TO 51
PENETRATIONCODE = 99999
WRITE(1,887)
887 FORMAT( 'DEPTH OF PENETRATION EXCEEDS PROFILE DEPTH',
* ' -- INSIDE GAMMA LOOP.')
GO TO 115

502 DEPTH2 = TOTALDEPTH
TOTALDEPTH = TOTALDEPTH + 1.0
TC_NUM = MOS(J) * TC_WATER
+ (1. - LAYERPOROSITY(J,IRU)) * TC_DRYSOIL * RATIO_TC_WAT_SOIL
+ (LAYERPOROSITY(J,IRU) - MOS(J)) * TC_AIR * RATIO_TC_AIR2
TC_DENOM = MOS(J)
+ (1. - LAYERPOROSITY(J,IRU)) * RATIO_TC_WAT_SOIL
+ (LAYERPOROSITY(J,IRU) - MOS(J)) * RATIO_TC_AIR2
TC_COMPOSITE = TC_NUM / TC_DENOM
HEAT_CAP_COMPOSITE = (MOS(J) + (1 - LAYERPOROSITY(J,IRU))) * HEAT_CAP_SOIL
LAT_HT_SOIL = LAT_HT_SOIL + MOS(J) * 80.0
HEAT_CAP_SOIL_SUM = HEAT_CAP_SOIL_SUM + HEAT_CAP_COMPOSITE
THERMAL_RESIST_SOIL = THERMAL_RESIST_SOIL + 1.0 / TC_COMPOSITE
TC_SUM = TOTALDEPTH / (THERMAL_RESIST_SNOW + THERMAL_RESIST_LITTER
+ THERMAL_RESIST_SOIL)
LATENTHEAT = (LAT_HT_SOIL + LAT_HT_LITTER) / TOTALDEPTH
HEAT_CAP_PROFILE = (HEAT_CAP_SNOW + HEAT_CAP_LITTER
+ HEAT_CAP_SOIL_SUM) / TOTALDEPTH

52
PENETRATION_NUMTR = TC_SUM * FREEZESUM * 8.64E4  
PENDENOM = LATENTHEAT + HEAT_CAP_PROFILE *  
          * MEAN_ANNTEMP_NUMTR

PENETRATION = 0.394 * ADJUST COEF *  
* SQRT(PENETRATION_NUMTR / PENDENOM)

IF ((P_MAX .GT. 1) .AND. (T_MAX .GT. 0)) THEN  
  IF (PENETRATION .GT. THAWDEPTHARRAY(T_MAX,IRU)) THEN  
    FREEZESUM = FREEZESUMARRAY(P_MAX - 1,IRU)  
    PDEPTHARRAY(P_MAX,IRU) = 0.0  
    FREEZESUMARRAY(P_MAX,IRU) = 0.0  
    P_MAX = P_MAX - 1  
    THAWDEPTHARRAY(T_MAX,IRU) = 0.0  
    THAWSUMARRAY(T_MAX,IRU) = 0.0  
    T_MAX = T_MAX - 1  
  END IF  
END IF  

IF (PENETRATION .GT. TOTALDEPTH * 0.394) .AND.  
  (J .LE. NUM_LAYERS)) GO TO 501  

TOTALDEPTH = DEPTH2 + 0.25  
DIFF_DEPTH = 0.75  
ELSE  
  DIFF_DEPTH = TOTALDEPTH - PENETRATION * 2.54  
  TOTALDEPTH = TOTALDEPTH - DIFF_DEPTH  
END IF  
END IF
Supplement 2.--Computer code for subroutine FRZ--Continued

LAT_HT_SOIL = LAT_HT_SOIL - (MOS(J) * DIFF_DEPTH * 80.0)
HEAT_CAP_SOIL_SUM = HEAT_CAP_SOIL_SUM
* - (HEAT_CAP_COMPOSITE * DIFF_DEPTH)
THERMAL_RESIST_SOIL = THERMAL_RESIST_SOIL - (DIFF_DEPTH /
* TC_COMPOSITE)
TC_SUM = TOTALDEPTH / (THERMAL_RESIST_SNOW + THERMAL_RESIST_LITTER
* + THERMAL_RESIST_SOIL)
LATENTHEAT = (LAT_HT_LITTER + LAT_HT_SOIL) / TOTALDEPTH
HEAT_CAP_PROFILE = (HEAT_CAP_SNOW + HEAT_CAP_LITTER
* + HEAT_CAP_SOIL_SUM) / TOTALDEPTH
PENETRATION_NUMTR = TC_SUM * FREEZESUM * 8.64E4
PENETRATION_DENOM = LATENTHEAT + HEAT_CAP_PROFILE *
* MEAN_ANN_TEMP_NUMTR
PENETRATION = 0.394 * ADJUST_COEF *
* SQRT(PENETRATION_NUMTR / PENETRATION_DENOM)
PENDEPTHARRAY(P_MAX,IRU) = PENETRATION
L_H(P_MAX,IRU) = LATENTHEAT
H'C_SOIL(P_MAX,IRU) = HEAT_CAP_SOIL_SUM
TC(P_MAX,IRU) = TC_SUM
T_R_SOIL(P_MAX,IRU) = THERMAL_RESIST_SOIL
FREEZESUMARRAY(P_MAX,IRU) = FREEZESUM
FRZ_THAW_FLAG = FRZ_THAW_FLAG - 1
PENETRATION_MAX_SOIL = PENDEPTHARRAY(1,IRU)
* - SNOWDEPTH - LITTERDEPTH

C ******************************************************
C ***** Compute small amount of constant heat from layers
C ***** below maximum frost penetration.
C ******************************************************

DEPTH = 0.0
56 DO 58 J = 1,NUM_LAYERS
DEPTH = DEPTH + LAYERDEPTH(J,IRU)
    IF (PENETRATION_MAX_SOIL .LT. DEPTH) GO TO 59
58 CONTINUE
59 MOS_UNDFROZE = 0.0
WEIGHTED_POROS = 0.0
DEPTHLEFT = 0.0
J_LEFT = J + 1

IF (J_LEFT .GT. NUM_LAYERS) THEN
    MOS_UNDFROZE = MOS(NUM_LAYERS)*(DEPTH - PENETRATION_MAX_SOIL)
    WEIGHTED_POROS = LAYER_POROSITY(NUM_LAYER,IRU) * (DEPTH -
* PENETRATION_MAX_SOIL)
    DEPTHLEFT = DEPTH - PENETRATION_MAX_SOIL
ELSE
    DO 62 K = J_LEFT,NUM_LAYERS
Supplement 2.--Computer code for subroutine FRZ--Continued

MOS UNDFROZE = MOS UNDFROZE + MOS(K) * LAYERDEPTH(K,IRU)
WEIGHTED_POROS = WEIGHTED_POROS + LAYERPOROSITY(K,IRU)
* * LAYERDEPTH(K,IRU)
62 DEPTHLEFT = DEPTHLEFT + LAYERDEPTH(K,IRU)

DEPTHLEFT = DEPTHLEFT + (DEPTH - PENETRATION_MAX_SOIL)
MOS UNDFROZE = MOS UNDFROZE + MOS(J) * 
* (DEPTH - PENETRATION_MAX_SOIL)
WEIGHTED_POROS = WEIGHTED_POROS + LAYERPOROSITY(J,IRU)
* * (DEPTH - PENETRATION_MAX_SOIL)
END IF

MOIST = MOS UNDFROZE / DEPTHLEFT
POROSITY_LOWER = WEIGHTED_POROS / DEPTHLEFT
64 ACZONE = (DEPTH_STABLE_TEMPS - PENETRATION_MAX_SOIL) * 2.54
TC_UNDFROZE_NUM = MOIST * TC_WATER
* + (1.0 - POROSITY_LOWER) * TC_DRYSOIL
* RATIO_TC_WAT_SOIL
* + (POROSITY_LOWER - MOIST) * TC_AIR
* RATIO_TC_AIR2
TC_UNDFROZE_DENOM = MOIST
* + (1.0 - POROSITY_LOWER) * RATIO_TC_WAT_SOIL
* + (POROSITY_LOWER - MOIST) * RATIO_TC_AIR2
TC UNDFROZE COMPOSITE = TC UNDFROZE_NUM / TC UNDFROZE_DENOM
LAT HT_UNIT_CHG = MOIST * 80.0
DEPTHREDUC BELOW = (MEAN_ANN_AIR TEMP / ACZONE) *
* TC UNDFROZE COMPOSITE * 8.64E4 * ADJUST_COEF /
* LAT HT UNIT CHG
PENDEPHTARRAY(1,IRU) = PENDEPHTARRAY(1,IRU)
* -(DEPTHREDUC BELOW * 0.394)
PEN_S = (PENDEPHTARRAY(1,IRU) * 2.54) ** 2
HC = (H_C_SOIL(1,IRU) + SNOWDEPTH * SNOW_DENSITY * 0.5 * 2.54
* + HEAT CAP LITTER) / (PENDEPHTARRAY(1,IRU) * 2.54)
FREEZESUMARRAY(1,IRU) = (PEN_S * L_H(1,IRU) + PEN_S * HC
* MEAN ANN AIR TEMP) / (TC(1,IRU)
* 8.64E4 * ADJUST COEF ** 2 - PEN_S * HC
* / (2.0 * DAYS_FREEZE(1,IRU)))

IF (P_MAX .EQ. 1) PENETRATION = PENDEPHTARRAY(1,IRU)

GO TO 80

C ******************************************************************************************************
C **** Snow exists!
C **** Compute frost penetration equation for the snow cover.
C *******************************************************************************************************
Supplement 2.-Computer code for subroutine FRZ--Continued

69 IF (SNOW DENSITY .EQ. 0.0) THEN
   DEN = 'NEW_SNOW_DENSITY'
ELSE
   DEN = SNOW DENSITY
END IF
DO 72 I = 1,P_MAX
   PENDEPTHARRAY(I,IRU) = PENDEPTHARRAY(I,IRU) - SNOWDEPTH LOSS
   + (NEW_SNOW / DEN)
72 IF (PENDEPTHARRAY(I,IRU) .LT. 0.0) PENDEPTHARRAY(I,IRU) = 0.0
C ***********************************************************
C **** Warm conditions.
C **** Frost index is less than 0.0.
C **** Go to # 130.
C ***********************************************************

IF (FREEZESUM .LT. 0.0) GO TO 130
IF (YEST_MEAN_AIR_TEMP .GT. 0.0 .AND. SNOWDEPTH .GT. 4.0 .AND. DAILY_MEAN_TEMP .GT. -5.0) GO TO 75
C ***********************************************************
C **** Compute frost penetration equation.
C **** THERMAL_RESIST_SNOW is computed using Abels' equation,
C ***********************************************************
HEAT_CAP_SNOW = SNOWDEPTH * SNOW_DENSITY * 0.40 * 2.54
THERMAL_RESIST_SNOW = SNOWDEPTH * 2.54 / 
* (0.0068 * SNOW_DENSITY ** 2)
TC_SUM = SNOWDEPTH * 2.54 / THERMAL_RESIST_SNOW
PENETRATION_NUMTR = TC_SUM * FREEZESUM * 8.64E4
PENETRATION_DENOM = HEAT_CAP_SNOW * MEAN_ANN_TEMP_NUMTR
PENETRATION = 0.394 * ADJUST_COEF * 
* SQRT(PENETRATION_NUMTR / PENETRATION_DENOM)
IF (PENETRATION .LT. SNOWDEPTH) THEN
   IF (PENDEPTHARRAY(P_MAX,IRU) .LT. SNOWDEPTH) GO TO 129
   ELSE
      TOTALDEPTH = SNOWDEPTH * 2.54
      IF (LITTERDEPTH .GT. 0.0) THEN
      C ***********************************************************
C **** Compute frost penetration for litter.
C ***********************************************************
      GO TO 120
      ELSE

Supplement 2.--Computer code for subroutine FRZ--Continued

C ********************** Compute frost penetration for soil.**********************

GO TO 49
END IF
END IF

75 IF (FROZENSOLIDFLAG .EQ. 1) GO TO 81

THAWFROSTCODE = 8
FREEZEFLAG = 1
PENETRATION = 0.0

GO TO 115

C Litter exists!
C Compute frost penetration equation for the litter.
C

120 IF (SNOW .LE. 0.0) THEN
    TOTALDEPTH = 0.0
    HEAT_CAP_SUM = 0.0
END IF

125 HEAT_CAP_LITTER = 0.06 * LITTERDEPTH * 2.54 + MOIST_LITTER * 2.54
TOTALDEPTH = TOTALDEPTH + LITTERDEPTH * 2.54
LAT_HT_LITTER = MOIST_LITTER * 80.0 * 2.54

IF (SNOWDEPTH .GE. LITTERDEPTH) THEN
    TC_LITTER = 0.8E-4 / 2.0
ELSE
    TC_LITTER = 0.8E-4 / (1. + (SNOWDEPTH / LITTERDEPTH))
END IF

THERMAL_RESIST_LITTER = LITTERDEPTH * 2.54 / TC_LITTER
TC_SUM = TOTALDEPTH / (THERMAL_RESIST_SNOW + THERMAL_RESIST_LITTER)
LATENTHEAT = LAT_HT_LITTER / TOTALDEPTH
HEAT_CAP_PROFILE = (HEAT_CAP_LITTER + HEAT_CAP_SNOW) / TOTALDEPTH
PENETRATION_NUMTR = TC_SUM * FREEZESUM * 8.64E4
PENETRATION_DENOM = LATENTHEAT + HEAT_CAP_PROFILE * MEAN_ANN_TEMP_NUMTR

PENETRATION = 0.394 * ADJUST_COEF * SQRT(PENETRATION_NUMTR / PENETRATION_DENOM)
Supplement 2.--Computer code for subroutine FRZ--Continued

IF(PENETRATION .GT. TOTALDEPTH * 0.394) GO TO 49

C **********************************************************
C ***** Go back to "gamma" loop.
C **********************************************************

FRZ_THAW_FLAG = FRZ_THAW_FLAG - 1
FROZENSOILFLAG = 0
THAWFROSTCODE = 7
FREEZEFAGL = 1
FREEZESUMARRAY(P_MAX, IRU) = FREEZESUM
PENDEPHTHARRAY(P_MAX, IRU) = PENETRATION

129 IF(PENDEPHTHARRAY(1, IRU) .GT. SNOWDEPTH + LITTERDEPTH) GO TO 56

GO TO 115

C **********************************************************
C ***** Determine the type of frost.
C ***** THAWFROSTCODE code indicates type of frost in the soil:
C ***** (1) Generally a quick freeze -- granular frost expected,
C ***** (2) Very moist soil -- needle ice and possible heaving expected,
C ***** (3) Concrete frost expected,
C ***** (4) Snow is melting and some thawing of soil from below is expected,
C ***** (5) Some thawing has taken place but the soil is still partly frozen,
C ***** (6) Soil is free of frost,
C ***** (7) Soil is freezing but conditions make the type of frost indeterminate,
C ***** (8) Frost did not penetrate the litter.
C **********************************************************

80 IF (FROZENSOILFLAG .EQ. 1) GO TO 81

C **********************************************************
C ***** Soil is supersaturated.
C **********************************************************

IF (YEST_WATER_POT .GT. 0.0 .OR. SUR_STORE_OVER_WILT .GT. SUR_LAYER_MOIST_POT) GO TO 94

86 IF (POTSATURATEDFLAG .GT. 0) GO TO 84
IF (ORGANIC_MATTER .GT. ORGANIC_MATTER1) GO TO 85
IF (PENETRATION / DAYS_FREEZE(P_MAX, IRU) .GT. 1.0) GO TO 105
IF (PENETRATION / DAYS_FREEZE(P_MAX, IRU) .GT. 0.5) GO TO 89
Supplement 2.--Computer code for subroutine FRZ--Continued

84 IF (PENETRATION_MAX_SOIL .LT. 1.0 .AND. THAWFROSTCODE .NE. 3)
* THAWFROSTCODE = 3
FROZENSOLIDFLAG = 1
GO TO 110

81 IF (YEST_TYPE_FROST .EQ. THAWFROSTCODE) THAWFROSTCODE = 3
GO TO 115

85 IF (ORGANIC_MATTER .GT. ORGANIC_MATTER2) GO TO 105

C ******************************************************************************
C **** Freeze less than 1.0 and greater than 0.5 inch per day.
C ******************************************************************************

89 IF (PENETRATION_MAX_SOIL .GT. 3.5) THEN
THAWFROSTCODE = 3
FROZENSOLIDFLAG = 1
ELSE
THAWFROSTCODE = 7
END IF
GO TO 110

94 IF (PENETRATION .LT. SNOWDEPTH + LITTERDEPTH) GO TO 110

PERC_DEPTH = DAILY_MAX_TEMP / (DAILY_MAX_TEMP - DAILY_MIN_TEMP)
* * 12.0 * MIN_INFILTR

IF (2. * DAILY_MEAN_TEMP - MEAN_AIR_TEMP .LT. 0.0) GO TO 96
IF ((YEST_WATER_POT .GT. PERC_DEPTH) .OR. 
(WATER_POT .GT. PERC_DEPTH)) GO TO 84

C ******************************************************************************
C **** If the ground is very moist or has thawed and the
C **** minimum air temperature has dropped to at least
C **** -2.78 degrees Celsius, it is assumed that porous
C **** stalactite frost will form.
C ******************************************************************************

96 IF ((DAILY_MIN_TEMP .GT. -2.78 .AND. DAILY_MEAN_TEMP .LT. 0.0) 
* .OR. (POTSATURATEDFLAG .GT. 0) .OR. 
* (PENETRATION_MAX_SOIL .GT. 3.5)) GO TO 84
THAWFROSTCODE = 2
GO TO 110
Supplement 2.--Computer code for subroutine FRZ--Continued

C ************************************************************
C **** Freeze is greater than 1 inch per day.
C ************************************************************

105 THAWFROSTCODE = 1
    PENETRATION_MAX_SOIL = PENDEPTHARRAY(I,IRU)
        - LITTERDEPTH - SNOWDEPTH

    IF (PENETRATION - LITTERDEPTH - SNOWDEPTH .LT.
        - PENETRATION_MAX_SOIL - 2.0) GO TO 130

    IF (PENETRATION_MAX_SOIL .GT. 3.5 .AND. AVAIL_WATER .GT.
        0.8 * PROFILE_MOIST_POT) THEN
        THAWFROSTCODE = 3
        FROZENSOLIDFLAG = 1
    END IF

C **********************************************************************
C **** Set PENETRATIONCODE, FROZENSOLIDFLAG, and FREEZEFLAG.
C
110 PENETRATIONCODE = 1
    IF (PENETRATION .LE. 0.0) THEN
        PENETRATION = 0.0
        FROZENSOLIDFLAG = 0
        PENETRATIONCODE = 0
    ELSE
        FREEZEFLAG = 1
    END IF

C ************************************************************
C **** Compute PENETRATION_MAX_SOIL and write out results of
C **** todays freezing or thawing.
C ************************************************************

115 YEST_TYPE_FROST = THAWFROSTCODE
    IF (THAWFROSTCODE .EQ. 3) POTSATURATEDFLAG = 1

    DO 103 I = 1,10
        FROST(I,IRU) = PENDEPTHARRAY(I,IRU) - SNOWDEPTH - LITTERDEPTH
    103 IF (FROST(I,IRU) .LT. 0.0) FROST(I,IRU) = 0.0
    PENETRATION_MAX_SOIL = FROST(1,IRU)
Supplement 2.--Computer code for subroutine FRZ--Continued

IF (PENETRATION_MAX_SOIL .LT. 0.0) PENETRATION_MAX_SOIL = 0.0
IF (PENDEPTHARRAY(1,IRU) .LT. 0.0) PENDEPTHARRAY(1,IRU) = 0.0

C ****************************************************************************
C **** Update values and go to next day.
C ****************************************************************************

IF (THAWDEPTH .GT. PENETRATION_MAX_SOIL) GO TO 160

YEST_MEAN_AIR_TEMP = DAILY_MEAN_TEMP
YEST_SNOW_DEPTH = SNOWDEPTH
YEST_WATER_POT = WATER_POT

WRITE(61,104)
104 FORMAT(' -- -- ----- ----- ----- ----- ----- ----- ----- ----- -- --',
     * ' ----- ----- ----- ----- ----- ----- ----- ----- ----- ----- -- --')

WRITE(61,106)
106 FORMAT(' MO DY YEAR IRU T-MAX T-MIN P-T-1 P-T-2 P-T-3 P-T-4',
     * ' P-T-5 P-T-6 P-T-7 P-T-8 P-T-9 P-T-10')

WRITE(61,104)

WRITE(61,107) MO, MDY, MYR, IRU, DAILY_MAX_TEMP, DAILY_MIN_TEMP,
     * PENETRATION_MAX_SOIL, FROST(2,IRU), FROST(3,IRU), FROST(4,IRU),
     * FROST(5,IRU), FROST(6,IRU), FROST(7,IRU), FROST(8,IRU),
     * FROST(9,IRU), FROST(10,IRU)
107 FORMAT(2I3,I5,I4,12F6.1)

WRITE(61,108) THAWDEPTHARRAY(1,IRU), THAWDEPTHARRAY(2,IRU),
     * THAWDEPTHARRAY(3,IRU),THAWDEPTHARRAY(4,IRU),THAWDEPTHARRAY(5,IRU),
     * THAWDEPTHARRAY(6,IRU),THAWDEPTHARRAY(7,IRU),THAWDEPTHARRAY(8,IRU),
     * THAWDEPTHARRAY(9,IRU),THAWDEPTHARRAY(10,IRU)
108 FORMAT(27X,10F6.1)

GO TO 999

C ****************************************************************************
C **** Came from main branch.
C **** Frost already exists and daily mean air temperature
C **** is above freezing.
C ****
C **** % ALPHA % ALPHA % ALPHA % ALPHA % ALPHA % ALPHA % ALPHA %
C ****
C ****************************************************************************

1300 IF (SNOW_DENSITY .EQ. 0.0) THEN
    DEN = NEW_SNOW_DENSITY
ELSE
   DEN = SNOW_DENSITY
END IF
DO 1305 I = 1,P_MAX
1305 PENDEPTHARRAY(I,IRU) = PENDEPTHARRAY(I,IRU) - SNOWDEPTHLOSS
   + (NEW_SNOW / DEN)
C *********************************************************************
C **** Came from # 71.
C **** Snow is greater than 0.0 and frost index is greater
C **** than 0.0 (warm).
C *********************************************************************
130 YESTERDAY = JULIAN_DATE
   IF ((DAYS_THAW_PERIOD .LT. 1) .OR. (THAW_SUM .LT. 0.0)) THEN
      THAW_SUM = 0.0
   END IF
C *********************************************************************
C **** Compute small amount of constant heat from layers
C **** below maximum frost penetration.
C *********************************************************************
DEPTH = 0.0
DO 1320 J = 1,NUM_LAYERS
   DEPTH = DEPTH + LAYERDEPTH(J,IRU)
   IF (PENETRATION_MAX_SOIL .LT. DEPTH) GO TO 1330
1320 CONTINUE
1330 MOS_UNDFROZE = 0.0
WEIGHTED_POROS = 0.0
DEPTHLEFT = 0.0
J_LEFT = J + 1
   IF (J_LEFT .GT. NUM_LAYERS) THEN
      MOS_UNDFROZE = MOS(NUM_LAYERS) * (DEPTH - PENETRATION_MAX_SOIL)
      WEIGHTED_POROS = LAYERPOROSITY(NUM_LAYERS,IRU) *
         (DEPTH - PENETRATION_MAX_SOIL - DEPTHLEFT)
   ELSE
      DO 1334 K = J_LEFT,NUM_LAYERS
         MOS_UNDFROZE = MOS_UNDFROZE + MOS(K) * LAYERDEPTH(K,IRU)
         WEIGHTED_POROS = WEIGHTED_POROS +
            LAYERPOROSITY(K,IRU) * LAYERDEPTH(K,IRU)
   END DO
62
Supplement 2.--Computer code for subroutine FRZ--Continued

1334 DEPTHLEFT = DEPTHLEFT + LAYERDEPTH(K,IRU)
DEPTHLEFT = DEPTHLEFT + (DEPTH - PENETRATION_MAX_SOIL)
MOS_UNDFROZE = MOS_UNDFROZE + MOS(J) *
* (DEPTH - PENETRATION_MAX_SOIL)
WEIGHTED_POROS = WEIGHTED_POROS + LAYERPOROSITY(J,IRU) *
* (DEPTH - PENETRATION_MAX_SOIL)
END IF
MOIST = MOS_UNDFROZE / DEPTHLEFT
POROSITY_LOWER = WEIGHTED_POROS / DEPTHLEFT

1325 ACZONE = (DEPTH_STABLE_TEMPS - PENETRATION_MAX_SOIL) * 2.54
TC_UNDFROZENUM = MOIST * TC_WATER *
+ (1.0 - POROSITY_LOWER) * TC_DRYSOIL *
+ (POROSITY_LOWER - MOIST) * TC_AIR *
TC_UNDFROZDENOM = MOIST *
+ (1.0 - POROSITY_LOWER) * RATIO_TC_WAT_SOIL *
+ (POROSITY_LOWER - MOIST) * RATIO_TC_AIR2
TC_UNDFROZE_COMPOSITE = TC_UNDFROZENUM / TC_UNDFROZE_DENOM
LAT_HT_UNIT_CHG = MOIST * 80.0

DEPTHREDUC BELOW = (MEAN ANN AIR TEMP / ACZONE) *
TC_UNDFROZE_COMPOSITE * 8.64E4 * ADJUST_COEF /
LAT_HT_UNIT_CHG
PENDEXPARRAY(1,IRU) = PENDEXPARRAY(1,IRU) *
- (DEPTHREDUC BELOW * 0.394)
PENDETRATION_MAX_SOIL = (PENDEXPARRAY(1,IRU) - SNOWDEPTH *
- LITTERDEPTH)

IF (SNOW_DEPTH .EQ. 0.0) THEN
TC_SUM = PENDEXPARRAY(1,IRU) * 2.54 /
* (LITTERDEPTH * 2.54 / TC_LITTER + T_R_SOIL(1,IRU))
ELSE
TC_SUM = PENDEXPARRAY(1,IRU) * 2.54 /
* ((SNOWDEPTH * 2.54 / (0.0068 * DEN ** 2))
* + (LITTERDEPTH * 2.54 / TC_LITTER) + T_R_SOIL(1,IRU))
END IF

PEN_S = (PENDEXPARRAY(1,IRU) * 2.54) ** 2
HC = (H_C_SOIL(1,IRU) + SNOWDEPTH * SNOW_DENSITY * 0.4 * 2.54 *
+ HEAT CAP LITTER) /
* (PENDEXPARRAY(1,IRU) * 2.54)
FREEZESUMARRAY(1,IRU) = (PEN_S * L_H(1,IRU) + PEN_S * HC *
* MEAN ANN AIR TEMP) / (TC_SUM *
* 8.64E4 * ADJUST_COEF ** 2 - PEN_S * HC /
/ (2.0 * DAYS_FREEZE(1,IRU))

63
IF (P_MAX .LE. 0) GO TO 160
IF (SNOW .NE. 0.0) THEN
  IF (DAILY_MEAN_TEMP .LT. 1.) THEN
    THAWFROSTCODE = 3
    GO TO 110
  ELSE
    No soil was thawed from above because snow still exists.
  END IF
END IF

THAWFROSTCODE = 4
GO TO 115
END IF

END IF

DAYS_THAW_PERIOD = DAYS_THAW_PERIOD + 1
IF (DAILY_MEAN_TEMP .LE. 0.0) THEN
  THAWFROSTCODE = 9
  GO TO 110
END IF

IF (PENETRATION .GT. 0.0) THEN
  T_MAX = T_MAX + 1
  DAYS_THAW_PERIOD = 0
  THAW_SUM = 0.0
  PENETRATION = 0.0
END IF

IF (THAWDEPTH .LE. 0.0) THAW_SUM = 0.0
THAW_SUM = THAW_SUM + DAILY_MEAN_TEMP

IF (((YEST_MEAN_AIR_TEMP .LT. 0.0) .AND.
  (DAYS_FREEZE(P_MAX, IRU) .NE. DAYS_THAW_PERIOD)) THEN
  THAW_FACTOR = (1.0 * YEST_MEAN_AIR_TEMP) / _
  (6.0 * (DAYS_FREEZE(P_MAX, IRU) - DAYS_THAW_PERIOD))
In the above equation, 1/2 was changed to 1/4 to avoid a negative square root later on. The actual constant should be checked.
Is "THAW_FACTOR" computed right? Should any adjustments be made?

ELSE
  THAW_FACTOR = 0.0
END IF

If litter exists, compute thaw equation for the litter.

IF (LITTERDEPTH .GT. 0.0) THEN
  LAT_HT_LITTER = MOIST_LITTER * 80.0 * 2.54
  HEAT_CAP_LITTER = 0.6 * LITTERDEPTH * 2.54
  TOTALDEPTH = LITTERDEPTH * 2.54
  LATENTHEAT = LAT_HT_LITTER / TOTALDEPTH
  HEAT_CAP_PROFILE = HEAT_CAP_LITTER / TOTALDEPTH
  THERMAL_RESIST_LITTER = LITTERDEPTH * 2.54 / 0.6E-3
  THAW_NUMTR = (TOTALDEPTH / THERMAL_RESIST_LITTER) * 
  THAW SUM * 8.64E4
  THAW DENOM = LATENTHEAT + HEAT_CAP_PROFILE * THAW_FACTOR
  IF (THAW_DENOM .LE. 0.) THAW_DENOM = 0.001
  THAWDEPTH = 0.394 * ADJUST COEF *
  SQRT(THAW_NUMTR / THAW_DENOM)
  IF (THAWDEPTH .LE. LITTERDEPTH) GO TO 158
END IF

Compute the thaw penetration equation centimeter by centimeter through the soil profile.

THERMAL_RESIST_SOIL = 0.0
LAT_HT_SOIL = 0.0
HEAT_CAP_SOIL_SUM = 0.0

J = 0
1362 J = J + 1
PEN_CTR = 0
1365 PEN_CTR = PEN_CTR + 1
IF (PEN_CTR * 0.394 .LE. LAYERDEPTH(J,IRU)) GO TO 1367
Supplement 2.--Computer code for subroutine FRZ--Continued

IF (J .LT. NUM LAYERS) GO TO 1362
PENETRATIONCODE = 99999
WRITE(1,889)
889 FORMAT(' THAW EXCEEDS SOIL PROFILE -- LEAVING ALPHA LOOP.')
GO TO 115

1367 DEPTH2 = TOTALDEPTH
TOTALDEPTH = TOTALDEPTH + 1.0
TC_NUM = MOS(J) * TC ICE * RATIO TC ICE
* + (1.0 - LAYERPOROSITY(J,IRU)) * TC DRYSOIL
* + (LAYERPOROSITY(J,IRU) - MOS(J)) * TC_AIR * RATIO_TC_AIR1
TC_DENOM = MOS(J) * RATIO TC ICE
* + (1.0 - LAYERPOROSITY(J,IRU))
* + (LAYERPOROSITY(J,IRU) - MOS(J)) * RATIO__TC_AIR1
TC_COMPOSITE = TC_NUM / TC_DENOM
HEAT_CAP_COMPOSITE = (MOS(J) * HEAT CAP ICE
* + (1.0 - LAYERPOROSITY(J,IRU))) * HEAT CAP SOIL
LAT HT SOIL = LAT HT SOIL + MOS(J) * 80.0
HEAT CAP SOIL SUM = HEAT CAP SOIL SUM + HEAT CAP COMPOSITE
LATENTHEAT = (LAT HT SOIL + LAT HT LITTER) / TOTALDEPTH
HEAT CAP PROFILE = (HEAT CAP LITTER + HEAT CAP SOIL SUM)
* / TOTALDEPTH
THERMAL RESIST SOIL = THERMAL RESIST SOIL + 1.0 / TC_COMPOSITE
TC_SUM = TOTALDEPTH / (THERMAL RESIST LITTER
* + THERMAL RESIST SOIL)

THAWNUMTR = 8.64E4 * TC_SUM * THAW_SUM

IF (THAWNUMTR .LE. 0.0) GO TO 158

THAW_DENOM = LATENTHEAT + HEAT CAP PROFILE * THAW_FACTOR
THAWDEPTH = 0.394 * ADJUST_COEF * SQRT(THAWNUMTR / THAW_DENOM)

C *****************************************
C **** Since a thaw has overtaken the top penetration layer,
C **** retract one penetration depth and one thaw depth.
C *****************************************

C IF ((P_MAX .GT. 1) .AND. (T_MAX .GT. 1) .AND.
* (THAWDEPTH .GT. PENDEPTHARRAY(P_MAX,IRU))) THEN
THAW SUM = THAWSUMARRAY(T_MAX - 1,IRU)
PENDEPTHARRAY(P_MAX,IRU) = 0.0
FREEZESUMARRAY(P_MAX,IRU) = 0.0
P_MAX = P_MAX - 1
THAWDEPTHARRAY(T_MAX,IRU) = 0.0
THAWSUMARRAY(T_MAX,IRU) = 0.0
T_MAX = T_MAX - 1
END IF

66
Supplement 2.--Computer code for subroutine FRZ--Continued

C *****************************************
C **** If profile has no frost, go to # 160.
C *****************************************

    IF ((P_MAX .EQ. 1) .AND. (THAWDEPTH .GT. PENDEPTHARRAY(1,IRU)))
      *    GO TO 160

    IF (THAWDEPTH .GT. TOTALDEPTH * 0.394, J .LE. NUM_LAYERS)
      *    GO TO 1365

C *****************************************
C **** Go back to main "alpha" loop.
C *****************************************

C **** Recompute TOTALDEPTH to compensate for the fraction
C **** of a centimeter and recompute the thaw penetration
C **** equation.
C *****************************************

    IF (THAWDEPTH .LE. TOTALDEPTH) THEN
      IF (THAWDEPTH .LT. DEPTH2) THEN
        TOTALDEPTH = DEPTH2 + 0.25
        DIFF_DEPTH = 0.75
      ELSE
        DIFF_DEPTH = TOTALDEPTH - THAWDEPTH
        TOTALDEPTH = TOTALDEPTH - DIFF_DEPTH
      END IF
    ELSE
      WRITE(1,7050)
      7050   FORMAT(1,7050) 7050 FORMAT(1,7050)
      ERROR! <------- ERROR! <-------
      SOIL PROFILE NOT DEEP ENOUGH!
    END IF

    LAT_HT_SOIL = LAT_HT_SOIL - (MOS(J) * DIFF_DEPTH * 80.0)
    HEAT_CAP_SOIL_SUM = HEAT_CAP_SOIL_SUM
      *       (HEAT_CAP_COMPOSITE * DIFF_DEPTH)
    THERMAL_RESIST_SOIL = THERMAL_RESIST_SOIL - (DIFF_DEPTH /
      *       TC_COMPOSITE)
    TC_SUM = TOTALDEPTH / (THERMAL_RESIST_LITTER
      *       + THERMAL_RESIST_SOIL)
    LATENTHEAT = (LAT_HT_LITTER + LAT_HT_SOIL) / TOTALDEPTH
    HEAT_CAP_PROFILE = (HEAT_CAP_LITTER + HEAT_CAP_SOIL_SUM)
      *       TOTALDEPTH

    THAW_NUMTR = TC_SUM * THAW SUM * 8.64E4
    THAW_DENOM = LATENTHEAT + HEAT_CAP_PROFILE * THAW_FACTOR
    THAWDEPTH = 0.394 * ADJUST COEF * SQRT(THAW_NUMTR / THAW_DENOM)
    THAWDEPTHARRAY(T_MAX,IRU) = THAWDEPTH
    THAWSUMARRAY(T_MAX,IRU) = THAW_SUM

67
Supplement 2.--Computer code for subroutine FRZ--Continued

IF (THAWDEPTH .GT. 0.0) THEN
    PENETRATIONCODE = 0
    PENETRATION = 0.0
END IF

158 FRZ_THAW_FLAG = 2

IF (P_MAX .LE. 0) GO TO 160

THAWFROSTCODE = 5

IF (THAWDEPTH .LT. 0.0) THEN
    THAWFROSTCODE = 9
    GO TO 110
END IF

C ****************************************************
C **** If daily mean air temperature is greater than 0.0 and
C **** minimum air temperature is less than 0.0,
C **** compute PERC_DEPTH.
C
C ****************************************************

IF (DAILY_MIN_TEMP .GT. 0.0) GO TO 110

PERC_DEPTH = DAILY_MAX_TEMP / (DAILY_MAX_TEMP - DAILY_MIN_TEMP) * 12.0 * MIN_INFILTR

IF (WATER_POT .GT. PERC_DEPTH) GO TO 84

IF (THAWDEPTH * (LAYERPOROSITY(1,IRU) - (LAYER_MOIST(1,IRU)/LAYERDEPTH(1,IRU))) .LT. PERC_DEPTH) GO TO 110

POT_SATURATEDFLAG = 1

GO TO 84

C ******************************************************************************
C **** Complete thaw of the soil profile has occurred or
C **** frost does not exist yet.
C **** Came from below #115, above #134, or below #158.
C **** No frost exists!
C **** Reset values!
C
C ******************************************************************************
Supplement 2.--Computer code for subroutine FRZ--Continued

160 DAYS FREEZE(P_MAX, IRU) = 0
PENETRATIONCODE = 0
HEAT CAP SNOW = 0.0
THERMAL RESIST SNOW = 0.0
THAWFROSTCODE = 6
POTSATURATEDFLAG = 0
PENDEPTARRAY(1,IRU) = 0.0
THAWDEPTHARRAY(1,IRU) = 0.0
MOIST LITTER = 0.0
THAWDEPH = 0.0
FREEZEEFLAG = 0
FROZENSOLIDFLAG = 0
P_MAX = 1
T_MAX = 0

GO TO 115

999 RETURN
END
Supplement 3.--Computer code for subroutine SMP

C Definitions of the variables that are used in SMP are listed below.
C
C -------------------------
C ACTUAL_ET Actual evapotranspiration (inches).
C AVAIL_WATER Daily available water in the soil profile (inches).
C DAILY_MAX_TEMP Daily maximum air temperature (degrees Celsius).
C ET_LOSS Computational term used in computing soil water losses due to evapotranspiration.
C EVAP_LAYERS Number of soil layers subject to direct evaporation.
C EVAPORATION Effective evaporation (inches).
C EXCS_SOIL_MOIST Water available for ground-water recharge (inches).
C FIRSTDAYFLAG Flag that is 0 if only the total soil water content for the profile on the first day is inputed.
C FLAG1 Flag that is 1 if soil water content for each soil layer for the first day is inputed.
C FLAG2 Flag that stops execution of a certain segment after the first time through.
C FRACTION_ET_LOSS Fraction of the evaporation loss that would come from a given soil layer.
C FRZ_FIELD_CAP_INCREMENT Change in field capacity due to various conditions (inches).
C IRU Hydrologic response unit.
C JLOOP Counter to count number of passes through soil water adjustment procedure. Used to prevent infinite looping.
C JULIAN_DATE Julian date.
C LAYER_DIFF Difference between the soil water in a layer and currently available "LAYER_MOIST_POT" (inches).
C LAYER_MOIST Daily soil water content of each layer (inches).
C LAYER_MOIST_POT Soil water between field capacity and wilting point for each layer (inches).
C MAX_INFEITRATON Maximum daily snowmelt infiltration capacity of soil profile (inches).
C NET_PRECIP Daily precipitation (inches).
C NEW_SNOW Daily precipitation in the form of snow (inches).
C NUM_LAYERS Number of soil layers.
C POT_SATURATEDFLAG Flag which, when set to 1, allows the surface soil layer to collect more water than the normal field capacity and increases the likelihood that concrete frost will form if it has not already.
C PROFILE_MOIST_POT Maximum available water-holding capacity of a soil profile: Sum of the variables "LAYER_MOIST_POT" (inches).
C RATIO_LAYER_DIFF Difference between ratios of soil water for adjacent soil layers.
Supplement 3.--Computer code for subroutine SMP--Continued

C **** RATIO_MOIST_N Ratio of soil water to the potential maximum soil
C **** water in layer N.
C **** RATIO_MOIST_NPLUS1 Ratio of soil water to the potential maximum soil
C **** water in layer N+1.
C **** RATIO_MOIST_NPLUS2 Ratio of soil water to the potential maximum soil
C **** water in layer N+2.
C **** RUNOFF Amount of water that runs off the profile (inches).
C **** SNOW Water equivalent of snowpack (inches).
C **** SNOWMELT Daily snowmelt (inches).
C **** SOIL_MOIST_COND Computational term used in determining
C **** "AVAIL_WATER" (inches).
C **** SURLAYER_MOIST_POT Soil water between field capacity and wilting point
C **** for the surface layer that is subject to direct
C **** evaporation (inches).
C **** SUR_STORE_OVER_WILT Soil water in the surface layers subject to direct
C **** evaporation (inches).
C **** WATER Water available for infiltration (inches).
C **** WATER_ADDED Water that is added to a soil layer (inches).
C **** WATERLOSS Water that is lost from a soil layer to evaporation
C **** (inches).
C **** YEST_MEAN_AIR_TEMP Yesterday's mean air temperature (degrees Celsius).
C ***********************************************

SUBROUTINE SMP(IRU, AVAIL_WATER, DAILY_MAX_TEMP, LAYER_MOIST,
* PROFILE_MOIST_POT, SUR_STORE_OVER_WILT,
* SURLAYER_MOIST_POT, JULIAN_DATE, NUM_LAYERS,
* POTSATURATEDFLAG, EVAPORATION, FRACTION_ET_LOSS,
* LAYER_MOIST_POT, RUNOFF, SNOWMELT, EVAP_LAYERS,
* FIRSTDAYFLAG, FLAG1, FLAG2, FRZ_FIELD_CAP_INCR,
* TRANSPIRFLAG, EXCS_SOIL_MOIST, ACTUAL_ET,
* NET_PRECIP, NEW_SNOW, SNOW, YEST_MEAN_AIR_TEMP,
* MAX_INFILTRATION)

REAL
* ACTUAL_ET,
* AVAIL_WATER,
* DAILY_MAX_TEMP,
* ET_LOSS(10),
* EVAPORATION,
* EXCS_SOIL_MOIST,
* FRACTION_ET_LOSS(10,50),
* LAYER_DIFF,
* LAYER_MOIST(10,50),
* LAYER_MOIST_POT(10,50),
* MAX_INFILTRATION,
* NET_PRECIP,
* NEW_SNOW,
* PROFILE_MOIST_POT,
* RATIO_LAYER_DIFF,
Supplement 3.--Computer code for subroutine SMP--Continued

* RATIO_MOIST_NPLUS1,
* RATIO_MOIST_NPLUS2,
* RUNOFF,
* SNOW,
* SNOWMELT,
* SOIL_MOIST_COND,
* SURFACE_MOIST_POT,
* SUR_STORE_OVER_WILT,
* WATER,
* WATER_ADDED,
* WATERLOSS,
* YEST_MEAN_AIR_TEMP

INTEGER
* DUMMY,
* EVAP_LAYERS,
* FIRSTDAYFLAG,
* FLAG1,
* FLAG2,
* IRU,
* J,
* JLOOP,
* JULIAN_DATE,
* N,
* NUM_LAYERS,
* POTSATURATEDFLAG

DUMMY = 0

DO 101 DUMMY = 1,10
101 ET LOSS(DUMMY) = 0.0

J = 0
JLOOP = 0
LAYER_DIFF = 0.0
N = 0
RATIO_LAYER_DIFF = 0.0
RATIO_MOIST_N = 0.0
RATIO_MOIST_NPLUS1 = 0.0
RATIO_MOIST_NPLUS2 = 0.0
RUNOFF = 0.0
SOIL_MOIST_COND = 0.0
WATER = 0.0
WATER_ADDED = 0.0
WATERLOSS = 0.0

IF (FIRSTDAYFLAG .EQ. 0) THEN
  FLAG1 = 0
  FLAG2 = 0
  DO 2 DUMMY = 1,NUM_LAYERS
Supplement 3.---Computer code for subroutine SMP--Continued

\begin{verbatim}
2   LAYER_MOIST(DUMMY,IRU) = AVAIL_WATER / NUM_LAYERS
   FIRSTDAYFLAG = 1
   END IF

C *****************************************************************************
C **** Increase the field capacity of the first soil layer
C **** or change the field capacity back to the original
C **** value.
C *****************************************************************************

   IF ((DAILY_MAX_TEMP .LT. 5.0) .AND. (FLAG1 .LE. 0)) THEN
     IF (FLAG2 .GT. 0) THEN
       PROFILE_MOIST_POT = PROFILE_MOIST_POT - LAYER_MOIST_POT(1,IRU)
       SURLAYER_MOIST_POT = SURLAYER_MOIST_POT
                      - LAYER_MOIST_POT(1,IRU)
       LAYER_MOIST_POT(1,IRU) = LAYER_MOIST_POT(1,IRU) / 3.0
       PROFILE_MOIST_POT = PROFILE_MOIST_POT
                      + LAYER_MOIST_POT(1,IRU)
       SURLAYER_MOIST_POT = SURLAYER_MOIST_POT
                      + LAYER_MOIST_POT(1,IRU)
       FLAG2 = 0
     ELSE
       FRZ_FIELD_CAP_INCR = 0.12 * LAYER_MOIST_POT(1,IRU)
       FLAG1 = 1
       LAYER_MOIST_POT(1,IRU) = LAYER_MOIST_POT(1,IRU)
                      - FRZ_FIELD_CAP_INCR
       PROFILE_MOIST_POT = PROFILE_MOIST_POT
                       + FRZ_FIELD_CAP_INCR
       SURLAYER_MOIST_POT = SURLAYER_MOIST_POT + FRZ_FIELD_CAP_INCR
     END IF
   ELSE IF ((DAILY_MAX_TEMP .GE. 5.0) .AND. (FLAG1 .GT. 0) .AND.
                (YEST_MEAN_AIR_TEMP .GE. 0.0)) THEN
     LAYER_MOIST_POT(1,IRU) = LAYER_MOIST_POT(1,IRU)
                      - FRZ_FIELD_CAP_INCR
     PROFILE_MOIST_POT = PROFILE_MOIST_POT - FRZ_FIELD_CAP_INCR
     FLAG1 = 0
   GO TO 5
   END IF

   IF ((POTSATURATEDFLAG .GT. 0) .AND. (FLAG2 .LE. 0)) THEN
     IF (FLAG1 .GT. 0) THEN
       LAYER_MOIST_POT(1,IRU) = LAYER_MOIST_POT(1,IRU)
                      - FRZ_FIELD_CAP_INCR
       PROFILE_MOIST_POT = PROFILE_MOIST_POT
                       - FRZ_FIELD_CAP_INCR
       FLAG1 = 0
     ELSE
       FLAG2 = 1
       PROFILE_MOIST_POT = PROFILE_MOIST_POT - LAYER_MOIST_POT(1,IRU)
   END IF
\end{verbatim}

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Supplement 3.--Computer code for subroutine SMP--Continued

\[
\text{SURLAYER MOIST POT} = \text{SURLAYER MOIST POT} \text{ - LAYER MOIST POT}(1,IRU) \\
\text{LAYER MOIST POT}(1,IRU) = \text{LAYER MOIST POT}(1,IRU) \times 3.0 \\
\text{PROFILE MOIST POT} = \text{PROFILE MOIST POT} + \text{LAYER MOIST POT}(1,IRU) \\
\text{SURLAYER MOIST POT} = \text{SURLAYER MOIST POT} + \text{LAYER MOIST POT}(1,IRU)
\]

END IF

ELSE IF (POTSATURATEDFLAG .EQ. 0 .AND. FLAG2 .GT. 0) THEN
\[
\text{PROFILE MOIST POT} = \text{PROFILE MOIST POT} - \text{LAYER MOIST POT}(1,IRU) \\
\text{SURLAYER MOIST POT} = \text{SURLAYER MOIST POT} - \text{LAYER MOIST POT}(1,IRU) \\
\text{LAYER MOIST POT}(1,IRU) = \text{LAYER MOIST POT}(1,IRU) / 3.0 \\
\text{PROFILE MOIST POT} = \text{PROFILE MOIST POT} + \text{LAYER MOIST POT}(1,IRU) \\
\text{SURLAYER MOIST POT} = \text{SURLAYER MOIST POT} + \text{LAYER MOIST POT}(1,IRU) \\
\text{FLAG2} = 0
\]
END IF

5 IF (DAILY_MAX_TEMP .LT. 0.0 .AND. SNOWMELT .LT. 0.001) RETURN

C *******************************************************
C **** If true, then return.
C ******************************************************

IF (SNOWMELT .GT. 0.0 ) THEN
\[\text{WATER} = \text{SNOWMELT}\]
ELSE
\[\text{WATER} = \text{NET_PRECIP} - \text{NEW_SNOW} + \text{SNOWMELT}\]
END IF

IF (WATER .LT. EVAPORATION) THEN
IF (SNOW .GT. 0.0) THEN
\[\text{ACTUAL ET} = \text{WATER}\]
GO TO 90
ELSE
GO TO 60
END IF
END IF

IF ((WATER .EQ. 0.0) .OR. (WATER .EQ. EVAPORATION)) THEN
\[\text{ACTUAL ET} = \text{WATER}\]
GO TO 90
END IF

ACTUAL_ET = EVAPORATION

C *******************************************************
C **** Depending on the amount of soil water in the first
C **** and second soil layers, compute the amount of
C **** water to runoff and the amount of water available
C **** for infiltration.
C
IF(WATER - EVAPORATION .GT. MAX_INFILTRATION) THEN
  RUNOFF = WATER - EVAPORATION - MAX_INFILTRATION
  WATER = WATER - RUNOFF
END IF
IF (LAYER_MOIST(1,IRU) .EQ. LAYER_MOIST_POT(1,IRU) .AND. WATER .GT. 0.0) THEN
  IF (LAYER_MOIST(2,IRU) .EQ. LAYER_MOIST_POT(2,IRU)) THEN
    WATER = WATER - EVAPORATION
    RUNOFF = 0.2 * WATER + RUNOFF
    WATER = 0.8 * WATER
  ELSE
    WATER = WATER - EVAPORATION
    RUNOFF = 0.1 * WATER + RUNOFF
    WATER = 0.9 * WATER
  END IF
END IF
WATER = WATER - EVAPORATION
AVAIL_WATER = AVAIL_WATER + WATER
IF (RUNOFF .LE. 0.0) GO TO 10
WRITE(61,600) RUNOFF
600 FORMAT(' IT IS LIKELY THAT ',F6.3,' INCHES HAVE RUN OFF. ')
10 IF (AVAIL_WATER .GE. PROFILE_MOIST_POT) GO TO 40
   JLOOP = 0
   WATER_ADDED = WATER
   N = 1
15 IF (LAYER_MOIST(N,IRU) .GE. LAYER_MOIST_POT(N,IRU)) THEN
   WATER_ADDED = WATER_ADDED + LAYER_MOIST(N,IRU)
   LAYER_MOIST(N,IRU) = LAYER_MOIST_POT(N,IRU)
   N = N + 1
   IF (N .EQ. NUM_LAYERS) THEN
     LAYER_MOIST(NUM_LAYERS,IRU) = LAYER_MOIST(NUM_LAYERS,IRU)
     N = N + 1
     IF (LAYER_DIFF .LT. WATER_ADDED) GO TO 25
     LAYER_MOIST(NUM_LAYERS,IRU) = LAYER_MOIST(NUM_LAYERS,IRU) + WATER_ADDED
    ELSE
      GO TO 15
    END IF
END IF
LAYER_DIFF = LAYER_MOIST_POT(N,IRU) - LAYER_MOIST(N,IRU)
IF (LAYER_DIFF .LT. WATER_ADDED) GO TO 25
LAYER_MOIST(N,IRU) = LAYER_MOIST(N,IRU) + WATER_ADDED
C ************************************************************
C **** Distribute (smooth) the soil water in the n, n + 1,
C **** and n + 2 layers.
C ************************************************************

20 IF (N .GE. NUM LAYERS) GO TO 90
   JLOOP = JLOOP + 1
   IF (JLOOP .GT. 10) STOP
   RATIO_MOIST_N = LAYER_MOIST(N,IRU) / LAYER_MOIST_POT(N,IRU)
   RATIO_MOIST_NPLUS1 = LAYER_MOIST(N+1,IRU)
   RATIO_LAYER_DIFF = RATIO_MOIST_N - RATIO_MOIST_NPLUS1
   IF (RATIO_LAYER_DIFF .GT. 0.2) THEN
      IF(N .EQ. 1 .AND. JLOOP .EQ. 1) *
        RATIO_LAYER_DIFF = RATIO_LAYER_DIFF * WATER_ADDED
      LAYER_MOIST(N,IRU) = LAYER_MOIST(N,IRU) + RATIO_LAYER_DIFF / 2.0
      LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) + RATIO_LAYER_DIFF / 2.0
      GO TO 20
   END IF
   IF (N .GT. NUM LAYERS - 2) GO TO 90
   RATIO_MOIST_NPLUS2 = LAYER_MOIST(N+2,IRU)
   RATIO_LAYER_DIFF = RATIO_MOIST_NPLUS1 - RATIO_MOIST_NPLUS2
   IF (RATIO_LAYER_DIFF .GT. 0.2) THEN
      LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) - RATIO_LAYER_DIFF / 2.0
      LAYER_MOIST(N+2,IRU) = LAYER_MOIST(N+2,IRU) + RATIO_LAYER_DIFF / 2.0
   ELSE
      GO TO 20
   END IF

C *************************************************************
C **** The nth layer has excess water.
C *************************************************************

25 WATER_ADDED = WATER_ADDED - LAYER_DIFF
   LAYER_MOIST(N,IRU) = LAYER_MOIST(N,IRU) + LAYER_DIFF
   LAYER_DIFF = LAYER_MOIST_POT(N+1,IRU) - LAYER_MOIST(N+1,IRU)
   IF (NUM LAYERS - N .LT. 2) THEN
      LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) + WATER_ADDED
      GO TO 90
   ELSE IF (LAYER_DIFF .LT. WATER_ADDED) THEN
      WATER_ADDED = WATER_ADDED - LAYER_DIFF

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Supplement 3.--Computer code for subroutine SMP--Continued

```
LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) + LAYER_DIFF
N = N + 2
GO TO 15
ELSE IF (NUM_LAYERS - N .LT. 3) THEN
    LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) + WATER_ADDED
    GO TO 90
END IF

LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) + WATER_ADDED
30 RATIO_MOIST_NPLUS1 = LAYER_MOIST(N+1,IRU) / LAYER_MOIST_POT(N+1,IRU)
   JLOOP = JLOOP + 1
IF (JLOOP .GT. 10) STOP

RATIO_MOIST_NPLUS2 = LAYER_MOIST(N+2,IRU) / LAYER_MOIST_POT(N+2,IRU)
RATIO_LAYER_DIFF = RATIO_MOIST_NPLUS1 - RATIO_MOIST_NPLUS2
IF (RATIO_LAYER_DIFF .GT. 0.3) THEN
    LAYER_MOIST(N+1,IRU) = LAYER_MOIST(N+1,IRU) - RATIO_LAYER_DIFF / 2.0
    LAYER_MOIST(N+2,IRU) = LAYER_MOIST(N+2,IRU) + RATIO_LAYER_DIFF / 2.0
    GO TO 30
END IF

IF (NUM_LAYERS - N .GE. 3) THEN
    N = N + 1
    GO TO 30
ELSE
    GO TO 90
END IF

C **************************************************************
C **** The amount of water available in the total soil
C **** profile is greater than the potential storage
C **** available.
C **** Excess water is available for recharge.
C **************************************************************

40 EXCS_SOIL_MOIST = AVAIL_WATER - PROFILE_MOIST_POT
AVAIL_WATER = PROFILE_MOIST_POT
SUR_STORE_OVER_WILT = SUR_LAYER_MOIST_POT
DO 50 J = 1,NUM_LAYERS
50   LAYER_MOIST(J,IRU) = LAYER_MOIST_POT(J,IRU)
IF (EXCS_SOIL_MOIST .LE. 0.0) GO TO 90
```

77
WRITE(61,610) JULIAN_DATE, EXCS_SOIL_MOIST
610 FORMAT(' ON DAY ',I3,' OF THIS MONTH THERE WAS ',F7.2,
     * ' RECHARGE. ')
GO TO 90
C **************************************************
C **** Evaporation is greater than water available for 
C **** infiltration or runoff.
C **************************************************
60 WATER_LOSS = EVAPORATION - WATER
   IF (NUM_LAYERS .EQ. 1) THEN
     LAYER_MOIST(1,IRU) = LAYER_MOIST(1,IRU) - WATER_LOSS
   IF (LAYER_MOIST(1,IRU) .LT. 0.0) THEN
     ACTUAL_ET = LAYER_MOIST(1,IRU) + WATER_LOSS + WATER
     LAYER_MOIST(1,IRU) = 0.00
   GO TO 90
   END IF
   END IF
   DO 70 J = 1,EVAP_LAYERS
     ET_LOSS(J) = FRACTION_ETLOSS(J,IRU) * WATER_LOSS
     IF (ET_LOSS(J) .GT. LAYER_MOIST(J,IRU)) THEN
       ET_LOSS(J) = LAYER_MOIST(J,IRU)
     END IF
     LAYER_MOIST(J,IRU) = LAYER_MOIST(J,IRU) - ET_LOSS(J)
   70 ACTUAL_ET = ACTUAL_ET + ET_LOSS(J)
   ACTUAL_ET = ACTUAL_ET + WATER
C **************************************************
C **** Compute the soil water in the surface layers 
C **** and the total soil water for the soil profile.
C **************************************************
90 SOIL_MOIST_COND = 0.0
   DO 92 J = 1,NUM_LAYERS
     SOIL_MOIST_COND = SOIL_MOIST_COND + LAYER_MOIST(J,IRU)
     IF (J .LE. EVAP_LAYERS) SUR_STORE_OVER_WILT = SOIL_MOIST_COND
   92 CONTINUE
   AVAIL_WATER = SOIL_MOIST_COND
95 RETURN
END
### Supplement 4.—Definition of subroutine variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTUAL_ET</td>
<td>Internal</td>
<td>Actual evapotranspiration (inches).</td>
</tr>
<tr>
<td>ACZONE</td>
<td>Internal</td>
<td>Distance between the depth of 0 degree Celsius isotherm of the soil and the depth of stable soil temperature (centimeters).</td>
</tr>
<tr>
<td>ADJUST_COEF</td>
<td>Input</td>
<td>Freeze and thaw adjustment coefficient.</td>
</tr>
<tr>
<td>AVAIL_WATER</td>
<td>Output</td>
<td>Daily available water in the soil profile (inches).</td>
</tr>
<tr>
<td>DAILY_MAX_TEMP</td>
<td>Input/output</td>
<td>Daily maximum air temperature (degrees Celsius).</td>
</tr>
<tr>
<td>DAILY_MEAN_TEMP</td>
<td>Internal</td>
<td>Daily mean air temperature (degrees Celsius).</td>
</tr>
<tr>
<td>DAILY_MIN_TEMP</td>
<td>Input/output</td>
<td>Daily minimum air temperature (degrees Celsius).</td>
</tr>
<tr>
<td>DAYS_FREEZE</td>
<td>Internal</td>
<td>Number of days in the current freeze period.</td>
</tr>
<tr>
<td>DAYS_THAW_PERIOD</td>
<td>Internal</td>
<td>Number of days in the current thaw period.</td>
</tr>
<tr>
<td>DEN</td>
<td>Internal</td>
<td>Computational term used for density of the snowpack (grams per cubic centimeter).</td>
</tr>
<tr>
<td>DEPTHLEFT</td>
<td>Internal</td>
<td>Depth of soil profile that is not frozen. Used in computing thawing from below (inches).</td>
</tr>
<tr>
<td>DEPTHREDC_BELOW</td>
<td>Internal</td>
<td>Reduction in frost depth due to heating from below (centimeters).</td>
</tr>
<tr>
<td>DEPTH_STABLE_TEMPS</td>
<td>Input</td>
<td>Depth of stable soil temperatures. The point in the ground at which daily and seasonal temperatures cease to cause measurable change (inches).</td>
</tr>
<tr>
<td>DEPTH2</td>
<td>Internal</td>
<td>Temporary value of depth of frost or thaw (centimeters).</td>
</tr>
<tr>
<td>DIFF_DEPTH</td>
<td>Internal</td>
<td>Fractional part of an interval to be frozen or thawed (centimeters).</td>
</tr>
<tr>
<td>ET_LOSS</td>
<td>Internal</td>
<td>Computational term used in computing soil water losses due to evapotranspiration.</td>
</tr>
<tr>
<td>EVAP_LAYERS</td>
<td>Input</td>
<td>Number of soil layers subject to direct evaporation.</td>
</tr>
<tr>
<td>EVAPORATION</td>
<td>Internal</td>
<td>Effective evaporation (inches).</td>
</tr>
<tr>
<td>EXCS_SOIL_MOIST</td>
<td>Output</td>
<td>Water available for ground-water recharge (inches).</td>
</tr>
<tr>
<td>Variable</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>FIRSTDAYFLAG</td>
<td>Input</td>
<td>Flag that is 0 if only the total soil water content for the profile on the first day is inputed. Flag that is 1 if soil water content for each soil layer for the first day is inputed.</td>
</tr>
<tr>
<td>FLAG1</td>
<td>Internal</td>
<td>Flag that stops execution of a certain segment after the first time through.</td>
</tr>
<tr>
<td>FLAG2</td>
<td>Internal</td>
<td>Flag that stops execution of a certain segment after the first time through.</td>
</tr>
<tr>
<td>FRACTION_ET_LOSS</td>
<td>Input</td>
<td>Fraction of the evaporation loss that would come from a given soil layer.</td>
</tr>
<tr>
<td>FREEZEFLAG</td>
<td>Input</td>
<td>Flag which indicates that some frost has occurred: 0: Off—no frost exists in soil profile, 1: On—frost exists in soil profile.</td>
</tr>
<tr>
<td>FREEZESUM</td>
<td>Internal</td>
<td>Current freezing index—cumulative degree days for mean air temperatures below 0 degree Celsius.</td>
</tr>
<tr>
<td>FREEZESUMARRAY</td>
<td>Internal</td>
<td>Array of freezing index for successive freezing cycles.</td>
</tr>
<tr>
<td>FROST</td>
<td>Output</td>
<td>Array of frost penetration depths for successive freezing cycles—soil only (inches).</td>
</tr>
<tr>
<td>FROZENSOLIDFLAG</td>
<td>Internal</td>
<td>Flag which indicates that the watershed has been frozen imperviously: 0: Not frozen imperviously, 1: Frozen imperviously.</td>
</tr>
<tr>
<td>FRZ_FIELD_CAP_INCR</td>
<td>Internal</td>
<td>Change in field capacity due to various conditions (inches).</td>
</tr>
<tr>
<td>FRZ_THAW_FLAG</td>
<td>Internal</td>
<td>Counter used to check on freezing following a day of thawing.</td>
</tr>
<tr>
<td>HC</td>
<td>Internal</td>
<td>Computational term used in computing heat capacity of the profile.</td>
</tr>
<tr>
<td>H_C_SOIL</td>
<td>Internal</td>
<td>Array of volumetric heat capacity of soil profile for successive freezing cycles (calories per cubic centimeter per degree Celsius).</td>
</tr>
</tbody>
</table>
### Supplement 4.—Definition of subroutine variables—Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAT_CAP_COMPOSITE</td>
<td>Internal</td>
<td>Volumetric heat capacity of partial soil profile (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>HEAT_CAP_ICE</td>
<td>Internal</td>
<td>Heat capacity of ice (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>HEAT_CAP_LITTER</td>
<td>Internal</td>
<td>Heat capacity of litter (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>HEAT_CAP_PROFILE</td>
<td>Internal</td>
<td>Volumetric heat capacity of the profile—snow, litter, and soil—undergoing freezing or thawing (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>HEAT_CAP_SNOW</td>
<td>Internal</td>
<td>Heat capacity of snow (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>HEAT_CAP_SOIL</td>
<td>Internal</td>
<td>Heat capacity of dry soil (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>HEAT_CAP_SOIL_SUM</td>
<td>Internal</td>
<td>Volumetric heat capacity of soil and water in the profile (calories per cubic centimeter per degree Celsius).</td>
</tr>
<tr>
<td>INCR_SNOW_DEPTH</td>
<td>Internal</td>
<td>Increase in snow depth (inches).</td>
</tr>
<tr>
<td>IRU</td>
<td>Input</td>
<td>Hydrologic response unit.</td>
</tr>
<tr>
<td>JLOOP</td>
<td>Internal</td>
<td>Counter to count number of passes through soil water adjustment procedure. Used to prevent infinite looping.</td>
</tr>
<tr>
<td>JULIAN_DATE</td>
<td>Input</td>
<td>Julian date.</td>
</tr>
<tr>
<td>LAT_HT_LITTER</td>
<td>Internal</td>
<td>Composite latent heat of the profile—litter and soil—undergoing freezing or thawing (calories per cubic centimeter).</td>
</tr>
<tr>
<td>LAT_HT_SOIL</td>
<td>Internal</td>
<td>Latent heat of the soil profile undergoing freezing or thawing (calories per cubic centimeter).</td>
</tr>
<tr>
<td>LAT_HT_UNIT_CHG</td>
<td>Internal</td>
<td>Latent heat of the soil profile below frost penetration (calories per cubic centimeter).</td>
</tr>
<tr>
<td>LAYER_DEPTH</td>
<td>Input</td>
<td>Thickness of each soil layer (inches).</td>
</tr>
</tbody>
</table>
### Supplement 4.—Definition of subroutine variables—Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAYER_DIFF</td>
<td>Internal</td>
<td>Difference between the soil water in a layer at &quot;LAYER_MOIST_POT&quot; and currently available &quot;LAYER_MOIST&quot; (inches).</td>
</tr>
<tr>
<td>LAYER_MOIST</td>
<td>Input</td>
<td>Daily soil water content of each layer (inches).</td>
</tr>
<tr>
<td>LAYER_MOIST_POT</td>
<td>Input</td>
<td>Soil water between field capacity and wilting point for each layer (inches).</td>
</tr>
<tr>
<td>LAYERPOROSITY</td>
<td>Input</td>
<td>Porosity of each layer (decimal fraction).</td>
</tr>
<tr>
<td>L_H</td>
<td>Internal</td>
<td>Array of latent heat for successive freezing cycles (calories per cubic centimeter).</td>
</tr>
<tr>
<td>LITTERDEPTH</td>
<td>Input</td>
<td>Depth of the litter layer (inches).</td>
</tr>
<tr>
<td>MAX_INFILTRATION</td>
<td>Internal</td>
<td>Maximum daily snowmelt infiltration capacity of soil profile (inches).</td>
</tr>
<tr>
<td>MEAN_ann_AIR_TEMP</td>
<td>Input</td>
<td>Mean annual air temperature (degrees Celsius).</td>
</tr>
<tr>
<td>MEAN_ann_TEMP_NUMTR</td>
<td>Internal</td>
<td>Computational term involving the numerator of the frost penetration equation.</td>
</tr>
<tr>
<td>MIN_INFILTR</td>
<td>Input</td>
<td>Minimum infiltration rate when the soil is near field capacity and is under frozen conditions (inches per hour).</td>
</tr>
<tr>
<td>MOIST</td>
<td>Internal</td>
<td>Soil water of layers below frost penetration (decimal fraction, volume).</td>
</tr>
<tr>
<td>MOIST_LITTER</td>
<td>Input</td>
<td>Water content of the litter layer (inches).</td>
</tr>
<tr>
<td>MOS</td>
<td>Internal</td>
<td>Water content of a soil layer (decimal fraction, volume).</td>
</tr>
<tr>
<td>MOS_UNDFROZE</td>
<td>Internal</td>
<td>Water content of the soil below frost penetration (inches).</td>
</tr>
<tr>
<td>NET_PRECIP</td>
<td>Input</td>
<td>Daily precipitation (inches).</td>
</tr>
<tr>
<td>NEW_SNOW</td>
<td>Internal</td>
<td>Daily precipitation in the form of snow (inches).</td>
</tr>
<tr>
<td>NEW_SNOW_DENSITY</td>
<td>Internal</td>
<td>Initial density of new-fallen snow (decimal percent).</td>
</tr>
<tr>
<td>NUM_LAYERS</td>
<td>Input</td>
<td>Number of soil layers.</td>
</tr>
<tr>
<td>ORGANIC_MATTER</td>
<td>Input</td>
<td>Organic material of the top soil layer (decimal fraction).</td>
</tr>
<tr>
<td>ORGANIC_MATTER1</td>
<td>Internal</td>
<td>Threshold for organic material below which puddling of the soil is likely to occur (decimal fraction).</td>
</tr>
<tr>
<td>Variable</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>ORGANIC_MATTER2</td>
<td>Internal</td>
<td>Threshold for organic material above which puddling of the soil is unlikely to occur (decimal fraction).</td>
</tr>
<tr>
<td>PEN_CTR</td>
<td>Internal</td>
<td>Counter to allow penetration to go centimeter by centimeter through soil layers.</td>
</tr>
<tr>
<td>PENDEPTHARRAY</td>
<td>Internal</td>
<td>Array of frost penetration depths for successive freezing cycles and includes snow and litter depths (inches).</td>
</tr>
<tr>
<td>PENETRATION_DENOM</td>
<td>Internal</td>
<td>Computational term involving the denominator of the frost penetration equation.</td>
</tr>
<tr>
<td>PENETRATION</td>
<td>Internal</td>
<td>Current depth of frost penetration (inches).</td>
</tr>
<tr>
<td>PENETRATIONCODE</td>
<td>Internal</td>
<td>The frost penetration code for the top soil layer: 0: No frost in the top layer, 1: Frost does exist in the top layer, 9999: Error---something is wrong.</td>
</tr>
<tr>
<td>PENETRATION_MAX_SOIL</td>
<td>Output</td>
<td>Maximum frost penetration into the soil. Does not include penetration through snow or litter (inches).</td>
</tr>
<tr>
<td>PENETRATION_NUMTR</td>
<td>Internal</td>
<td>Computational term involving the numerator of the frost penetration equation.</td>
</tr>
<tr>
<td>PEN_S</td>
<td>Internal</td>
<td>Computational term used in the frost penetration equation.</td>
</tr>
<tr>
<td>PERCDEPTH</td>
<td>Internal</td>
<td>Depth of percolation of excess water to lower layers that might occur on a day when the mean temperature is above freezing and the minimum is below freezing (inches).</td>
</tr>
<tr>
<td>POROSITY_LOWER</td>
<td>Internal</td>
<td>Porosity of soil layers below frost penetration (decimal fraction).</td>
</tr>
<tr>
<td>POTSATURATEDFLAG</td>
<td>Internal</td>
<td>Flag which, when set to 1, allows the surface soil layer to collect more water than the normal field capacity and increases the likelihood that concrete frost will form if it has not already.</td>
</tr>
<tr>
<td>Variable</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>PROFILE_MOIST_POT</td>
<td>Input</td>
<td>Maximum available water-holding capacity of a soil profile: Sum of the variables &quot;LAYER_MOIST_POT&quot; (inches).</td>
</tr>
<tr>
<td>RATIO_LAYER_DIFF</td>
<td>Internal</td>
<td>Difference between ratios of soil water for adjacent soil layers.</td>
</tr>
<tr>
<td>RATIO_MOIST_N</td>
<td>Internal</td>
<td>Ratio of soil water to the potential maximum soil water in layer N.</td>
</tr>
<tr>
<td>RATIO_MOIST_NPLUS1</td>
<td>Internal</td>
<td>Ratio of soil water to the potential maximum soil water in layer N+1.</td>
</tr>
<tr>
<td>RATIO_MOIST_NPLUS2</td>
<td>Internal</td>
<td>Ratio of soil water to the potential maximum soil water in layer N+2.</td>
</tr>
<tr>
<td>RATIO_TC_AIR1</td>
<td>Internal</td>
<td>Ratio of the thermal conductivities of mineral soil to air.</td>
</tr>
<tr>
<td>RATIO_TC_AIR2</td>
<td>Internal</td>
<td>Ratio of the thermal conductivities of mineral soil to air.</td>
</tr>
<tr>
<td>RATIO_TC_ICE</td>
<td>Internal</td>
<td>Ratio of the thermal conductivities of mineral soil to ice.</td>
</tr>
<tr>
<td>RATIO_TC_WAT_SOIL</td>
<td>Internal</td>
<td>Ratio of the thermal conductivities of water to soil.</td>
</tr>
<tr>
<td>RUNOFF</td>
<td>Output</td>
<td>Amount of water that runs off the profile (inches).</td>
</tr>
<tr>
<td>SNOW</td>
<td>Internal</td>
<td>Water equivalent of snowpack (inches).</td>
</tr>
<tr>
<td>SNOW_DENSITY</td>
<td>Internal</td>
<td>Density of the snowpack (grams per cubic centimeter).</td>
</tr>
<tr>
<td>SNOWDEPTH</td>
<td>Internal</td>
<td>Depth of snowpack (inches).</td>
</tr>
<tr>
<td>SNOWDEPTH_LOSS</td>
<td>Internal</td>
<td>Loss in depth of snowpack (inches).</td>
</tr>
<tr>
<td>SNOWMELT</td>
<td>Output</td>
<td>Daily snowmelt (inches).</td>
</tr>
<tr>
<td>SOIL_MOIST_COND</td>
<td>Internal</td>
<td>Computational term used in determining &quot;AVAIL_WATER&quot; (inches).</td>
</tr>
<tr>
<td>SUR_LAYER_MOIST_POT</td>
<td>Internal</td>
<td>Soil water between field capacity and wilting point for the surface layer that is subject to direct evaporation (inches).</td>
</tr>
<tr>
<td>SUR_STORE_OVER_WILT</td>
<td>Input</td>
<td>Soil water in the surface layers subject to direct evaporation (inches).</td>
</tr>
<tr>
<td>TC</td>
<td>Internal</td>
<td>Array of thermal conductivity of the profile for successive freezing cycles (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_AIR</td>
<td>Internal</td>
<td>Thermal conductivity of air (calories per centimeter per second per degree Celsius).</td>
</tr>
</tbody>
</table>
### Supplement 4.—Definition of subroutine variables—Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC_COMPOSITE</td>
<td>Internal</td>
<td>Composite thermal conductivity of the soil (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_DENOM</td>
<td>Internal</td>
<td>Computational term used in computing &quot;TC_COMPOSITE.&quot;</td>
</tr>
<tr>
<td>TC_DRYSOIL</td>
<td>Internal</td>
<td>Thermal conductivity of dry soil (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_ICE</td>
<td>Internal</td>
<td>Thermal conductivity of ice (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_LITTER</td>
<td>Internal</td>
<td>Thermal conductivity of litter (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_NUM</td>
<td>Internal</td>
<td>Computational term used in computing &quot;TC_COMPOSITE.&quot;</td>
</tr>
<tr>
<td>TC_SUM</td>
<td>Internal</td>
<td>Current thermal conductivity of the profile (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_UNDFROZE_COMPOSITE</td>
<td>Internal</td>
<td>Thermal conductivity of soil below frost penetration (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>TC_UNDFROZE_DENOM</td>
<td>Internal</td>
<td>Computational term used in computing &quot;TC UNDFROZE COMPOSITE.&quot;</td>
</tr>
<tr>
<td>TC_UNDFROZE_NUM</td>
<td>Internal</td>
<td>Computational term used in computing &quot;TC UNDFROZE COMPOSITE.&quot;</td>
</tr>
<tr>
<td>TC_WATER</td>
<td>Internal</td>
<td>Thermal conductivity of water (calories per centimeter per second per degree Celsius).</td>
</tr>
<tr>
<td>THAW_DENOM</td>
<td>Internal</td>
<td>Computational term involving the denominator of the thaw equation.</td>
</tr>
<tr>
<td>THAWDEPTH</td>
<td>Internal</td>
<td>Current depth of thaw (inches).</td>
</tr>
<tr>
<td>THAWDEPTHARRAY</td>
<td>Output</td>
<td>Array of depths for successive thawing cycles (inches).</td>
</tr>
<tr>
<td>THAW_FACTOR</td>
<td>Internal</td>
<td>Factor used in computing heat capacity during thaw.</td>
</tr>
<tr>
<td>THAWFROSTCODE</td>
<td>Internal</td>
<td>Code indicating type of frost in the soil:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1: Generally a quick freeze--granular frost expected,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2: Very moist ground--needle ice and possible heaving expected,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3: Concrete frost expected with impervious soil,</td>
</tr>
<tr>
<td>Variable</td>
<td>Type</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>THAW_NUMTR</td>
<td>Internal</td>
<td>Computational term involving the numerator of the thaw equation.</td>
</tr>
<tr>
<td>THAW_SUM</td>
<td>Internal</td>
<td>Current thaw index -- cumulative degree days for mean air temperatures above 0 degree Celsius.</td>
</tr>
<tr>
<td>THAWSUMARRAY</td>
<td>Internal</td>
<td>Array of thaw indexes for successive thawing cycles (inches).</td>
</tr>
<tr>
<td>THERMAL_RESIST_LITTER</td>
<td>Internal</td>
<td>Thermal resistance of litter (centimeters seconds degrees Celsius per calorie).</td>
</tr>
<tr>
<td>THERMAL_RESIST_SNOW</td>
<td>Internal</td>
<td>Thermal resistance of snow (centimeters seconds degrees Celsius per calorie).</td>
</tr>
<tr>
<td>THERMAL_RESIST_SOIL</td>
<td>Internal</td>
<td>Thermal resistance of soil (centimeters seconds degrees Celsius per calorie).</td>
</tr>
<tr>
<td>TOTALDEPTH</td>
<td>Internal</td>
<td>Computational term used to determine the depth of frost or thaw (centimeters).</td>
</tr>
<tr>
<td>TRANSPIRFLAG</td>
<td>Internal</td>
<td>A flag which is 0 if the vegetation is such that transpiration is taking water from deeper layers in the soil profile. It is 1 when either the cover or the season is such that water loss is by evaporation only and indicates that only the surface layers are active in soil water exchange processes. Not used in SMP or FRZ. Used in PRMS as switch to enter SMP or FRZ.</td>
</tr>
</tbody>
</table>

4: Snow is melting and some thawing of soil from below is expected,
5: Some thawing has taken place but the soil is still partially frozen,
6: Soil is free of frost,
7: Soil is freezing but conditions make the type of frost indeterminant,
8: Frost did not penetrate the litter,
9: Error -- something is wrong.
### Supplement 4. — Definition of subroutine variables — Continued

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_R_SOIL</td>
<td>Internal</td>
<td>Array of thermal resistance of the soil for successive freezing cycles (centimeters seconds degrees Celsius per calorie).</td>
</tr>
<tr>
<td>WATER</td>
<td>Internal</td>
<td>Water available for infiltration (inches).</td>
</tr>
<tr>
<td>WATER_ADDED</td>
<td>Internal</td>
<td>Water that is added to a soil layer (inches).</td>
</tr>
<tr>
<td>WATER_LOSS</td>
<td>Internal</td>
<td>Water that is lost from a soil layer to evaporation (inches).</td>
</tr>
<tr>
<td>WATER_POT</td>
<td>Internal</td>
<td>Water available for runoff, infiltration, or evaporation (inches).</td>
</tr>
<tr>
<td>WEIGHTED_POROS</td>
<td>Internal</td>
<td>Porosity of soil layer weighted by the thickness of each layer (decimal fraction).</td>
</tr>
<tr>
<td>YESTERDAY</td>
<td>Internal</td>
<td>Yesterday used for testing whether days of thaw are consecutive.</td>
</tr>
<tr>
<td>YEST_MEAN_AIR_TEMP</td>
<td>Internal</td>
<td>Yesterday's mean air temperature (degrees Celsius).</td>
</tr>
<tr>
<td>YEST_SNOW_DEPTH</td>
<td>Internal</td>
<td>Yesterday's depth of snowpack (inches).</td>
</tr>
<tr>
<td>YEST_TYPE_FROST</td>
<td>Internal</td>
<td>Yesterday's frost type.</td>
</tr>
<tr>
<td>YEST_WATER_POT</td>
<td>Internal</td>
<td>Yesterday's &quot;WATER_POT&quot; (inches).</td>
</tr>
</tbody>
</table>
**Supplement 5.--Additional data required for FRZ and SMP**

Additional data are required to run PRMS with FRZ and SMP. Input group 9 was added and is read in on input unit 60 in subroutine SMBAL. The input data for group 9 defines the soil profile characteristics for a hydrologic response unit. Because the input and output for PRMS are in inch-pound units, the additional input data required for FRZ and SMP also are in inch-pound units. The following is the listing for input group 9.

<table>
<thead>
<tr>
<th>Record</th>
<th>Columns</th>
<th>Format</th>
<th>Variables</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-7</td>
<td>'01FROST'</td>
<td>I.D.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>F5.0</td>
<td>MEAN_ANN_AIR_TEMP</td>
<td>Mean annual air temperature (degrees Celsius).</td>
</tr>
<tr>
<td></td>
<td>16-20</td>
<td>F5.0</td>
<td>DEPTH_STABLE_TEMPS</td>
<td>Depth of stable soil temperatures (inches).</td>
</tr>
<tr>
<td></td>
<td>21-25</td>
<td>F5.0</td>
<td>LITTERDEPTH</td>
<td>Depth of the litter layer (inches).</td>
</tr>
<tr>
<td></td>
<td>26-30</td>
<td>I5.0</td>
<td>NUM_LAYERS</td>
<td>Number of soil layers.</td>
</tr>
<tr>
<td></td>
<td>31-35</td>
<td>I5.0</td>
<td>EVAP_LAYERS</td>
<td>Number of soil layers subject to direct evaporation.</td>
</tr>
<tr>
<td></td>
<td>36-40</td>
<td>F5.3</td>
<td>ORGANIC_MATTER</td>
<td>Organic matter of the first soil layer (decimal fraction).</td>
</tr>
<tr>
<td></td>
<td>41-45</td>
<td>F5.2</td>
<td>MIN_INFLTR</td>
<td>Minimum infiltration rate when the soil is near field capacity and is under frozen conditions (inches per hour).</td>
</tr>
<tr>
<td></td>
<td>46-50</td>
<td>F5.2</td>
<td>MOIST_LITTER</td>
<td>Water content of the litter layer (inches).</td>
</tr>
<tr>
<td>2</td>
<td>1-8</td>
<td>'02LDEPTH'</td>
<td>I.D.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-60</td>
<td>10F5.2</td>
<td>LAYERDEPTH(I)</td>
<td>Thickness of each soil layer for I=1, NUM_LAYERS (inches).</td>
</tr>
<tr>
<td>3</td>
<td>1-8</td>
<td>'03LPROS'</td>
<td>I.D.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-60</td>
<td>10.F5.2</td>
<td>LAYERPOROSITY(I)</td>
<td>Porosity of each soil layer for I=1, NUM_LAYERS (decimal fraction).</td>
</tr>
<tr>
<td>4</td>
<td>1-5</td>
<td>'LPOT'</td>
<td>I.D.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10.F5.2</td>
<td></td>
<td>LAYER_MOIST_POT(I)</td>
<td>Water capacity of each soil layer for I=1, NUM_LAYERS (inches).</td>
</tr>
</tbody>
</table>
### Supplement 5—Additional data required for FRZ and SMP—Continued

<table>
<thead>
<tr>
<th>Record</th>
<th>Columns</th>
<th>Format</th>
<th>Variables</th>
<th>Definition</th>
</tr>
</thead>
</table>
| 5      | 1-8     | 'LMOIST' | I.D.                      | Water content of each soil layer for I=1,
|        |         |        |                            | NUM_LAYERS (inches).                                               |
|        | 10-60   | 10F5.2 | LAYER_MOIST(I)            |                                                                   |
| 6      | 1-8     | 'ETLOSS' | I.D.                      | Fraction of the evaporation loss that would come from
|        |         |        |                            | each layer for I=1,
|        |         |        |                            | NUM_LAYERS.                                                       |
|        | 10-60   | 10F5.2 | FRACTION_ET_LOSS(I)       |                                                                   |
| 7      | 1-6     | 'ADJUST' | I.D.                      | Flag that is 0 if only the
|        |         |        |                            | total soil water content for the profile on the first day
|        |         |        |                            | is inputed. Flag that is 1 if soil water content for
|        |         |        |                            | each soil layer for the first day is inputed.                    |
|        | 10-15   | I5     | FIRSTDAYFLAG              | Freeze and thaw adjustment coefficient.                           |
|        | 16-20   | F5.2   | ADJUST_COEF               |                                                                   |
Supplement 6. Input data for calibration simulation for plot 2, 1985-86

The input used for the calibration using 1985-86 data for plot 2 includes input groups 1, 6, and 9. Input group 1 contains the physical description of the runoff plot, input group 6 contains the snowpack adjustment, and input group 9 contains additional soil profile characteristics of the runoff plot that are required by the SMP and FRZ subroutines.

Input group 1

| SIM/OPT | 0 1 0 0 0 0 0 2 |
| SIM/COMP | 0 0 1 0 |
| TITL | RUNOFF SIMULATIONS FOR PLOT 2, 1985-86 WINTER |
| INIT1 | 1 1 1 1 1 0 0.012108 |
| INIT2 | 1985 10 1 1986 3 31 |
| MFNS-MFN | 10 3 |
| PRINT-OP | 3 10 3 3 1 365 0 |
| PLOT | 0 |
| DATATYPE | 6 1 0 1 1 1 0 0 1 0 |
| PARM | 00000 000000000030000065 00045 |
| STAT | 00003 0000000000600001 00006 |
| STAIDC | D460238098014410 D460238098014410 D460238098014410 |
| STAIDP | D460238098014410 |
| RD | 1 HOR | 1.00 1.00 |
| RDM | -0.35-0.44 0.96 0.16 0.09 0.07 0.07 0.14 0.09 0.14 0.52-0.48 |
| RDG | 45.6987.63 -63.4-31.1-15.8-14.0-48.0-11.6-23.1-79.563.93 |
| RAD-COR | 1.00 1.00 .85 |
| CLIM-PR | 1310 0.20 0.50 0 0 6 9 |
| CTTW | 0.0150.0150.0020.0100.0100.0100.0100.0100.0100.0050.0150.015 1.00 |
| PAT | 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 5.0 |
| AJM | 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 |
| TLX | 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 |
| TNL | 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 |
| EVC | 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 |
| SNO-VAR | 31 105 .715 0.35 .10 .35 0.10 1.0 |
| CEN | 0.0 0.0 0.0 0.0 1.0 2.0 3.0 3.0 2.0 1.0 0.0 0.0 |
| KADJ | 35 |
| RES | 0.0 |
| GW | 0.0 |
| KRSP | 1 |
| RESMX-EX | 1.0 1.0 |
| SEP | 1.0 |
| SNE | 0.0 |
| RCB | 0.000 |
| RCF-RCP | 1.00 1.00 |
| RU1 | 1 10.384 1310 1 0.00 0.00 1.00 0.00 0.00 0.00 0.00 410022.24 0.0 0.0 |
| RU2 | 1 110.50 3.12 3.60 1.24 0.80 1.00 0.00 0.00 0.00 4.00 1 1 0 |
| RU3 | 1 1.012108 1.00 1.00 0.93 700.0 |

90
Supplement 6.—Input data for calibration simulation for plot 2.

1985-86—Continued

<table>
<thead>
<tr>
<th>Input group 6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>01PKADJ-WE</td>
<td>1.74</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input group 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>01FROST 7.41 95.0 0.5 4</td>
</tr>
<tr>
<td>42L/DEPTH 12.0 12.0 16.0 30.0</td>
</tr>
<tr>
<td>43L/POROS 0.40 0.38 0.36 0.37</td>
</tr>
<tr>
<td>44L/POT 1.80 1.80 2.40 4.50</td>
</tr>
<tr>
<td>45L/MOIST 0.69 0.55 0.51 1.35</td>
</tr>
<tr>
<td>46L/LOSS 1.00 0.00</td>
</tr>
<tr>
<td>47ADJUST 1 2.62</td>
</tr>
<tr>
<td>2 .009 0.05 .025</td>
</tr>
</tbody>
</table>
## Output for calibration simulation for plot 2

<table>
<thead>
<tr>
<th>MO</th>
<th>DY</th>
<th>YEAR</th>
<th>IRU</th>
<th>T-MAX</th>
<th>T-MIN</th>
<th>P-T-1</th>
<th>P-T-2</th>
<th>P-T-3</th>
<th>P-T-4</th>
<th>P-T-5</th>
<th>P-T-6</th>
<th>P-T-7</th>
<th>P-T-8</th>
<th>P-T-9</th>
<th>P-T-10</th>
</tr>
</thead>
<tbody>
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<td>23</td>
<td>1986</td>
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<td>5.5</td>
<td>-3.5</td>
<td>22.9</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
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