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

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U.S. Geological Survey Open-File Report 91-462

Prepared in cooperation with the

NORTH DAKOTA STATE WATER COMMISSION

Bismarck, North Dakota

1991

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

Multiply	By	To obtain
calorie per centimeter per second per degree Celsius [((cal/cm)/s)/°C]	241.9	British thermal unit per foot per hour per degree Fahrenheit
calorie per cubic centimeter (cal/cm^3)	0.1210	British thermal unit per cubic foot
calorie per cubic centimeter per degree Celsius [(cal/cm^3)/°C]	62.50	British thermal unit per cubic foot per degree Fahrenheit
calorie per gram per degree Celsius [(cal/g)/°C]	1.00	British thermal unit per pound per degree Fahrenheit
calorie per square centimeter (cal/cm^2)	3.687	British thermal unit per square foot
calorie per square centimeter per second [(cal/cm^2)/s]	0.001024	British thermal unit per square foot per hour
centimeter (cm)	0.03281	foot
centimeter per hour (cm/h)	2.54	inch per hour
centimeter second degree Celsius per calorie [(cm·s·°C)/cal]	0.004134	foot hour degree Fahrenheit per British thermal unit
cubic centimeter (cm^3)	0.6102	cubic inch
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
square centimeter	0.15500	square inch
square centimeter second degree Celsius per calorie [(cm^2·s·°C)/cal]	0.0005689	square foot hour degree Fahrenheit per British thermal unit
square kilometer (km^2)	0.3861	square mile

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

$$°F = 1.8x(°C)+32$$

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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 Lielmezs (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), Dingman (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 km^2). 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 km^2 in Colorado to 21.9 km^2 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 ground-water 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 ground-water 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)

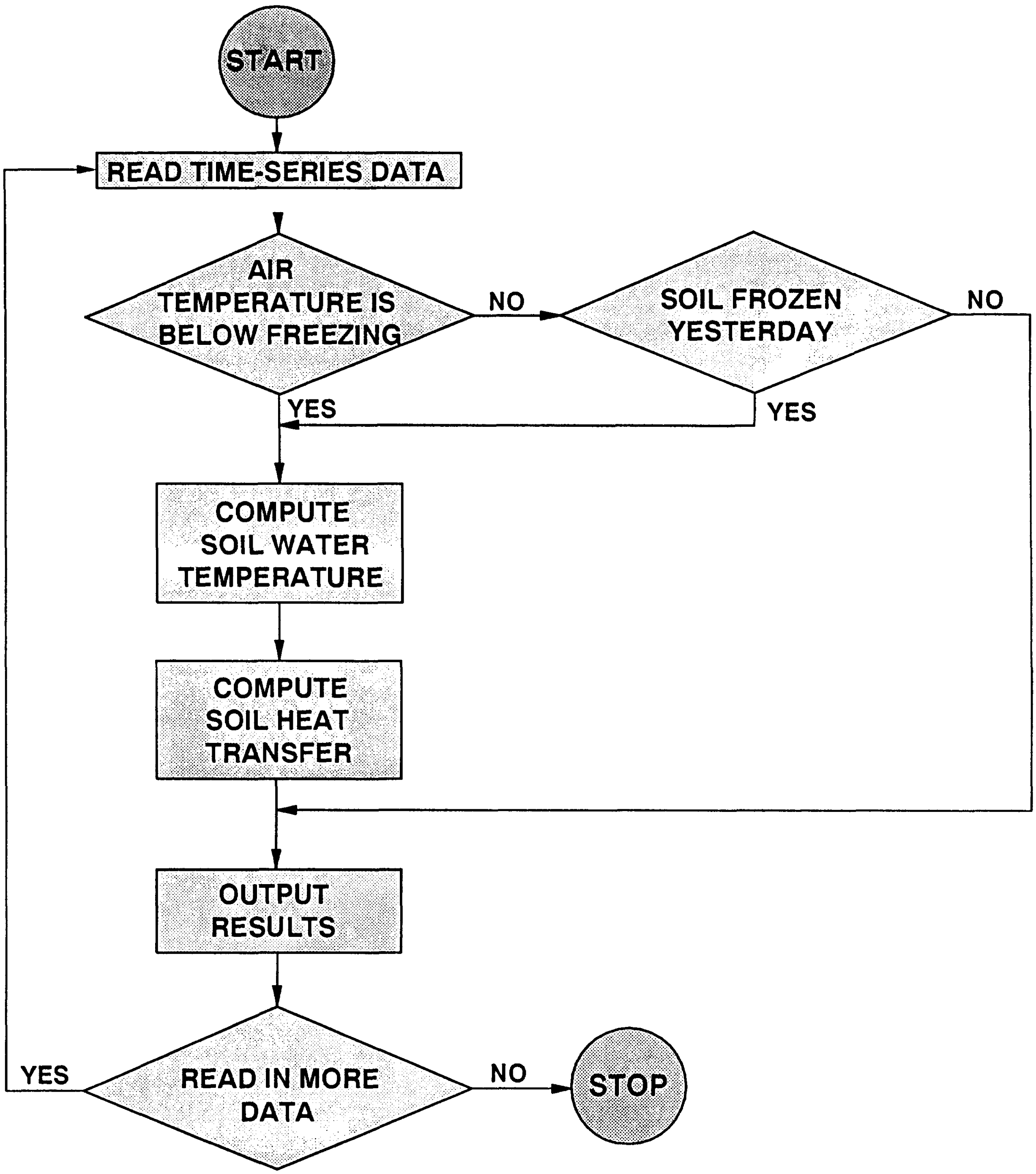

Figure 1.--Flow chart of the conceptual model.

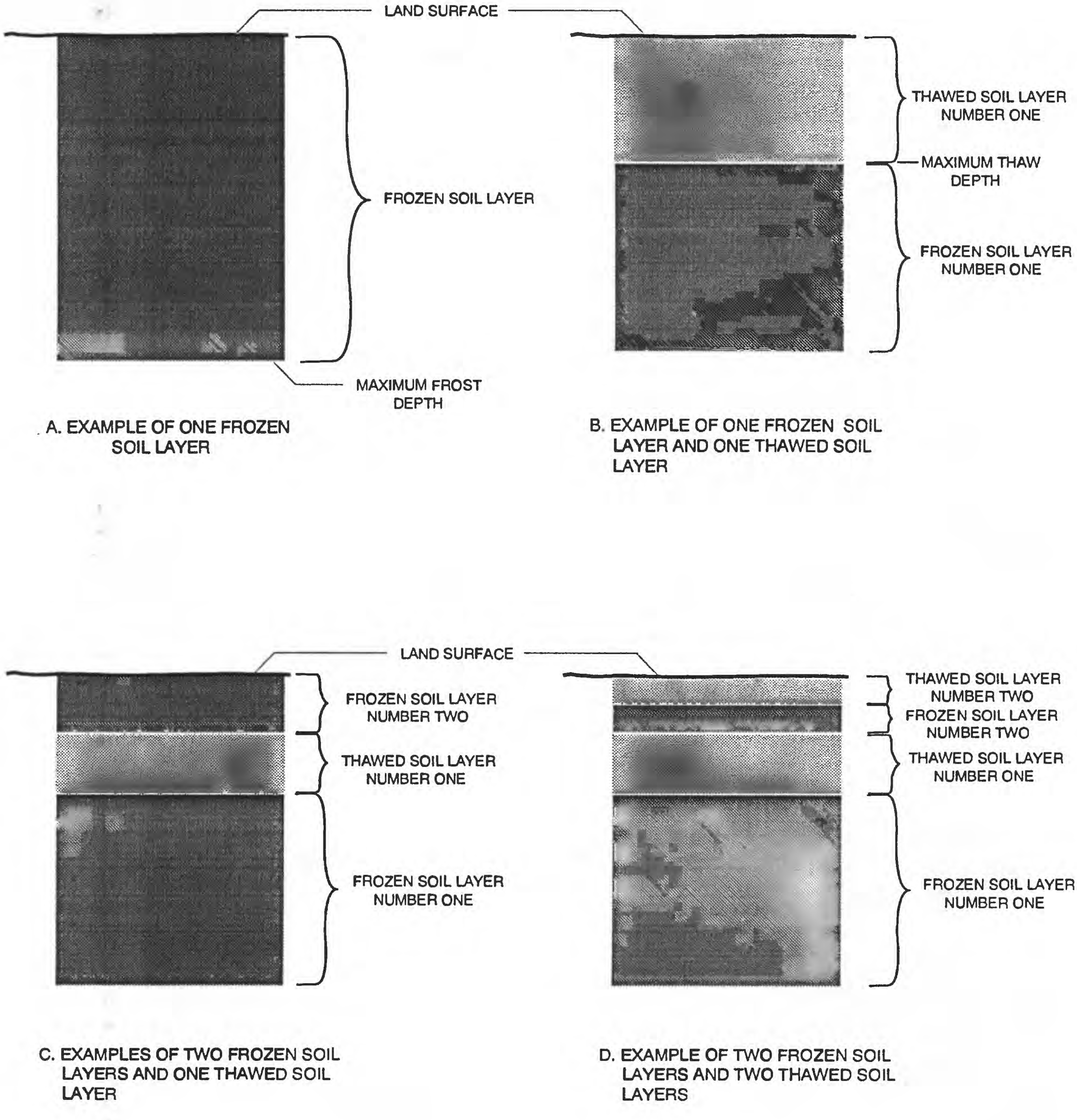

Figure 2.--Diagrammatic representation of a soil profile with different number of freezing and thawing layers.

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

$$X_f = [(86{,}400 K_f I_f)/(L + C(T_a + I_f/2t))]^{0.5} \qquad (1)$$

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

$$X_r = 86{,}400 K_u (T_a/(X_a - X_f))/L \qquad (2)$$

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

$$X_t = [86{,}400 K_u I_t / (L + C I_t)]^{0.5} \tag{3}$$

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

$$K_i = (K_s V_s G_s + K_w V_w G_w + K_a V_a G_a) / (V_s G_s + V_w G_w + V_a G_a) \tag{4}$$

where K_i is the composite thermal conductivity of the ith layer, in calories per centimeter per second per degree Celsius;
K_s is the thermal conductivity of soil in the ith layer, in calories per centimeter per second per degree Celsius;
V_s is the volumetric fraction of soil in the ith layer;
G_s 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

$$K_{sn} = 0.0068 D_s^2 \tag{5}$$

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

$$C_i = V_s C_s + V_w C_w + V_a C_a \tag{6}$$

where C_i 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/cm^3, the average value for heat capacity of the soil, C_s, is 0.46 (cal/cm^3)/°C. The heat capacity of water, C_w, is 1.00 (cal/cm^3)/°C for liquid water and 0.45 (cal/cm^3)/°C for ice at 0°C. The heat capacity of air (0.00030 (cal/cm^3)/°C) is negligible compared to the other heat capacities and can be neglected. The heat capacity, C_i, in the case involving liquid water can be given as

$$C_i = (1-P_i)0.46 + V_w(1.00) \tag{7}$$

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

$$C_i = (1-P_i)0.46 + V_w(0.45). \tag{8}$$

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/cm^3)/°C; for new snow, 0.15 (cal/cm^3)/°C; and for litter, 0.06 (cal/cm^3)/°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

$$R_i = X_i / K_i \tag{9}$$

where R_i is the thermal resistance of the ith layer, in square centimeters seconds degrees Celsius per calorie, and

X_i is the thickness of the ith layer, in centimeters.

The total thermal resistance, R_t, for n layers is

$$R_t = X_1/K_1 + X_2/K_2 + \ldots + X_n/K_n \tag{10}$$

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

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

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

$$C_t = (\sum C_i X_i)/(\sum X_i) \tag{12}$$

$$L_t = (\sum L_i X_i)/(\sum X_i) \tag{13}$$

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 ith 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 conductivity, 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_i) and the ratio for the next lower layer (D_{i+1}) are given as

$$D_i = M_i / M_{fi} \tag{14}$$

$$D_{i+1} = M_{i+1} / M_{f(i+1)} \tag{15}$$

where D_i is the ratio of soil water of the ith layer;
M_i is the soil water content of the ith layer, in cubic centimeters per cubic centimeter;
M_{fi} is the field capacity of the ith layer, in cubic centimeters per cubic centimeter;
D_{i+1} is the ratio of soil water of the i+1 layer;
M_{i+1} is the soil water content of the i+1 layer, in cubic centimeters per cubic centimeter; and
$M_{f(i+1)}$ is the field capacity of the i+1 layer, in cubic centimeters per cubic centimeter.

If the difference between the ratios, D_o, where $D_o = D_i - D_{i+1}$, is greater than 0.2, then water content of the ith layer, M_i, is reduced by half the ratio difference and the water content of the i+1 layer is increased by half the ratio difference as

$$M_i = M_i - D_o / 2 \tag{16}$$

$$M_{i+1} = M_{i+1} + D_o / 2 \tag{17}$$

This process is repeated until the differences in the ratios, D_o, is less than or equal to 0.2. The process is repeated again for the i+1 and i+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]

Subroutine	Description
Daily components:	
BASFLW	Computes base flow and subsurface flow components of the streamflow hydrograph.
CALIN	Computes change in snowpack when a net gain in heat energy has occurred.
CALOSS	Computes change in snowpack when a net loss in heat energy has occurred.
INTLOS	Computes the evaporation and sublimation of intercepted rain and snow.
PETS	Computes daily estimate of potential evapotranspiration.
PKADJ	Adjusts snowpack water equivalent based on snow-course data.
PRECIP	Computes precipitation form, total precipitation depth, depth intercepted by vegetation, and the net precipitation.
RESVRD	Performs daily routing for surface-water detention reservoirs.
SMBAL	Performs daily soil water accounting.
SNOBAL	Computes snowpack energy balance.
SOLRAD	Computes daily incoming shortwave solar radiation for each hydrologic response unit.
SOLTAB	Computes potential solar radiation and daylight hours for radiation planes.
SRFRO	Computes daily storm runoff from rainfall.
SUMALL	Computes daily, monthly, and annual data summaries for total basin and individual hydrologic response units.
TEMP	Adjusts daily maximum and minimum air temperature to account for differences in elevation and aspect from point of measurement to each hydrologic response unit.
TIMEY	Performs initialization and maintenance of the time accounting variables.

Table 1.--Listing of subroutines in the Precipitation-Runoff Modeling System--Continued

Subroutine	Description
Storm components:	
AM	Computes kinematic routing parameters α and m.
RESVRU	Performs storm-period routing for surface-water detention reservoirs.
ROUTE	Performs channel routing of water and sediment.
UNITD	Computes rainfall excess and performs overland flow routing of water and sediment.
UNSM	Performs subsurface and ground-water reservoir routing for storms.
Optimization components:	
BDRY	Determines whether any of the parameters being optimized lie close to their boundaries and penalizes the objective function if they do.
COROPT	Performs a correlation analysis of the residuals in a daily optimization.
OPINIT	Reads input data and initializes variables for optimization.
PARAM	Adjusts selected model parameters at the beginning of each parameter fitting iteration.
ROSOPT	Initializes model variables and selected model parameters at the beginning of each parameter fitting iteration.
SCALE	Scales parameters and constraint values and unscales parameter and constraint values.
SNORT	Determines which of new search directions is most parallel to each of the old directions following an end of stage.
SUB1	Controls the main strategy of the Rosenbrock optimization procedure.
SUB3	Does Gram-Schmidt orthogonalization to establish new orthogonal search directions.

Table 1.--Listing of subroutines in the Precipitation-Runoff Modeling System--Continued

Subroutine	Description
Sensitivity analysis components:	
MATINV	Performs matrix inversion.
OPINIT	Reads input data and initializes variables for a sensitivity analysis.
PARAM	Adjusts selected model parameters for use in sensitivity analysis routines.
SENMAT	Computes the sensitivity matrix.
SENST	Controls the main strategy of the sensitivity analysis procedure.
Statistical analysis components:	
STATS	Computes daily statistics.
SUMUNT	Computes summary statistics.
Data handling components:	
BLKDAT	Initializes data for common areas.
DATIN	Reads input of model options, parameters, and variables.
DVPLOT	Provides line printer plot of predicted and observed daily mean streamflow.
DVRETR	Selects required daily records from direct access file.
INVIN	Reads input data for storm periods and handles accounting for storms.
PRTHYD	Provides tabular output of stormflow hydrograph.
UVPLOT	Provides line printer plot of predicted and observed stormflow hydrographs and sediment concentration graphs.
UVRET	Selects required storm records from direct access file.

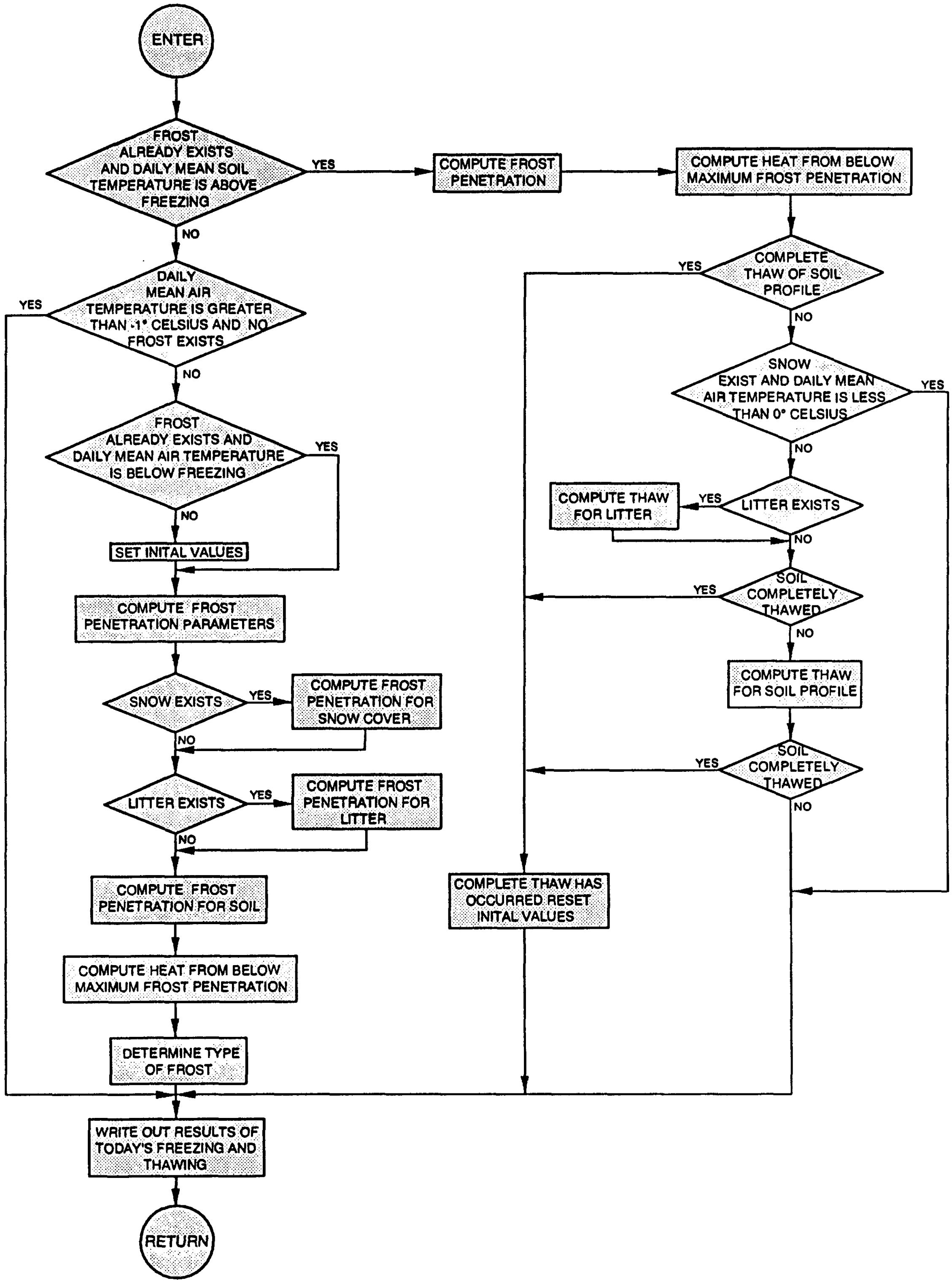

Figure 3.--Flow chart of the subroutine FRZ, which simulates heat transfer.

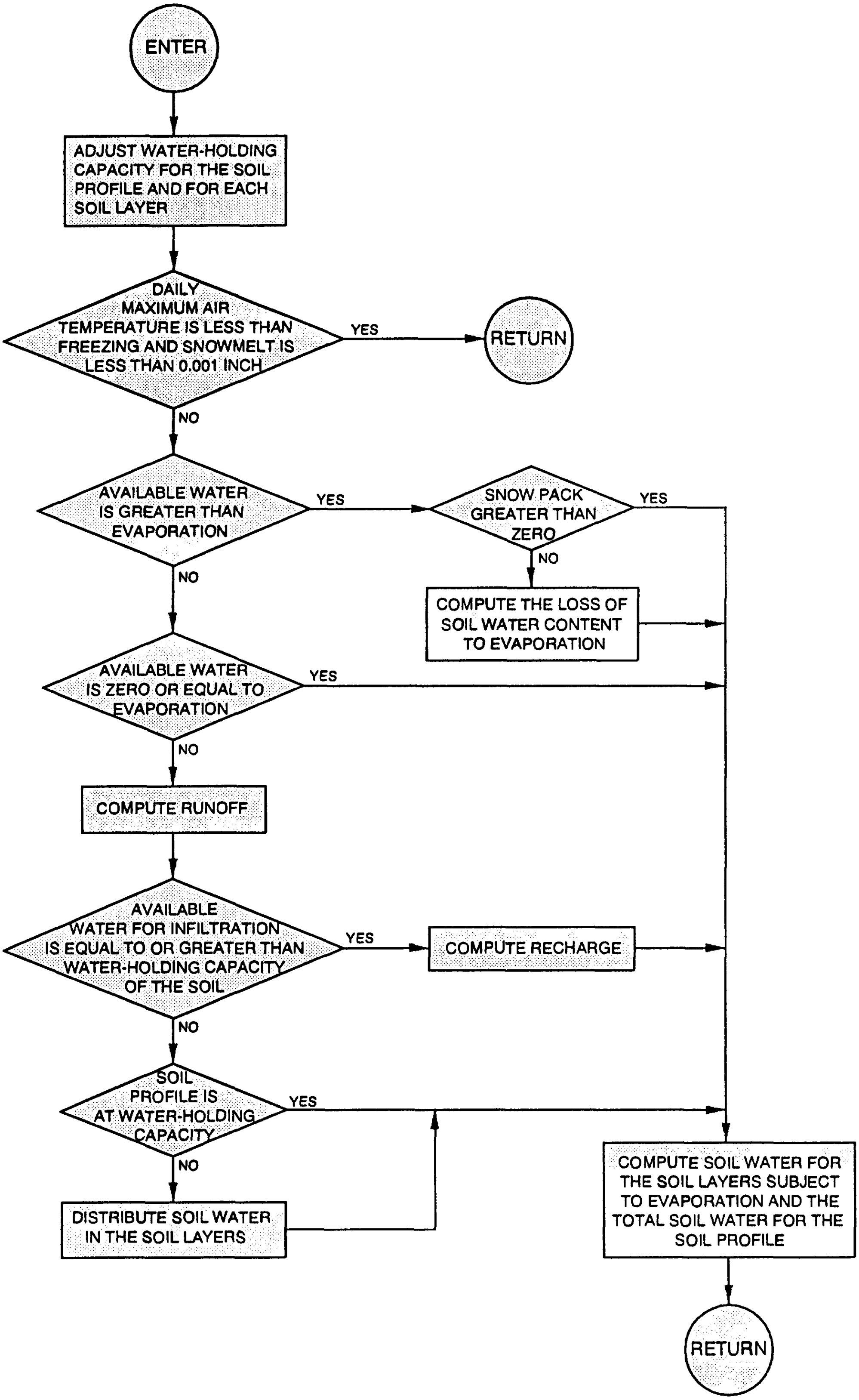

Figure 4.--Flow chart of the subroutine SMP, which simulates water transfer.

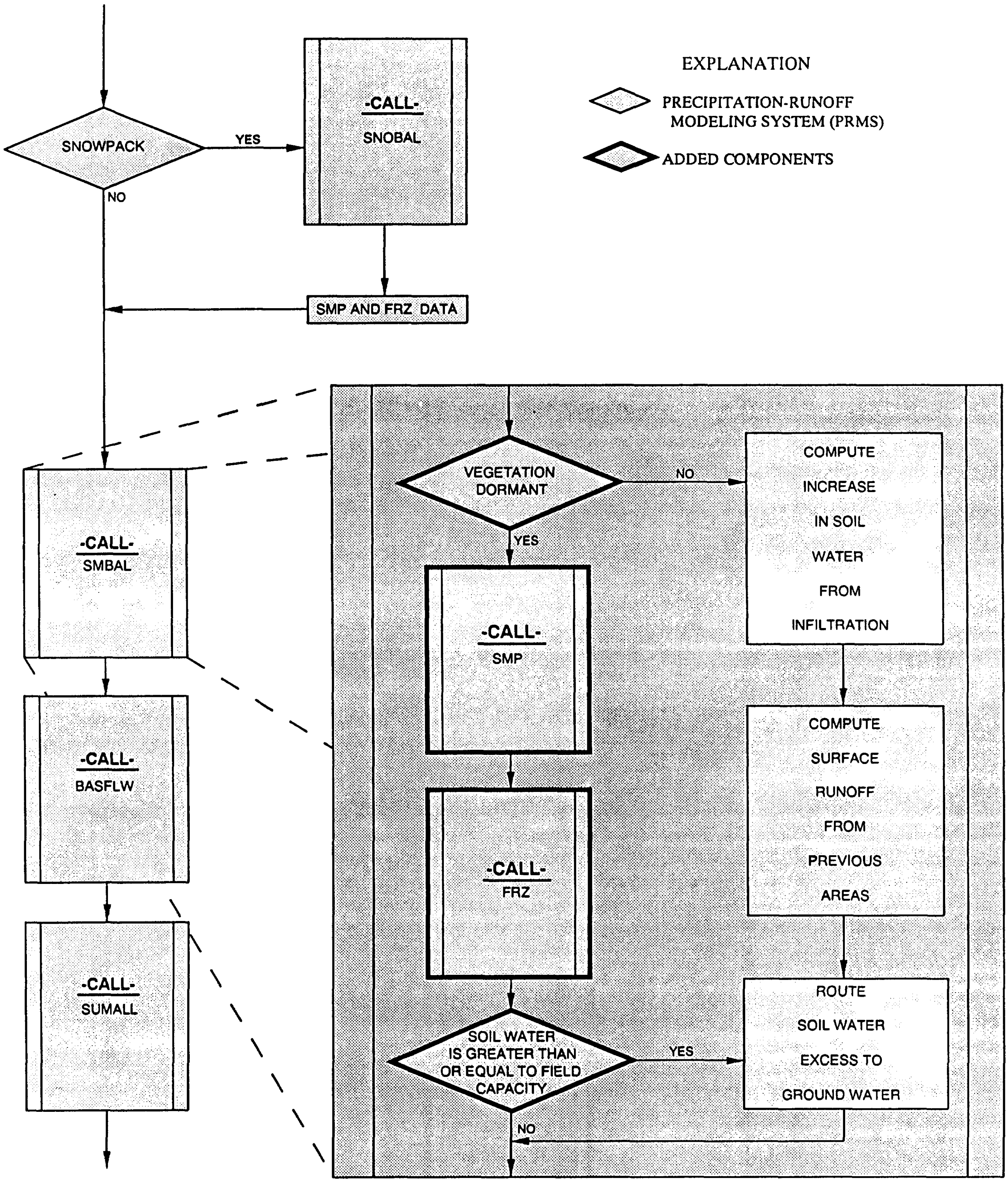

Figure 5.--Flow chart showing the coupling of the subroutine FRZ, which simulates heat transfer, and the subroutine SMP, which simulates water transfer, to the Precipitation-Runoff Modeling System. (Abbreviations correspond to those defined in table 1.)

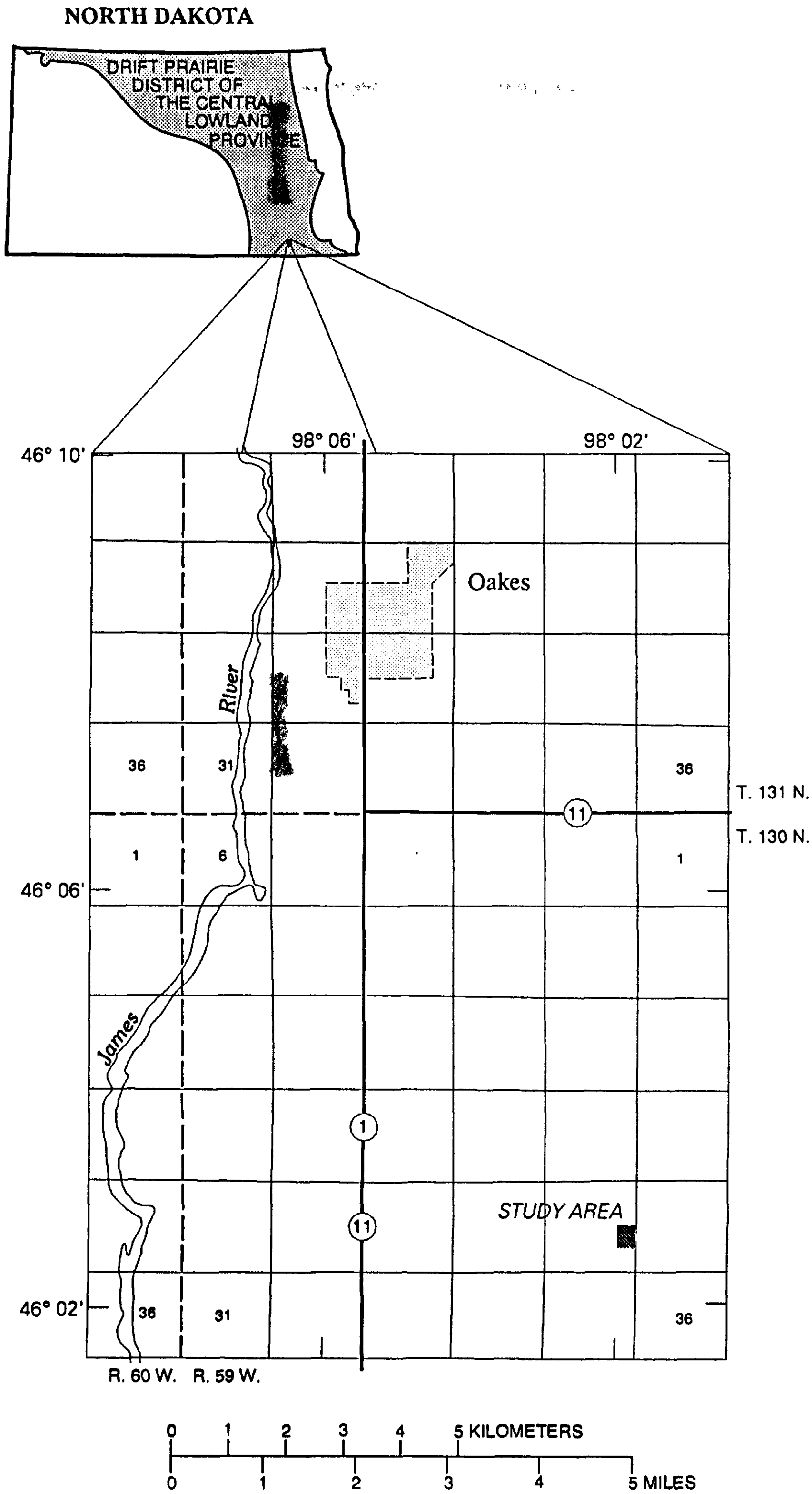

Figure 6.--Location of the study area.

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_a 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:

$$\text{DEPTH\_STABLE\_TEMP} = [0.0002K/(CW)]^{0.5} \tag{18}$$

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 1.99×10^{-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

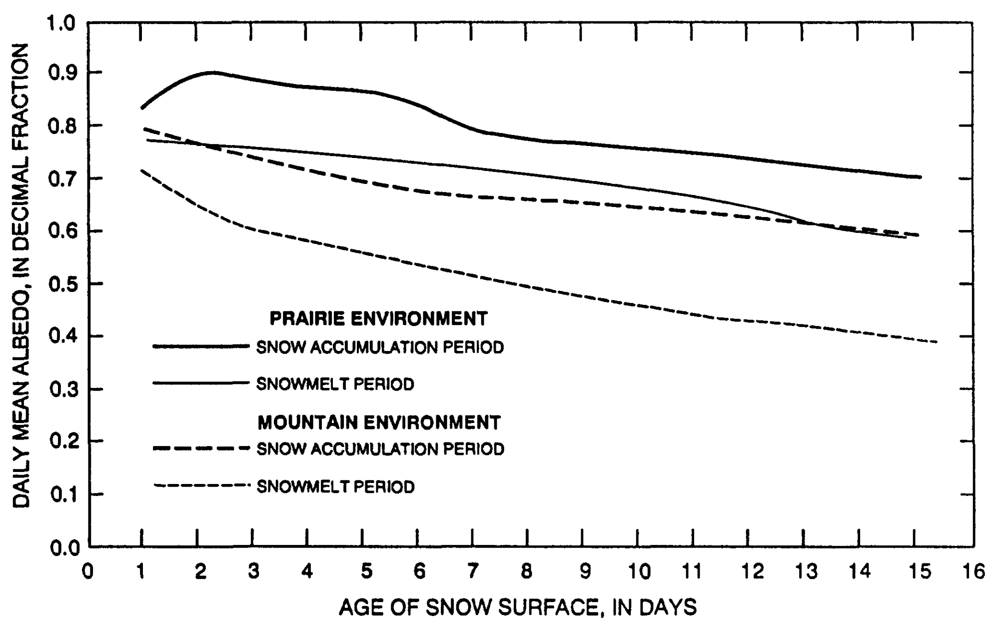

Figure 7.--Decay of albedo with the age of snow.

Table 2.--Average thermal properties of soils

[Modified from Van Wijk and de Vries, 1966]

Soil type	Porosity (decimal fraction)	Volumetric water content (decimal fraction)	Thermal conductivity (10^{-3} calories per centimeter per second per degree Celsius)	Volumetric heat capacity (calories per cubic centimeter per degree Celsius)	Depth of stable soil temperature (meters)
Sand	0.4	0.0	0.7	0.3	1.53
	.4	.2	4.2	.5	2.90
	.4	.4	5.2	.7	2.73
Clay	.4	.0	.6	.3	1.42
	.4	.2	2.8	.5	2.37
	.4	.4	3.8	.7	2.33
Peat	.8	.0	.14	.12	1.08
	.8	.4	.7	.52	1.16
	.8	.8	1.2	.92	1.14

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]

Parameter	Plot 1, 1985-86	Plot 2, 1985-86	Plot 3, 1985-86
	(square millimeters)		
DEPTH_STABLE_TEMP (depth of stable soil temperature)	1,900 (4 percent)	3,200 (10 percent)	1,700 (5 percent)
ADJUST_COEF (freeze and thaw adjustment coefficient)	4,400 (10 percent)	2,500 (8 percent)	4,300 (13 percent)
MEAN_ANN_AIR_TEMP (mean annual air temperature)	2,500 (5 percent)	2,200 (7 percent)	500 (2 percent)
Mean squared error of prediction	45,900	33,500	33,700

indication of parameter interaction; small correlation exists between parameters that were evaluated by the sensitivity analysis. The sensitivity analysis also indicated that the relative influence of the time-series data for a particular day of the simulation on the optimization was small.

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

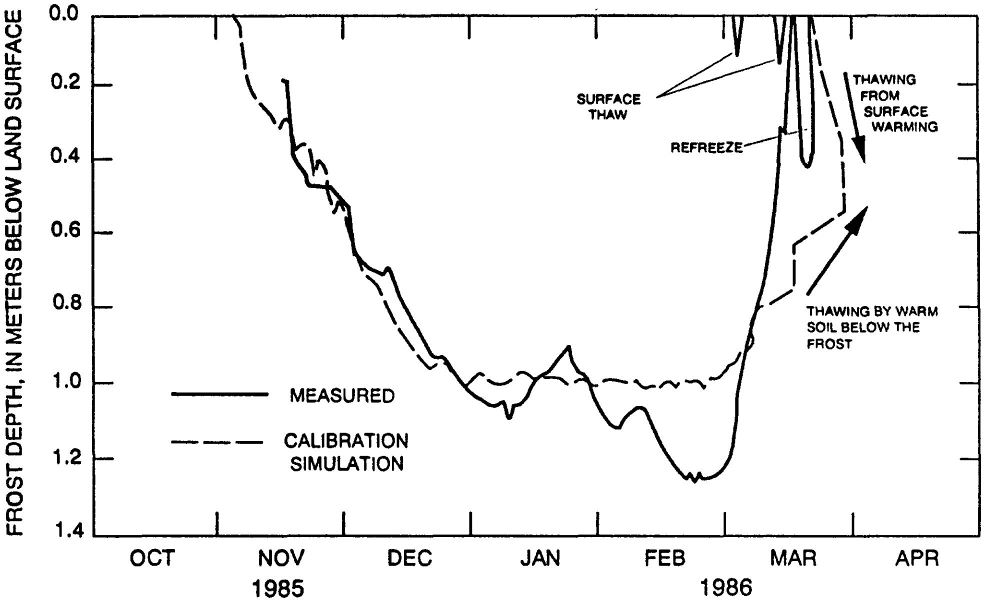

Figure 8.--Measured frost depths and calibration simulation of frost depths for plot 2, October 1985 through April 1986.

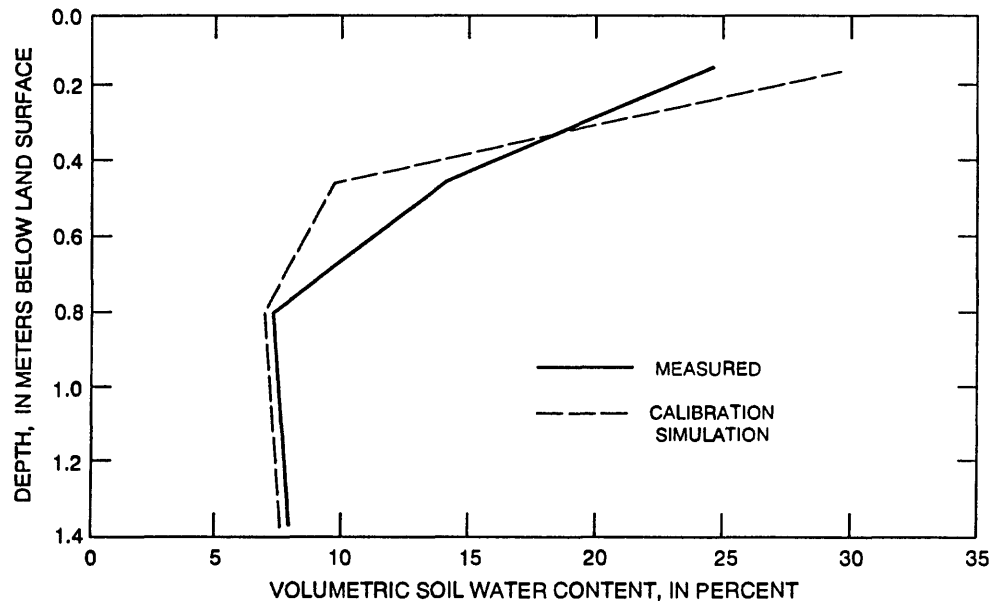

Figure 9.--Measured soil water profile and calibration simulation of soil water profile for plot 2, March 24, 1986.

Table 4.--Summary of the results of model calibration for plot 2 using 1985-86 data

	Measured	Simulated
Change in soil water, in millimeters	[1]73.2	[1]74.9
Recharge, in millimeters	--	[2]0
Runoff, in millimeters	0	0
Maximum frost depth, in meters	[3]1.29	1.01
Date of final thaw	[4]3/25/86	3/31/86

[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.
[4]Complete thaw in plot 2 varied from March 23 to March 28, 1986. The mean date of thaw of plot 2 is March 25, 1986.

of the performance of only the SMP and FRZ subroutines would have been preferred, but the model-generated values from other PRMS subroutines are used in SMP and FRZ and, conversely, model-generated values from SMP and FRZ are used in other subroutines of PRMS. Therefore, the modeled simulations are the combined effects of all subroutines used in PRMS.

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

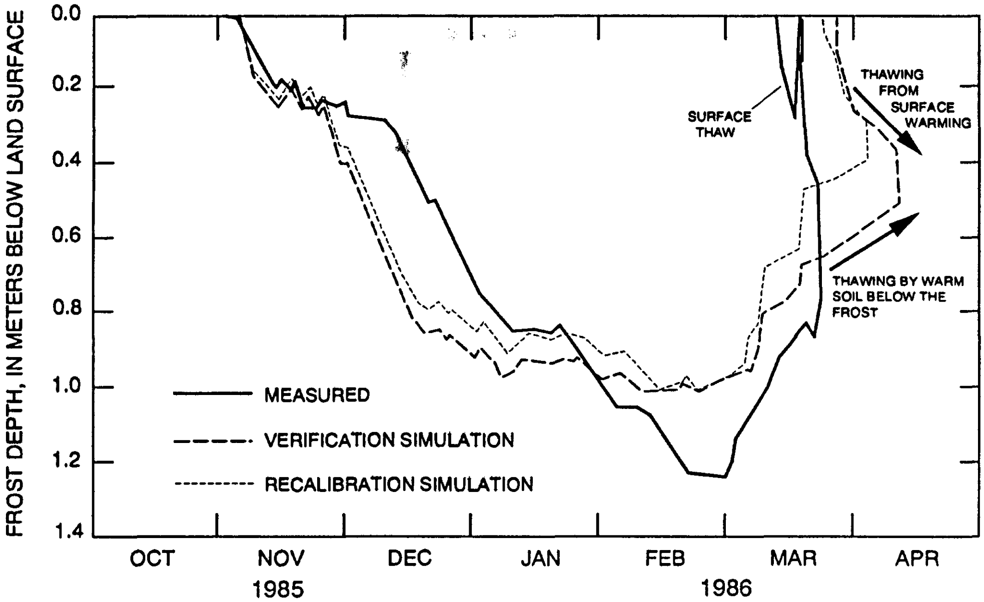

Figure 10.--Measured frost depths and verification and recalibration simulations of frost depths for plot 1, October 1985 through April 1986.

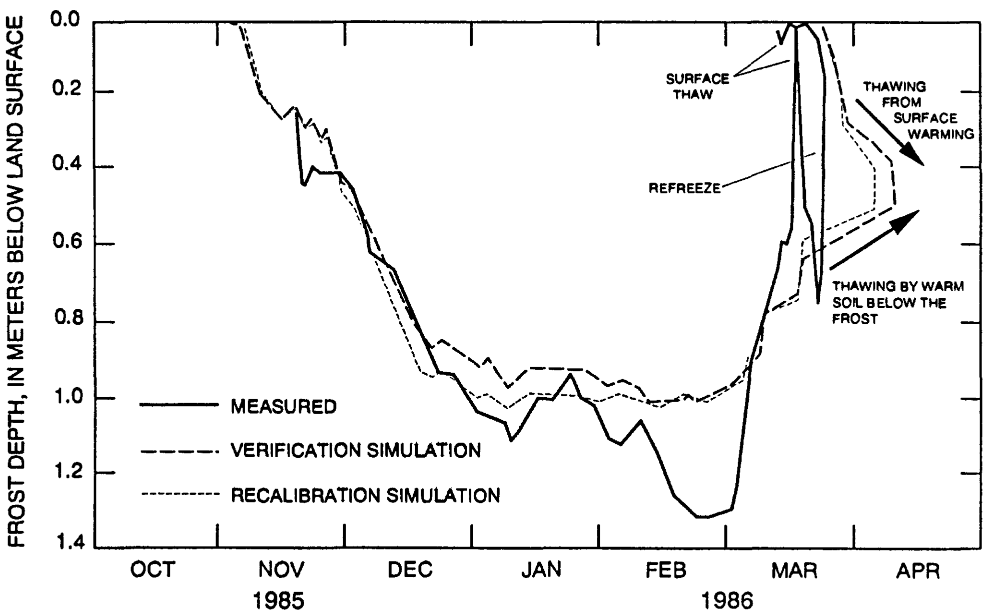

Figure 11.--Measured frost depths and verification and recalibration simulations of frost depths for plot 3, October 1985 through April 1986.

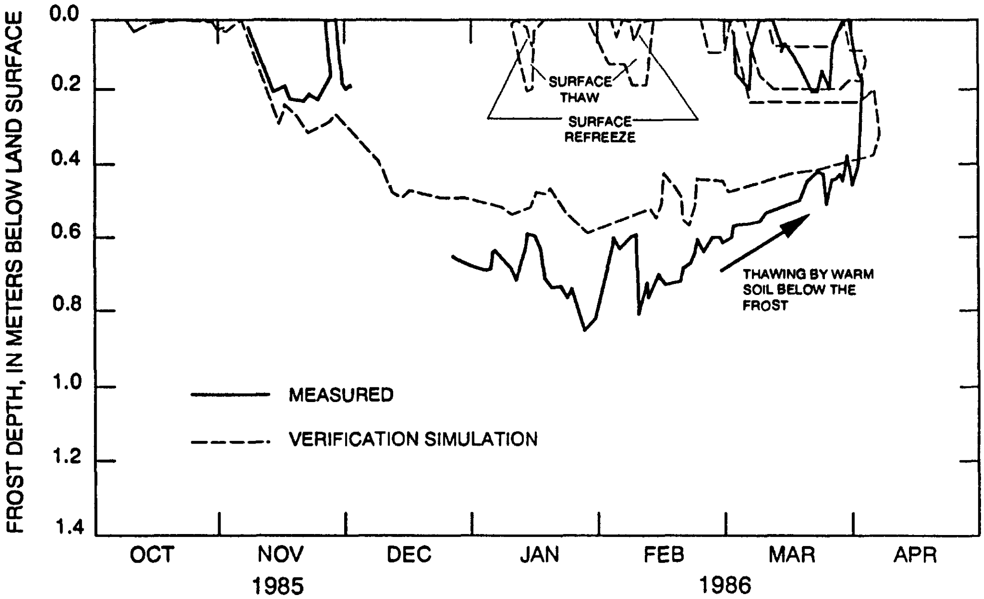

Figure 12.--Measured frost depths and verification simulation of frost depths for plot 1, October 1986 through April 1987.

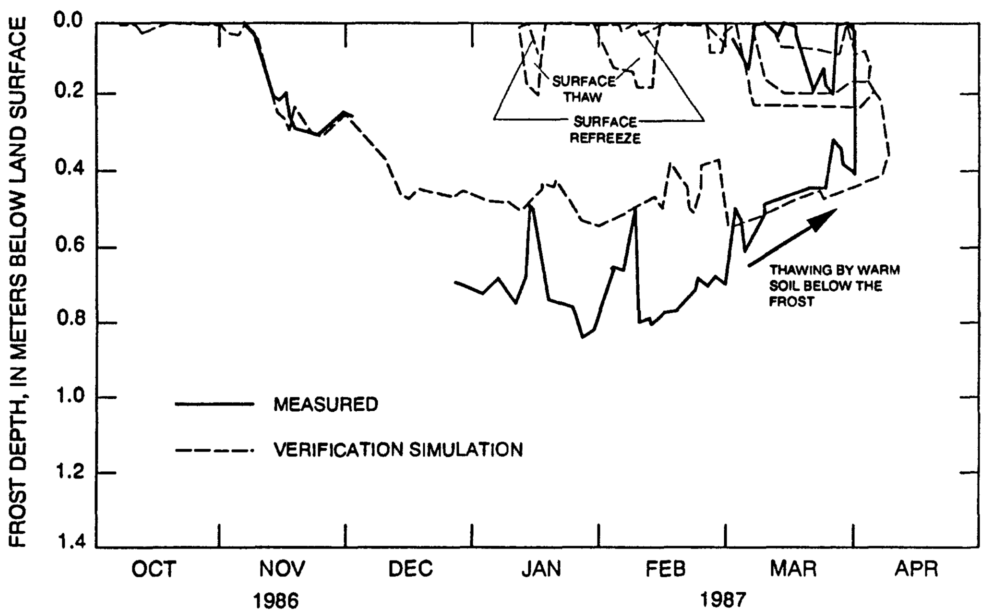

Figure 13.--Measured frost depths and verification simulation of frost depths for plot 2, October 1986 through April 1987.

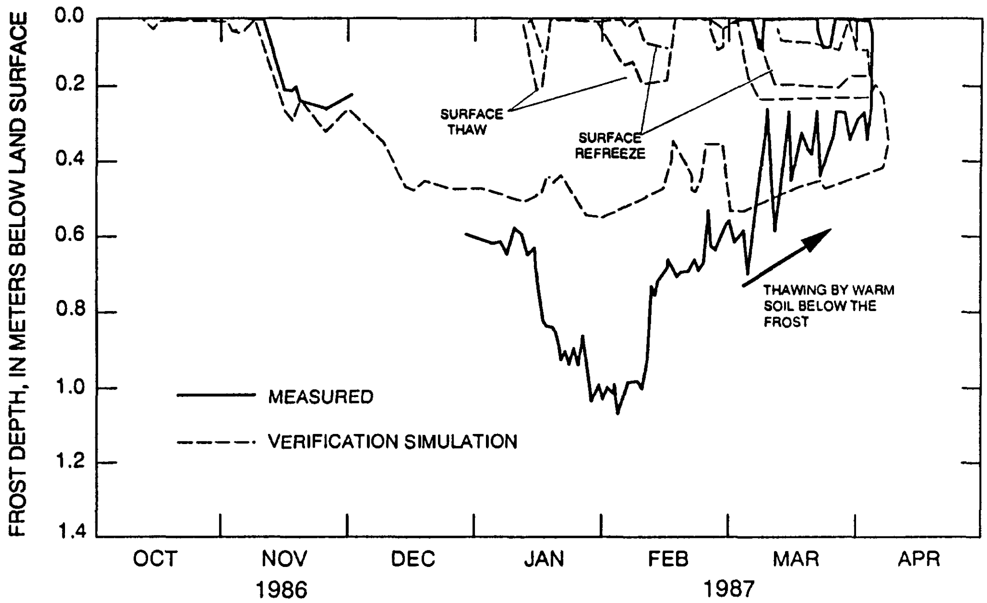

Figure 14.--Measured frost depths and verification simulation of frost depths for plot 3, October 1986 through April 1987.

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]

	Plot 1, 1985-86			Plot 3, 1985-86			Plot 1, 1986-87		Plot 2, 1986-87		Plot 3, 1986-87	
	Measured	Verification	Recalibration	Measured	Verification	Recalibration	Measured	Verification	Measured	Verification	Measured	Verification
Change in soil water, in millimeters	[1]100	[1]45	[1]102	[2]56	[2]76	[2]80	[3]81	[3]98	[3]83	[3]109	[3]92	[3]103
Ground-water recharge, in millimeters	--	[4]0	[4]0	--	[4]0	[4]0	--	[5]0	--	[5]0	--	[5]0
Runoff, in millimeters	14.2	16.5	0	9.0	3.3	0	5.8	.3	3.0	0	6.5	0
Maximum frost depth, in meters	1.24	1.00	1.00	1.31	1.00	1.02	.85	.59	.87	.56	1.06	.55
Date of final thaw	[6]3/25/86	4/12/86	4/04/86	[6]3/26/86	4/11/86	4/06/86	[6]4/04/87	4/08/87	[6]4/04/87	4/09/87	[6]4/04/87	4/09/87

[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.
[5]Recharge from October 1, 1986, through April 10, 1987.
[6]The mean date of final thaw of plot.

Table 6.--Model parameter values for original calibration and recalibration

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

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°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 then if the definition is soil with temperatures less than 0°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°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.

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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

$$q = K(dT/dX) \tag{19}$$

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 I_f/X. I_f is a frost index and commonly is referred to as degree-day. I_f is summed over a number of days and is defined as

$$I_f = \sum (T_b - T_d) \tag{20}$$

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, I_f, will be positive during freezing. Substituting I_f/X into equation 19 gives

$$q = 86{,}400 K I_f / X \tag{21}$$

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

$$dq = 86{,}400 K I_f / X \; dt \tag{22}$$

or for dt equals 1 day

$$Q = 86{,}400 K I_f / X \tag{23}$$

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

$$Q = XL + XCT_a \tag{24}$$

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 $CI_f/(2t)$ where t is the duration of the freezing period in days. Adding this term to equation 24 gives

$$Q = XL+XCT_a+XCI_f/(2t). \qquad (25)$$

Setting equation 25 to 23 and solving for X gives

$$X_f = [(86{,}400K_fI_f)/(L+C(T_a+I_f/(2t)))]^{0.5} \qquad (26)$$

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

$$Q = 86{,}400K_u(T_a/(X_a-X_f)) \qquad (27)$$

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

$$Q = LX_r \qquad (28)$$

where X_r is the depth that the frost is reduced, in centimeters. Setting equation 27 to equation 28 and solving for X_r gives

$$X_r = 86{,}400K_u(T_a/(X_a-X_f))/L. \qquad (29)$$

Supplement 2.--<u>Computer code for subroutine FRZ</u>

```
C *****************************************************************************
C ****                      Definitions of the variables that are used
C ****                        in FRZ are listed below.
C *****************************************************************************
C **** ACZONE               Distance between the depth of 0 degree Celsius
C ****                        isotherm of the soil and the depth of stable
C ****                        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
C ****                        (grams per cubic centimeter).
C **** DEPTHLEFT            Depth of soil profile that is not frozen.  Used
C ****                        in computing thawing from below (inches).
C **** DEPTHREDUC_BELOW     Reduction in frost depth due to heating from
C ****                        below (centimeters).
C **** DEPTH_STABLE_TEMPS   Depth of stable soil temperatures.  The point in
C ****                        the ground at which daily and seasonal tempera-
C ****                        tures cease to cause measureable change (inches).
C **** DEPTH2               Temporary value of depth of frost or thaw
C ****                        (centimeters).
C **** DIFF_DEPTH           Fractional part of an interval to be frozen or
C ****                        thawed (centimeters).
C **** FREEZEFLAG           Flag which indicates that some frost has
C ****                        occurred:
C ****                        0:  Off--no frost exists in soil profile,
C ****                        1:  On--frost exists in soil profile.
C **** FREEZESUM            Current freezing index--cumulative degree days
C ****                        for mean air temperatures below 0 degree Celsius.
C **** FREEZESUMARRAY       Array of freezing index for successive freezing
C ****                        cycles.
C **** FROST                Array of frost penetration depths for successive
C ****                        freezing cycles--soil only (inches).
C **** FROZENSOLIDFLAG      Flag which indicates that the watershed has been
C ****                        frozen imperviously:
C ****                        0:  Not frozen imperviously,
C ****                        1:  Frozen imperviously.
C **** FRZ_THAW_FLAG        Counter used to check on freezing following a day
C ****                        of thawing.
C **** HC                   Computational term used in computing heat
C ****                        capacity of the profile.
C **** H_C_SOIL             Array of volumetric heat capacity of soil profile
C ****                        for successive freezing cycles (calories per
C ****                        cubic centimeter per degree Celsius).
```

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C **** HEAT_CAP_COMPOSITE    Volumetric heat capacity of partial soil profile
C ****                         (calories per cubic centimeter per degree
C ****                         Celsius).
C **** HEAT_CAP_ICE          Heat capacity of ice (calories per cubic
C ****                         centimeter per degree Celsius).
C **** HEAT_CAP_LITTER       Heat capacity of litter (calories per cubic
C ****                         centimeter per degree Celsius).
C **** HEAT_CAP_PROFILE      Volumetric heat capacity of the profile--snow,
C ****                         litter, and soil--undergoing freezing or thawing
C ****                         (calories per cubic centimeter per degree
C ****                         Celsius).
C **** HEAT_CAP_SNOW         Heat capacity of snow (calories per cubic
C ****                         centimeter per degree Celsius).
C **** HEAT_CAP_SOIL         Heat capacity of dry soil (calories per cubic
C ****                         centimeter per degree Celsius).
C **** HEAT_CAP_SOIL_SUM     Volumetric heat capacity of soil and water in the
C ****                         profile (calories per cubic centimeter per
C ****                         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
C ****                         soil--undergoing freezing or thawing (calories
C ****                         per cubic centimeter).
C **** LAT_HT_LITTER         Latent heat of the litter (calories per cubic
C ****                         centimeter).
C **** LAT_HT_SOIL           Latent heat of the soil profile undergoing freez-
C ****                         ing or thawing (calories per cubic centimeter).
C **** LAT_HT_UNIT_CHG       Latent heat of the soil profile below frost
C ****                         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
C ****                         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
C ****                         frost penetration equation.
C **** MIN_INFILTR           Minimum infiltration rate when the soil is near
C ****                         field capacity and is under frozen conditions
C ****                         (inches per hour).
C **** MOIST                 Soil water of layers below frost penetration
C ****                         (decimal fraction, volume).
C **** MOIST_LITTER          Water content of the litter layer (inches).
C **** MOS                   Water content of a soil layer (decimal fraction,
C ****                         volume).
C **** MOS_UNDFROZE          Water content of the soil below frost penetration
C ****                         (inches).
C **** NET_PRECIP            Daily precipitation (inches).
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C **** NEW_SNOW                Daily precipitation in the form of snow (inches).
C **** NEW_SNOW_DENSITY        Initial density of new-fallen snow (decimal
C ****                           percent).
C **** NUM_LAYERS              Number of soil layers.
C **** ORGANIC_MATTER          Organic material of the top soil layer (decimal
C ****                           fraction).
C **** ORGANIC_MATTER1         Threshold for organic material below which
C ****                           puddling of the soil is likely to occur
C ****                           (decimal fraction).
C **** ORGANIC_MATTER2         Threshold for organic material above which
C ****                           puddling of the soil is unlikely to occur
C ****                           (decimal fraction).
C **** PEN_CTR                 Counter to allow penetration to go centimeter by
C ****                           centimeter through soil layers.
C **** PENDEPTHARRAY           Array of frost penetration depths for successive
C ****                           freezing cycles and includes snow and litter
C ****                           depths (inches).
C **** PENETRATI_DENOM         Computational term involving the denominator of
C ****                           the frost penetration equation.
C **** PENETRATION             Current depth of frost penetration (inches).
C **** PENETRATIONCODE         The frost penetration code for the top soil
C ****                           layer:
C ****                           0:  No frost in the top layer,
C ****                           1:  Frost does exist in the top layer,
C ****                           9999:  Error--something is wrong.
C **** PENETRATION_MAX_SOIL    Maximum frost penetration into the soil.  Does
C ****                           not include penetration through snow or litter
C ****                           (inches).
C **** PENETRATION_NUMTR       Computational term involving the numerator of the
C ****                           frost penetration equation.
C **** PEN_S                   Computational term used in the frost penetration
C ****                           equation.
C **** PERC_DEPTH              Depth of percolation of excess water to lower
C ****                           layers that might occur on a day when the mean
C ****                           temperature is above freezing and the minimum
C ****                           is below freezing (inches).
C **** POROSITY_LOWER          Porosity of soil layers below frost penetration
C ****                           (decimal fraction).
C **** POTSATURATEDFLAG        Flag which, when set to 1, allows the surface
C ****                           soil layer to collect more water than the normal
C ****                           field capacity and increases the likelihood that
C ****                           concrete frost will form if it has not already.
C **** PROFILE_MOIST_POT       Maximum available water-holding capacity of a
C ****                           soil profile:  Sum of the variables
C ****                           "LAYER_MOIST_POT" (inches).
C **** RATIO_TC_AIR1           Ratio of the thermal conductivities of mineral
C ****                           soil to air.
C **** RATIO_TC_AIR2           Ratio of the thermal conductivities of mineral
C ****                           soil to air.
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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
C ****                          direct evaporation (inches).
C **** SUR_STORE_OVER_WILT    Soil water in the surface layers subject to
C ****                          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).
```

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C **** THAW_FACTOR            Factor used in computing heat capacity during
C ****                          thaw.
C **** THAWFROSTCODE          Code indicating type of frost in the soil:
C ****                          1:  Generally a quick freeze--granular frost
C ****                              expected,
C ****                          2:  Very moist ground--needle ice and possible
C ****                              heaving expected,
C ****                          3:  Concrete frost expected with impervious soil,
C ****                          4:  Snow is melting and some thawing of soil
C ****                              from below is expected,
C ****                          5:  Some thawing has taken place but the soil
C ****                              is still partially frozen,
C ****                          6:  Soil is free of frost,
C ****                          7:  Soil is freezing but conditions make the
C ****                              type of frost indeterminant,
C ****                          8:  Frost did not penetrate the litter,
C ****                          9:  Error--something is wrong.
C **** THAW_NUMTR             Computational term involving the numerator of the
C ****                          thaw equation.
C **** THAW_SUM               Current thaw index--cumulative degree days for
C ****                          mean air temperatures above 0 degree Celsius.
C **** THAWSUMARRAY           Array of thaw indexes for successive thawing
C ****                          cycles (inches).
C **** THERMAL_RESIST_LITTER Thermal resistance of litter (centimeters seconds
C ****                          degrees Celsius per calorie).
C **** THERMAL_RESIST_SNOW   Thermal resistance of snow (centimeters seconds
C ****                          degrees Celsius per calorie).
C **** THERMAL_RESIST_SOIL   Thermal resistance of soil (centimeters seconds
C ****                          degrees Celsius per calorie).
C **** TOTALDEPTH             Computational term used to determine the depth of
C ****                          frost or thaw (centimeters).
C **** T_R_SOIL               Array of thermal resistance of the soil for
C ****                          successive freezing cycles (centimeters seconds
C ****                          degrees Celsius per calorie).
C **** WATER_POT              Water available for runoff, infiltration, or
C ****                          evaporation (inches).
C **** WEIGHTED_POROS         Porosity of soil layer weighted by the thickness
C ****                          of each layer (decimal fraction).
C **** YESTERDAY              Yesterday used for testing whether days of thaw
C ****                          are consecutive.
C **** YEST_MEAN_AIR_TEMP     Yesterday's mean air temperature (degrees
C ****                          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).
C ******************************************************************************
```

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

```
      SUBROUTINE FRZ(IRU, AVAIL_WATER, DAILY_MAX_TEMP, LAYER_MOIST,
     *        PROFILE_MOIST_POT, SUR_STORE_OVER_WILT,
     *        SURLAYER_MOIST_POT, JULIAN_DATE, NUM_LAYERS,
     *        POTSATURATEDFLAG, ADJUST_COEF, MEAN_ANN_AIR_TEMP,
     *        DAILY_MIN_TEMP, DEPTH_STABLE_TEMPS, FREEZESUM,
     *        FREEZESUMARRAY, H_*_SOIL, HEAT_CAP_LITTER,
     *        HEAT_CAP_SNOW, INCR_SNOW_DEPTH, L_H,
     *        LAYERDEPTH, LAYERPOROSITY, LITTERDEPTH,
     *        MIN_INFILTR, MOIST_LITTER, NET_PRECIP, NEW_SNOW,
     *        ORGANIC_MATTER1,
     *        ORGANIC_MATTER2, ORGANIC_MATTER, PENDEPTHARRAY,
     *        PENETRATION, PENETRATION_MAX_SOIL, SNOW, SNOW_DENSITY,
     *        NEW_SNOW_DENSITY, SNOWDEPTH, T_R_SOIL, TC_WATER, THAW_SUM,
     *        THAWDEPTH, THAWDEPTHARRAY, THAWSUMARRAY,
     *        YEST_MEAN_AIR_TEMP, DAYS_FREEZE,
     *        DAYS_THAW_PERIOD, FREEZEFLAG,
     *        FROZENSOLIDFLAG, FRZ_THAW_FLAG, P_MAX,
     *        PENETRATIONCODE, T_MAX, TEMPORARY,
     *        THAWFROSTCODE, WATER_POT, YEST_SNOW_DEPTH, YEST_TYPE_FROST,
     *        YEST_WATER_POT, YESTERDAY, TC)

$INSERT ALL.COM

C ***************************************************************************
C ****             ALL.COM is a common block defined in PRMS.  For a
C ****               listing of the variables used in the common block
C ****               and the subroutines that use the common block, see
C ****               the PRMS user manual.
C ***************************************************************************

      REAL
     * ACZONE,
     * ADJUST_COEF,
     * AVAIL_WATER,
     * DAILY_MAX_TEMP,
     * DAILY_MEAN_TEMP,
     * DAILY_MIN_TEMP,
     * DEPTHLEFT,
     * DEPTHREDUC_BELOW,
     * DEPTH_STABLE_TEMPS,
     * DEPTH2,
     * DIFF_DEPTH,
     * FREEZESUM,
     * FREEZESUMARRAY(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(10,50),
     * LAYER_MOIST(10,50),
     * LAYERPOROSITY(10,50),
     * L_H(10,50),
     * LITTERDEPTH,
     * MEAN_ANN_AIR_TEMP,
     * MEAN_ANN_TEMP_NUMTR,
     * MIN_INFILTR,
     * MOIST,
     * MOIST_LITTER,
     * MOS(10),
     * MOS_UNDFROZE,
     * NET_PRECIP,
     * NEW_SNOW,
     * NEW_SNOW_DENSITY
     * ORGANIC_MATTER,
     * ORGANIC_MATTER1,
     * ORGANIC_MATTER2,
     * PENDEPTHARRAY(10,50),
     * PENETRATI_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(10,50),
```

```
     *  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,
     *  FROZENSOLIDFLAG,
     *  FRZ_THAW_FLAG,
     *  I,
     *  IRU,
     *  J_LEFT,
     *  JULIAN_DATE,
     *  K,
     *  NUM_LAYERS,
     *  PEN_CTR,
     *  PENETRATIONCODE,
     *  P_MAX,
     *  POTSATURATEDFLAG,
     *  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
 LATENTHEAT = 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
 PENETRATI_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
```

```
      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
        SNOWDEPTH_LOSS = YEST_SNOW_DEPTH - SNOWDEPTH
      ELSE
        SNOWDEPTH_LOSS = 0.0
      END IF
      DAILY_MEAN_TEMP = (DAILY_MAX_TEMP + DAILY_MIN_TEMP) * 0.5

C ***************************************************************************
C ****             Compute the soil water for each layer.
C ***************************************************************************

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

C ***************************************************************************
C ****             If frost already exists and mean daily air temperature
C ****               is above freezing, go to # 1300.
C ****
C ****                      >>%%%%%%% ALPHA %%%%%%%>>
C ****
C ***************************************************************************

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

C ***************************************************************************
C ****             If daily mean air temperature is greater than -1.0
C ****               and no frost exists in the soil, go to # 115.
C ****
```

```
C ****                    >>%%%%%%% BETA %%%%%%%>>
C ****
C ****************************************************************************

      IF (DAILY_MEAN_TEMP .GT. -1.0 .AND. PENETRATIONCODE .NE. 1)
     *                                                          GO TO 115

C ****************************************************************************
C ****           If frost already exists and daily mean air temperature
C ****             is below freezing, go to # 45.
C ****
C ****                   >>%%%%%%% GAMMA %%%%%%%>>
C ****
C ****************************************************************************

      IF (FREEZEFLAG .EQ. 1) GO TO 45

C ****************************************************************************
C ****           If no frost exists and daily mean air temperature
C ****             is less than or equal to -1.0, continue and set
C ****             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
      FROZENSOLIDFLAG = 0
      POTSATURATEDFLAG = 0
      THAW_SUM = 0.0
      TOTALDEPTH = 0.0
      YEST_TYPE_FROST = 0

      DO 11 DUMMY2 = 1,50
         DO 10 DUMMY = 1,10
            FREEZESUMARRAY(DUMMY,DUMMY2) = 0.0
   10       CONTINUE
   11    CONTINUE

C ****************************************************************************
C ****           Just came from initializing values (frost does not
C ****             exist and daily mean air temperature is below
```

```
C ****                freezing) or came from main branch (frost already
C ****                exists and daily mean air temperature is below
C ****                freezing).
C ****              Compute the frost penetration parameters.
C ****              Check if snow loss is greater than 0.0.
C ****
C ****      % GAMMA % GAMMA % GAMMA % GAMMA % GAMMA % GAMMA % GAMMA %
C ****
C ***************************************************************************

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

C ***************************************************************************
C ****              Remember old thaw depth.
C ***************************************************************************

        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)))

C ***************************************************************************
C ****              If snow exists, go to # 69.
C ***************************************************************************

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

C ***************************************************************************
C ****              If litter exists, go to # 120.
C ***************************************************************************
```

```
        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
```

```
C ****************************************************************************
C ****              There are 8.64E4 seconds per day.
C ****              1.0 centimeter is equal to 0.394 inch.
C ****              TOTALDEPTH is in centimeters.
C ****              PENETRATION is in inches.
C ****************************************************************************

      PENETRATION_NUMTR = TC_SUM * FREEZESUM * 8.64E4
      PENETRATI_DENOM = LATENTHEAT + HEAT_CAP_PROFILE *
     *                                      MEAN_ANN_TEMP_NUMTR

C ****************************************************************************
C ****              Compute frost penetration in inches.
C ****************************************************************************

      PENETRATION = 0.394 * ADJUST_COEF *
     *              SQRT(PENETRATION_NUMTR / PENETRATI_DENOM)

        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)
            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
        END IF

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

C ****************************************************************************
C ****              Go back to main gamma loop.
C ****              Recompute TOTALDEPTH to compensate for the fraction
C ****                of a centimeter and recompute the frost penetration.
C ****************************************************************************

        IF (PENETRATION .LE. TOTALDEPTH * 0.394) THEN
          IF (PENETRATION .LT. DEPTH2 * 0.394) THEN
            TOTALDEPTH = DEPTH2 + 0.25
            DIFF_DEPTH = 0.75
          ELSE
              DIFF_DEPTH = TOTALDEPTH - PENETRATION * 2.54
              TOTALDEPTH = TOTALDEPTH - DIFF_DEPTH
          END IF
        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_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
      PENETRATI_DENOM = LATENTHEAT + HEAT_CAP_PROFILE *
     *                                   MEAN_ANN_TEMP_NUMTR
      PENETRATION = 0.394 * ADJUST_COEF *
     *              SQRT(PENETRATION_NUMTR / PENETRATI_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 = LAYERPOROSITY(NUM_LAYER,IRU) * (DEPTH -
     *                   PENETRATION_MAX_SOIL)
        DEPTHLEFT = DEPTH - PENETRATION_MAX_SOIL
      ELSE
        DO 62 K = J_LEFT,NUM_LAYERS
```

```
         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
      PENDEPTHARRAY(1,IRU) = PENDEPTHARRAY(1,IRU)
     *                                  - (DEPTHREDUC_BELOW * 0.394)
      PEN_S = (PENDEPTHARRAY(1,IRU) * 2.54) ** 2
      HC = (H_C_SOIL(1,IRU) + SNOWDEPTH * SNOW_DENSITY * 0.5 * 2.54
     *                     + HEAT_CAP_LITTER) / (PENDEPTHARRAY(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 = PENDEPTHARRAY(1,IRU)

         GO TO 80

C ****************************************************************************
C ****           Snow exists!
C ****           Compute frost penetration equation for the snow cover.
C ****************************************************************************
```

```
 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 .AND. SNOWDEPTH .GT. 4. .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 ****              See Anderson, E. A., 1976, page 31.
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
    PENETRATI_DENOM = HEAT_CAP_SNOW * MEAN_ANN_TEMP_NUMTR
    PENETRATION = 0.394 * ADJUST_COEF *
   *                SQRT(PENETRATION_NUMTR / PENETRATI_DENOM)
      IF (PENETRATION .LT. SNOWDEPTH) THEN
        IF (PENDEPTHARRAY(P_MAX,IRU) .GT. 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
```

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

          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 ****************************************************************************
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
      PENETRATI_DENOM = LATENTHEAT + HEAT_CAP_PROFILE *
     *                                      MEAN_ANN_TEMP_NUMTR

      PENETRATION = 0.394 * ADJUST_COEF *
     *              SQRT(PENETRATION_NUMTR / PENETRATI_DENOM)
```

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

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

     FRZ_THAW_FLAG = FRZ_THAW_FLAG - 1
     FROZENSOLIDFLAG = 0
     THAWFROSTCODE = 7
     FREEZEFLAG = 1
     FREEZESUMARRAY(P_MAX,IRU) = FREEZESUM
     PENDEPTHARRAY(P_MAX,IRU) = PENETRATION

 129  IF(PENDEPTHARRAY(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
C ****                      frost expected,
C ****                  (2) Very moist soil -- needle ice and
C ****                      possible heaving expected,
C ****                  (3) Concrete frost expected,
C ****                  (4) Snow is melting and some thawing of
C ****                      soil from below is expected,
C ****                  (5) Some thawing has taken place but the
C ****                      soil is still partly frozen,
C ****                  (6) Soil is free of frost,
C ****                  (7) Soil is freezing but conditions
C ****                      make the type of frost indeterminate,
C ****                  (8) Frost did not penetrate the litter.
C *****************************************************************************

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

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

      IF (YEST_WATER_POT .GT. 0.0 .OR. SUR_STORE_OVER_WILT .GT.
     *                                 SURLAYER_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
```

```
  84   IF (PENETRATION_MAX_SOIL .LT. 1.0 .AND. THAWFROSTCODE .NE. 3)
     *                                                    GO TO 85
     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
       IF (FRZ_THAW_FLAG .NE. 1) GO TO 86
     THAWFROSTCODE = 2
         GO TO 110
```

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

  105 THAWFROSTCODE = 1
      PENETRATION_MAX_SOIL = PENDEPTHARRAY(1,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 ****
C ****         % BETA % BETA % BETA % BETA % BETA % BETA % BETA % BETA %
C ****
C ****************************************************************************

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

      DO  103  I = 1,10
        FROST(I,IRU) = PENDEPTHARRY(I,IRU) - SNOWDEPTH - LITTERDEPTH
  103   IF (FROST(I,IRU) .LT. 0.0) FROST(I,IRU) = 0.0

      PENETRATION_MAX_SOIL = FROST(1,IRU)
```

```
      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) - SNOWDEPTH_LOSS
     *                         + (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 = DEPTH - PENETRATION_MAX_SOIL
      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)
```

```
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
    *                                        * 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
     PENDEPTHARRAY(1,IRU) = PENDEPTHARRAY(1,IRU)
    *                                   - (DEPTHREDUC_BELOW * 0.394)
     PENETRATION_MAX_SOIL = (PENDEPTHARRAY(1,IRU) - SNOWDEPTH
    *                                              - LITTERDEPTH)

     IF (SNOW_DEPTH .EQ. 0.0) THEN
       TC_SUM = PENDEPTHARRAY(1,IRU) * 2.54 /
    *                 (LITTERDEPTH * 2.54 / TC_LITTER + T_R_SOIL(1,IRU))
     ELSE
       TC_SUM = PENDEPTHARRAY(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 = (PENDEPTHARRAY(1,IRU) * 2.54) ** 2
     HC = (H_C_SOIL(1,IRU) + SNOWDEPTH * SNOW_DENSITY * 0.4 * 2.54
    *                      + HEAT_CAP_LITTER) /
    *                        (PENDEPTHARRAY(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)))
```

```
      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

C ****************************************************************************
C ****             No soil was thawed from above because snow still
C ****               exists.
C ****************************************************************************

          THAWFROSTCODE = 4
          GO TO 115
        END IF
      END IF

C ****************************************************************************
C ****             No snow exists!
C ****             If daily mean air temperature is greater than 0.0
C ****               degree Celsius then compute thaw penetration
C ****               equation.
C ****************************************************************************

    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))
```

```
C ****************************************************************************
C ****              In the above equation, 1/2 was changed to 1/4
C ****                to avoid a negative square root later on.
C ****              The actual constant should be checked.
C ****              Is "THAW_FACTOR" computed right?
C ****              Should any adjustments be made?
C ****************************************************************************

        ELSE
          THAW_FACTOR = 0.0
        END IF

C ****************************************************************************
C ****              If litter exists, compute thaw equation for the litter.
C ****************************************************************************

        IF (LITTERDEPTH .GT. 0.0) THEN
          LAT_HT_LITTER = MOIST_LITTER * 80.0 * 2.54
          HEAT_CAP_LITTER = 0.6 * LITTERDEPTH * 2.54
     *                              + MOIST_LITTER * 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

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

      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
```

```
        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)

      THAW_NUMTR = 8.64E4 * TC_SUM * THAW_SUM

        IF (THAW_NUMTR .LE. 0.0) GO TO 158

      THAW_DENOM = LATENTHEAT + HEAT_CAP_PROFILE * THAW_FACTOR
      THAWDEPTH = 0.394 * ADJUST_COEF * SQRT(THAW_NUMTR / THAW_DENOM)

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

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 ****             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(' *****----> 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
```

```
      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 ******************************************************************************

      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

    POTSATURATEDFLAG = 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 ******************************************************************************
```

```
160 DAYS_FREEZE(P_MAX, IRU) = 0
    PENETRATIONCODE = 0
    HEAT_CAP_SNOW = 0.0
    THERMAL_RESIST_SNOW = 0.0
    THAWFROSTCODE = 6
    POTSATURATEDFLAG = 0
    PENDEPTHARRAY(1,IRU) = 0.0
    THAWDEPTHARRAY(1,IRU) = 0.0
    MOIST_LITTER = 0.0
    THAWDEPTH = 0.0
    FREEZEFLAG = 0
    FROZENSOLIDFLAG = 0
    P_MAX = 1
    T_MAX = 0

        GO TO 115

999 RETURN
    END
```

Supplement 3.--Computer code for subroutine SMP

```
C ****************************************************************************
C ****                        Definitions of the variables that are used in
C ****                          SMP are listed below.
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
C ****                          losses due to evapotranspiration.
C **** EVAP_LAYERS            Number of soil layers subject to direct
C ****                          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
C ****                          for the profile on the first day is inputed.
C ****                          Flag that is 1 if soil water content for each
C ****                          soil layer for the first day is inputed.
C **** FLAG1                  Flag that stops execution of a certain segment
C ****                          after the first time through.
C **** FLAG2                  Flag that stops execution of a certain segment
C ****                          after the first time through.
C **** FRACTION_ET_LOSS       Fraction of the evaporation loss that would come
C ****                          from a given soil layer.
C **** FRZ_FIELD_CAP_INCR     Change in field capacity due to various conditions
C ****                          (inches).
C **** IRU                    Hydrologic response unit.
C **** JLOOP                  Counter to count number of passes through soil
C ****                          water adjustment procedure.  Used to prevent
C ****                          infinite looping.
C **** JULIAN_DATE            Julian date.
C **** LAYER_DIFF             Difference between the soil water in a layer at
C ****                          "LAYER_MOIST_POT" and currently available
C ****                          "LAYER_MOIST" (inches).
C **** LAYER_MOIST            Daily soil water content of each layer (inches).
C **** LAYER_MOIST_POT        Soil water between field capacity and wilting point
C ****                          for each layer (inches).
C **** MAX_INFILTRATION       Maximum daily snowmelt infiltration capacity of
C ****                          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 **** POTSATURATEDFLAG       Flag which, when set to 1, allows the surface soil
C ****                          layer to collect more water than the normal field
C ****                          capacity and increases the likelihood that
C ****                          concrete frost will form if it has not already.
C **** PROFILE_MOIST_POT      Maximum available water-holding capacity of a soil
C ****                          profile:  Sum of the variables "LAYER_MOIST_POT"
C ****                          (inches).
C **** RATIO_LAYER_DIFF       Difference between ratios of soil water for
C ****                          adjacent soil layers.
```

```
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 **** WATER_LOSS          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,
     * RATIO_MOIST_N,
```

```
     * RATIO_MOIST_NPLUS1,
     * RATIO_MOIST_NPLUS2,
     * RUNOFF,
     * SNOW,
     * SNOWMELT,
     * SOIL_MOIST_COND,
     * SURLAYER_MOIST_POT,
     * SUR_STORE_OVER_WILT,
     * WATER,
     * WATER_ADDED,
     * WATER_LOSS,
     * 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
      WATER_LOSS = 0.0

      IF (FIRSTDAYFLAG .EQ. 0) THEN
        FLAG1 = 0
        FLAG2 = 0
        DO 2 DUMMY = 1,NUM_LAYERS
```

```
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
        GO TO 3
      ELSE
3       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
        GO TO 4
      ELSE
4       FLAG2 = 1
        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)
        END IF

      ELSE IF (POTSATURATEDFLAG .EQ. 0 .AND. 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
      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
         WATER = SNOWMELT
      ELSE
        WATER = NET_PRECIP - NEW_SNOW + SNOWMELT
      END IF

      IF (WATER .LT. EVAPORATION) THEN
        IF (SNOW .GT. 0.0) THEN
          ACTUAL_ET = WATER
          GO TO 90
        ELSE
          GO TO 60
        END IF
      END IF

      IF ((WATER .EQ. 0.0) .OR. (WATER .EQ. EVAPORATION)) THEN
        ACTUAL_ET = 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 - EVAPORTATION - 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_POT(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)
     *                                               + WATER_ADDED
          GO TO 90
        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)
     *                                      / LAYER_MOIST_POT(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)
     *                                        / LAYER_MOIST_POT(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
        GO TO 20
      ELSE
        GO TO 90
      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
```

```
      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 = SURLAYER_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
```

```
      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_ET_LOSS(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

Variable	Type	Description
ACTUAL_ET	Internal	Actual evaportranspiration (inches).
ACZONE	Internal	Distance between the depth of 0 degree Celsius isotherm of the soil and the depth of stable soil temperature (centimeters).
ADJUST_COEF	Input	Freeze and thaw adjustment coefficient.
AVAIL_WATER	Output	Daily available water in the soil profile (inches).
DAILY_MAX_TEMP	Input/output	Daily maximum air temperature (degrees Celsius).
DAILY_MEAN_TEMP	Internal	Daily mean air temperature (degrees Celsius).
DAILY_MIN_TEMP	Input/output	Daily minimum air temperature (degrees Celsius).
DAYS_FREEZE	Internal	Number of days in the current freeze period.
DAYS_THAW_PERIOD	Internal	Number of days in the current thaw period.
DEN	Internal	Computational term used for density of the snowpack (grams per cubic centimeter).
DEPTHLEFT	Internal	Depth of soil profile that is not frozen. Used in computing thawing from below (inches).
DEPTHREDUC_BELOW	Internal	Reduction in frost depth due to heating from below (centimeters).
DEPTH_STABLE_TEMPS	Input	Depth of stable soil temperatures. The point in the ground at which daily and seasonal temperatures cease to cause measurable change (inches).
DEPTH2	Internal	Temporary value of depth of frost or thaw (centimeters).
DIFF_DEPTH	Internal	Fractional part of an interval to be frozen or thawed (centimeters).
ET_LOSS	Internal	Computational term used in computing soil water losses due to evapotranspiration.
EVAP_LAYERS	Input	Number of soil layers subject to direct evaporation.
EVAPORATION	Internal	Effective evaporation (inches).
EXCS_SOIL_MOIST	Output	Water available for ground-water recharge (inches).

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
FIRSTDAYFLAG	Input	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.
FLAG1	Internal	Flag that stops execution of a certain segment after the first time through.
FLAG2	Internal	Flag that stops execution of a certain segment after the first time through.
FRACTION_ET_LOSS	Input	Fraction of the evaporation loss that would come from a given soil layer.
FREEZEFLAG	Input	Flag which indicates that some frost has occurred: 0: Off--no frost exists in soil profile, 1: On--frost exists in soil profile.
FREEZESUM	Internal	Current freezing index--cumulative degree days for mean air temperatures below 0 degree Celsius.
FREEZESUMARRAY	Internal	Array of freezing index for successive freezing cycles.
FROST	Output	Array of frost penetration depths for successive freezing cycles--soil only (inches).
FROZENSOLIDFLAG	Internal	Flag which indicates that the watershed has been frozen imperviously: 0: Not frozen imperviously, 1: Frozen imperviously.
FRZ_FIELD_CAP_INCR	Internal	Change in field capacity due to various conditions (inches).
FRZ_THAW_FLAG	Internal	Counter used to check on freezing following a day of thawing.
HC	Internal	Computational term used in computing heat capacity of the profile.
H_C_SOIL	Internal	Array of volumetric heat capacity of soil profile for successive freezing cycles (calories per cubic centimeter per degree Celsius).

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
HEAT_CAP_COMPOSITE	Internal	Volumetric heat capacity of partial soil profile (calories per cubic centimeter per degree Celsius).
HEAT_CAP_ICE	Internal	Heat capacity of ice (calories per cubic centimeter per degree Celsius).
HEAT_CAP_LITTER	Internal	Heat capacity of litter (calories per cubic centimeter per degree Celsius).
HEAT_CAP_PROFILE	Internal	Volumetric heat capacity of the profile--snow, litter, and soil--undergoing freezing or thawing (calories per cubic centimeter per degree Celsius).
HEAT_CAP_SNOW	Internal	Heat capacity of snow (calories per cubic centimeter per degree Celsius).
HEAT_CAP_SOIL	Internal	Heat capacity of dry soil (calories per cubic centimeter per degree Celsius).
HEAT_CAP_SOIL_SUM	Internal	Volumetric heat capacity of soil and water in the profile (calories per cubic centimeter per degree Celsius).
INCR_SNOW_DEPTH	Internal	Increase in snow depth (inches).
IRU	Input	Hydrologic response unit.
JLOOP	Internal	Counter to count number of passes through soil water adjustment procedure. Used to prevent infinite looping.
JULIAN_DATE	Input	Julian date.
LATENTHEAT	Internal	Composite latent heat of the profile--litter and soil--undergoing freezing or thawing (calories per cubic centimeter).
LAT_HT_LITTER	Internal	Latent heat of the litter (calories per cubic centimeter).
LAT_HT_SOIL	Internal	Latent heat of the soil profile undergoing freezing or thawing (calories per cubic centimeter).
LAT_HT_UNIT_CHG	Internal	Latent heat of the soil profile below frost penetration (calories per cubic centimeter).
LAYERDEPTH	Input	Thickness of each soil layer (inches).

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
LAYER_DIFF	Internal	Difference between the soil water in a layer at "LAYER_MOIST_POT" and currently available "LAYER_MOIST" (inches).
LAYER_MOIST	Input	Daily soil water content of each layer (inches).
LAYER_MOIST_POT	Input	Soil water between field capacity and wilting point for each layer (inches).
LAYERPOROSITY	Input	Porosity of each layer (decimal fraction).
L_H	Internal	Array of latent heat for successive freezing cycles (calories per cubic centimeter).
LITTERDEPTH	Input	Depth of the litter layer (inches).
MAX_INFILTRATION	Internal	Maximum daily snowmelt infiltration capacity of soil profile (inches).
MEAN_ANN_AIR_TEMP	Input	Mean annual air temperature (degrees Celsius).
MEAN_ANN_TEMP_NUMTR	Internal	Computational term involving the numerator of the frost penetration equation.
MIN_INFILTR	Input	Minimum infiltration rate when the soil is near field capacity and is under frozen conditions (inches per hour).
MOIST	Internal	Soil water of layers below frost penetration (decimal fraction, volume).
MOIST_LITTER	Input	Water content of the litter layer (inches).
MOS	Internal	Water content of a soil layer (decimal fraction, volume).
MOS_UNDFROZE	Internal	Water content of the soil below frost penetration (inches).
NET_PRECIP	Input	Daily precipitation (inches).
NEW_SNOW	Internal	Daily precipitation in the form of snow (inches).
NEW_SNOW_DENSITY	Internal	Initial density of new-fallen snow (decimal percent).
NUM_LAYERS	Input	Number of soil layers.
ORGANIC_MATTER	Input	Organic material of the top soil layer (decimal fraction).
ORGANIC_MATTER1	Internal	Threshold for organic material below which puddling of the soil is likely to occur (decimal fraction).

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
ORGANIC_MATTER2	Internal	Threshold for organic material above which puddling of the soil is unlikely to occur (decimal fraction).
PEN_CTR	Internal	Counter to allow penetration to go centimeter by centimeter through soil layers.
PENDEPTHARRAY	Internal	Array of frost penetration depths for successive freezing cycles and includes snow and litter depths (inches).
PENETRATI_DENOM	Internal	Computational term involving the denominator of the frost penetration equation.
PENETRATION	Internal	Current depth of frost penetration (inches).
PENETRATIONCODE	Internal	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.
PENETRATION_MAX_SOIL	Output	Maximum frost penetration into the soil. Does not include penetration through snow or litter (inches).
PENETRATION_NUMTR	Internal	Computational term involving the numerator of the frost penetration equation.
PEN_S	Internal	Computational term used in the frost penetration equation.
PERC_DEPTH	Internal	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_LOWER	Internal	Porosity of soil layers below frost penetration (decimal fraction).
POTSATURATEDFLAG	Internal	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.

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
PROFILE_MOIST_POT	Input	Maximum available water-holding capacity of a soil profile: Sum of the variables "LAYER_MOIST_POT" (inches).
RATIO_LAYER_DIFF	Internal	Difference between ratios of soil water for adjacent soil layers.
RATIO_MOIST_N	Internal	Ratio of soil water to the potential maximum soil water in layer N.
RATIO_MOIST_NPLUS1	Internal	Ratio of soil water to the potential maximum soil water in layer N+1.
RATIO_MOIST_NPLUS2	Internal	Ratio of soil water to the potential maximum soil water in layer N+2.
RATIO_TC_AIR1	Internal	Ratio of the thermal conductivities of mineral soil to air.
RATIO_TC_AIR2	Internal	Ratio of the thermal conductivities of mineral soil to air.
RATIO_TC_ICE	Internal	Ratio of the thermal conductivities of mineral soil to ice.
RATIO_TC_WAT_SOIL	Internal	Ratio of the thermal conductivities of water to soil.
RUNOFF	Output	Amount of water that runs off the profile (inches).
SNOW	Internal	Water equivalent of snowpack (inches).
SNOW_DENSITY	Internal	Density of the snowpack (grams per cubic centimeter).
SNOWDEPTH	Internal	Depth of snowpack (inches).
SNOWDEPTH_LOSS	Internal	Loss in depth of snowpack (inches).
SNOWMELT	Output	Daily snowmelt (inches).
SOIL_MOIST_COND	Internal	Computational term used in determining "AVAIL_WATER" (inches).
SURLAYER_MOIST_POT	Internal	Soil water between field capacity and wilting point for the surface layer that is subject to direct evaporation (inches).
SUR_STORE_OVER_WILT	Input	Soil water in the surface layers subject to direct evaporation (inches).
TC	Internal	Array of thermal conductivity of the profile for successive freezing cycles (calories per centimeter per second per degree Celsius).
TC_AIR	Internal	Thermal conductivity of air (calories per centimeter per second per degree Celsius).

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
TC_COMPOSITE	Internal	Composite thermal conductivity of the soil (calories per centimeter per second per degree Celsius).
TC_DENOM	Internal	Computational term used in computing "TC_COMPOSITE."
TC_DRYSOIL	Internal	Thermal conductivity of dry soil (calories per centimeter per second per degree Celsius).
TC_ICE	Internal	Thermal conductivity of ice (calories per centimeter per second per degree Celsius).
TC_LITTER	Internal	Thermal conductivity of litter (calories per centimeter per second per degree Celsius).
TC_NUM	Internal	Computational term used in computing "TC_COMPOSITE."
TC_SUM	Internal	Current thermal conductivity of the profile (calories per centimeter per second per degree Celsius).
TC_UNDFROZE_COMPOSITE	Internal	Thermal conductivity of soil below frost penetration (calories per centimeter per second per degree Celisus).
TC_UNDFROZE_DENOM	Internal	Computational term used in computing "TC_UNDFROZE_COMPOSITE."
TC_UNDFROZE_NUM	Internal	Computational term used in computing "TC_UNDFROZE_COMPOSITE."
TC_WATER	Internal	Thermal conductivity of water (calories per centimeter per second per degree Celsius).
THAW_DENOM	Internal	Computational term involving the denominator of the thaw equation.
THAWDEPTH	Internal	Current depth of thaw (inches).
THAWDEPTHARRAY	Output	Array of depths for successive thawing cycles (inches).
THAW_FACTOR	Internal	Factor used in computing heat capacity during thaw.
THAWFROSTCODE	Internal	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,

Variable	Type	Description
		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.
THAW_NUMTR	Internal	Computational term involving the numerator of the thaw equation.
THAW_SUM	Internal	Current thaw index--cumulative degree days for mean air temperatures above 0 degree Celsius.
THAWSUMARRAY	Internal	Array of thaw indexes for successive thawing cycles (inches).
THERMAL_RESIST_LITTER	Internal	Thermal resistance of litter (centimeters seconds degrees Celsius per calorie).
THERMAL_RESIST_SNOW	Internal	Thermal resistance of snow (centimeters seconds degrees Celsius per calorie).
THERMAL_RESIST_SOIL	Internal	Thermal resistance of soil (centimeters seconds degrees Celsius per calorie).
TOTALDEPTH	Internal	Computational term used to determine the depth of frost or thaw (centimeters).
TRANSPIRFLAG	Internal	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.

Supplement 4.--Definition of subroutine variables--Continued

Variable	Type	Description
T_R_SOIL	Internal	Array of thermal resistance of the soil for successive freezing cycles (centimeters seconds degrees Celsius per calorie).
WATER	Internal	Water available for infiltration (inches).
WATER_ADDED	Internal	Water that is added to a soil layer (inches).
WATER_LOSS	Internal	Water that is lost from a soil layer to evaporation (inches).
WATER_POT	Internal	Water available for runoff, infiltration, or evaporation (inches).
WEIGHTED_POROS	Internal	Porosity of soil layer weighted by the thickness of each layer (decimal fraction).
YESTERDAY	Internal	Yesterday used for testing whether days of thaw are consecutive.
YEST_MEAN_AIR_TEMP	Internal	Yesterday's mean air temperature (degrees Celsius).
YEST_SNOW_DEPTH	Internal	Yesterday's depth of snowpack (inches).
YEST_TYPE_FROST	Internal	Yesterday's frost type.
YEST_WATER_POT	Internal	Yesterday's "WATER_POT" (inches).

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.

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

Supplement 5.--Additional data required for FRZ and SMP--Continued

Record	Columns	Format	Variables	Definition
5	1-8	'LMOIST'	I.D.	
	10-60	10F5.2	LAYER_MOIST(I)	Water content of each soil layer for I=1, NUM_LAYERS (inches).
6	1-8	'ETLOSS'	I.D.	
	10-60	10F5.2	FRACTION_ET_LOSS(I)	Fraction of the evaporation loss that would come from each layer for I=1, NUM_LAYERS.
7	1-6	'ADJUST'	I.D.	
	10-15	I5	FIRSTDAYFLAG	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.
	16-20	F5.2	ADJUST_COEF	Freeze and thaw adjustment coefficient.

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

```
01SIM/OPT      0    1    0    0    0    0    0         0         2
02SIM/COMP          0    0    1    0
03TITL     RUNOFF SIMULATIONS FOR PLOT 2, 1985-86 WINTER
04INIT1        1    1    1    1    1    0 0.012108
05INIT2     1985   10    1 1986    3   31
06MFS-MFN     10    3
07PRINT-OP     3   10    3    3    1  365    0
08PLOT         0
09DATATYPE     6    1    0    1    1    1    1    0    0    1    0
10PARM     00060     0002000020000300006 5          00045
11STAT     00003     0000100002000060000 1          00006
12STAIDC   D460238098014410                     D460238098014410  D460238098014410
12STAIDC   D460238098014410  D460238098014410
12A           11         12   13   14   15
13STAIDP   D460238098014410
13A           16
14RD 1    HOR            0.0 135.46.04
15RDM      -0.35-0.44 0.96 0.16 0.09 0.07 0.07 0.14 0.09 0.14 0.52-0.48
16RDC      45.6987.63     -63.4-31.1-15.8-14.0-48.0-11.6-23.1-79.563.93
17RAD-COR   1.00 1.00            .85
18CLIM-PR        1310 0.20 0.50    0    0                        6    9
19CTW      0.0150.0150.0020.0100.0100.0100.0100.0100.0100.0050.0150.015 1.00
20PAT        5.0  5.0  5.0  5.0  5.0  5.0  5.0  5.0  5.0  5.0  5.0  5.0
21AJMX       1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
22TLX        0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
23TLN        0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
24EVC        0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
25SNO-VAR     31  105 .715 0.35  .10  .35 0.10  1.0
26CEN        0.0  0.0  0.0  0.0  1.0  2.0  3.0  3.0  2.0  1.0  0.0  0.0
27PKADJ       35
28RES        0.0
29GW         0.0
30KRSP         1
31RESMX-EX   1.0  1.0
32RSEP       1.0
33GSNKE      0.0
34RCB      .0000
35RCF-RCP        1.00      1.00
36RU1    1  10.384    1310    1 0.00 0.00 1.00 0.00 0.00 0.00 410022.24   0.0  0.0
37RU2    1     110.50 3.12 3.60 1.24 0.80 1.00 0.00      0.00 0.00 4.00    1   1   0
38RU3    1  1.012108 1.00 1.00 0.93 700.
```

Supplement 6.--Input data for calibration simulation for plot 2, 1985-86--Continued

Input group 6

```
01PKADJ-WE 1.74
```

Input group 9

```
01FROST     7.41 95.0  0.5    4    2 .009 0.05 .025
42L/DEPTH   12.0 12.0 16.0 30.0
43L/POROS   0.40 0.38 0.36 0.37
44L/POT     1.80 1.80 2.40 4.50
45L/MOIST   0.69 0.55 0.51 1.35
46L/LOSS    1.00 0.00
47ADJUST       1 2.62
```

Supplement 7.--Output for calibration simulation for plot 2

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
3	23	1986	1	5.5	-3.5	22.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	24	1986	1	12.2	1.4	22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	25	1986	1	14.9	0.8	22.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	26	1986	1	8.1	-2.6	21.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	27	1986	1	18.7	-2.2	21.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						8.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	28	1986	1	27.2	2.2	21.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						10.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	29	1986	1	25.6	6.1	20.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						12.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	30	1986	1	18.9	-1.0	20.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
						14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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
3	31	1986	1	17.4	-0.3	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	0.0	0.0	0.0	0.0