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# LONG TERM MODELLING OF PERMAFROST DYNAMICS

Final Technical Report

by

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## ABSTRACT

The PERIMOVE model is capable of simulating moisture and heat transfers within soil profiles. In addition, the simulation of these processes formed the basis for the prediction of the volume changes that moisture redistribution and freezing create within soil profiles and the resulting movement of material and loss of soil strength during freezing and thawing cycles. In order to aid the development and validation of the model a suite of data sources have been identified and assembled. These have enabled model testing at each stage of development. Areas of further work are suggested.

## 1 ORIGINAL OBJECTIVES

### *ORIGINAL OBJECTIVE:*

**To develop a 2-dimensional, physically based model for mass and heat transfer, driving a creep process model for cold regions slopes.**

Harris *et al* (1993) describe some results of a NERC funded project involving a large scale laboratory experiment into frost creep and gelifluction processes. These processes can be identified as distinct where creep describes the downslope movement of material due to gravitational resettlement of soil during thawing as a result of heave occurring during a freeze cycle and gelifluction describes the downslope deformation of a saturated mass of soil overlying a frozen soil layer during the thaw cycle. Figure 1 shows their results for four different soil types and the relative importance of creep and gelifluction processes in controlling downslope movement for the different soil types is apparent. Because of the significance of gelifluction in producing downslope movement of material it was decided that the original objective should be altered to include gelifluction processes in addition to creep processes.

The term **solifluction** has replaced the term creep in the original objective as the former term embraces both frost creep and gelifluction movements as defined in Harris (1987). Collaboration of this project with that of Harris has taken place and is described in more detail in later sections.

An additional change in the original objective is that the model should strictly be termed a pseudo 2-dimensional model. Although the basic heat and moisture transfer model could operate in 2-dimensions the increase in complexity resulting from the incorporation of volume change make a fully 2-dimensional scheme beyond the means of this project. Ideally the model would operate within a continuously deforming 2-dimensional mesh structure. Possibilities for the extension to this structure are discussed in section 6. PERIMOVE in its current form however

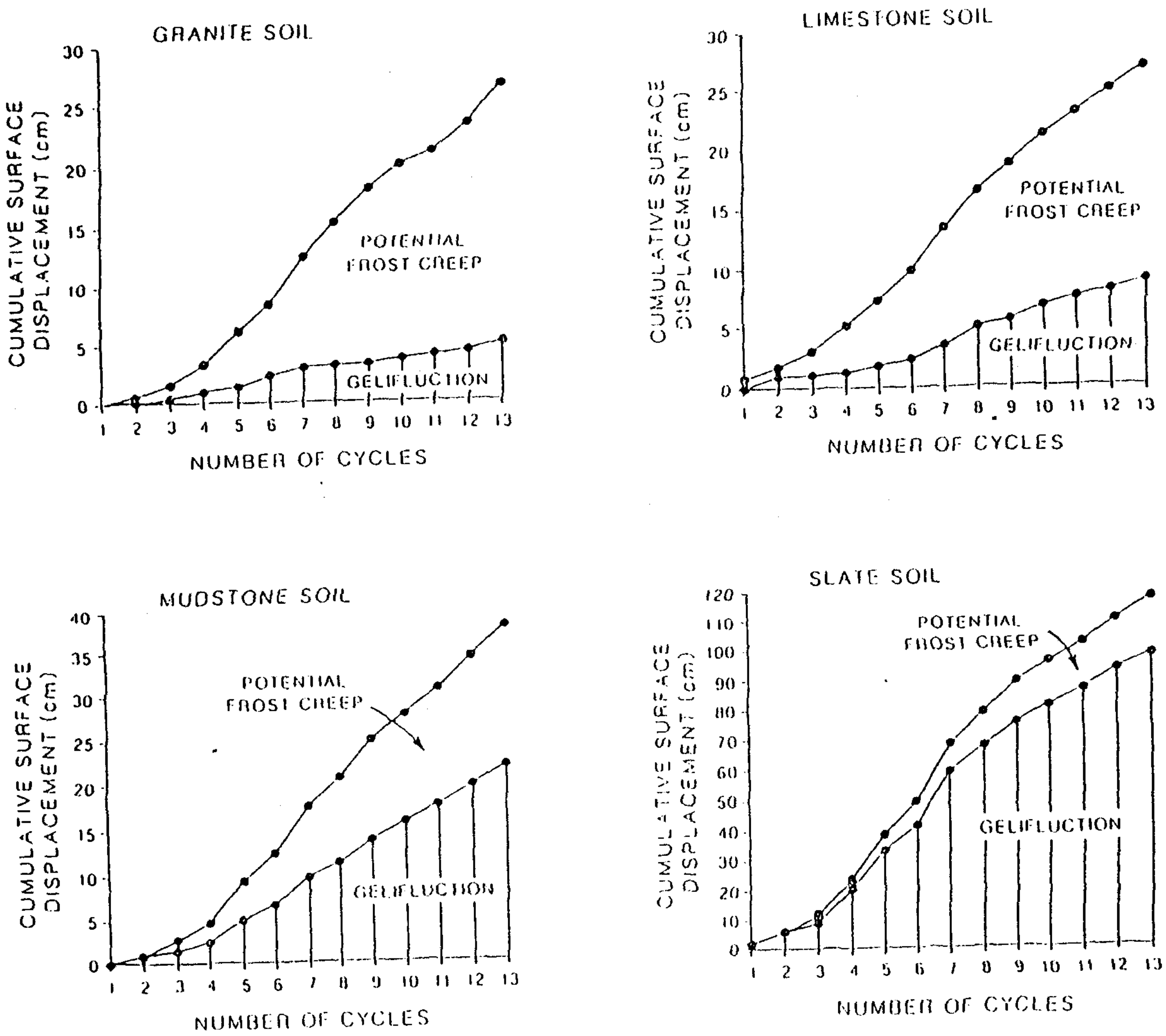


Figure 1: Relative importance of frost creep and gelifluction processes for selected soil types (note variation in vertical scales), Harris *et al* (1993).

is capable of simulating the 2-dimensional transfers of material which occur over freeze/thaw cycles.

## 2 DEVELOPMENT OF METHODS AND TECHNIQUES

Three areas of development are outlined below. The first section outlines the structure and equation base of the PERIMOVE model. The second section outlines the data preprocessing scheme and the third section describes the data sources that have been collated to supply data which have contributed to the development and the validation of the model. Figure 2 summarises the development and validation route for the model and also suggests to further areas of development for the model.

### i) Description of processes, equations and spatial discretisation approach selected for the PERIMOVE model

#### *Spatial Discretisation*

The slope profile is represented as a series of columns of equal width and breadth. Each column is further subdivided to create cells which are then treated as homogeneous units within the model. The computation point is at the centre of each cell and all thermal and hydraulic properties are assigned to that point. These block-centred computation points represent the mathematical nodes for the finite difference mass-energy calculations performed by the model. Mass and energy transfers take place on the basis of the thermal and hydrological gradients which are calculated between cells and phase change processes are governed by the within cell conditions.

A maximum of two hydrologically distinct layers may be identified (as defined by suction-moisture curves and characteristic freezing curves). The boundary between them is determined by specification of the lowest cell in the upper layer so that the rest of the column comprises the second layer.

Each slope section is modelled in isolation therefore three-dimensional attributes such as aspect, convergent and divergent slope forms are not included in the present model.

#### ***Process and Equation Base***

Three major sets of equations can be identified which describe the three major groups of processes which need to be included in a modelling scheme. These are:

processes of heat flow in soils
processes of phase change in freezing and thawing soils

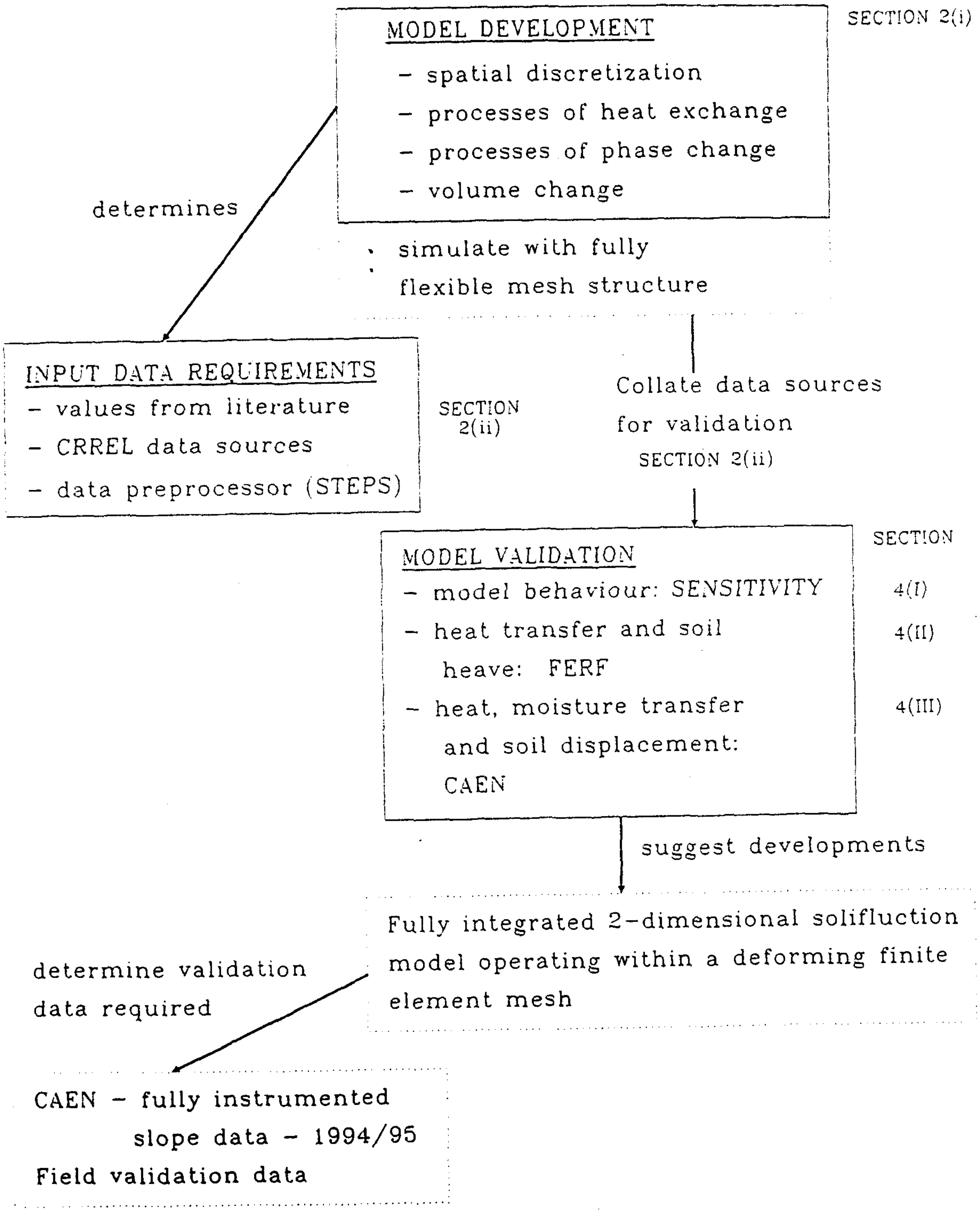


Figure 2: Summary diagram of stages in model development and application. Solid line boxes indicate the scope of this project and dotted lines indicate areas for further research.

processes of water transfer through the profile.

Although these processes all interact it is possible to consider them independently in order to outline the major equations describing each of the processes.

### *Processes of heat flow within soil*

Heat flow within soils takes place by a variety of processes. In periglacial situations the two major processes responsible for heat transfer are conduction through the soil/water/ice medium and transfer of latent heat by liquid flow. Additional processes such as heat flow by radiation, heat generated by mechanical work of the particles and sensible heat convection are generally considered to be of minor importance and are currently excluded from the PERIMOVE model.

**Thermal Conductivity** is a measure of the quantity of heat that will flow through a unit area of a substance of unit thickness in unit time under a temperature gradient. It is usually measured in W $m^{-1}$ $K^{-1}$.

In situations where ground temperatures fall below 0°C the thermal conductivity of soils cannot be assumed constant as freezing soils have a temperature dependent ice content and the thermal conductivity of ice is four times that of water. In soils undergoing freeze/thaw the ice/water ratios change rapidly. In periglacial situations where soil temperatures are frequently in the range 0 to -3°C, failure to account for the temperature dependence of thermal conductivity may lead to unacceptable errors in the modelling stage so temperature dependant relationships are incorporated in the PERIMOVE model.

DeVries (1952) developed the equation for calculation of thermal conductivity in a multi-component system:

$$Kt = \frac{\sum_{i=o}^{n} x_i \, kt_i \, F_i}{\sum_{i=o}^{n} x_i \, F_i} \qquad \text{(eq. 1)}$$

Kt = thermal conductivity of the system (W $m^{-1}$ $K^{-1}$)
n = number of different kinds of particles in the continuous media
$x_i$ = volume fraction of ith kind of particle (%)
$k_{ti}$ = thermal conductivity of ith kind of particles (W $m^{-1}$ $K^{-1}$)
$F_i$ = ratio of average temperature in the ith kind of particles to average temperature in the continuous media

this means that for a water, ice and soil system the equation is (by Penner, 1970):

$$Kt = \frac{x_w kt_w F_w + x_i kt_i F_i + x_s kt_s F_s}{x_w F_w + x_i F_i + x_s F_s}$$

(eq. 2)

subscripts:
$w$ = water, $(F_w = 1)$
$i$ = ice
$s$ = soil

PERIMOVE uses the above formula in which both ice and water thermal conductivities are considered temperature dependent below 0°C. The relationships of thermal conductivity with temperature are input to the model as a series of data pairs of conductivity and temperature and interpolation between data points is made to 'look-up' conductivity values for the current temperature of the particular computation cell.

The above equation does not include latent heat transfer effects and as stated above significant errors can occur in predictions if these are omitted. Latent heat is released during freezing and absorbed during thawing and means that a partially frozen soil behaves as if it has a greatly increased heat capacity. Latent heat is considered in the following section.

Once a thermal conductivity has been established it can be used to describe transfer of heat by conduction by application of Fourier's Law:

$$h_x = -Kt_x \frac{\delta TA}{\delta x}$$

where:

$h_x$ = rate of energy flow in x direction (W)
$Kt$ = thermal conductivity in specified direction ($W\ m^{-1}\ K^{-1}$)
$T$ = temperature (K)
$A$ = area ($m^2$)

Fourier's law states that the rate of energy flow in the direction of temperature drop is proportional to the area through which the energy flows and the temperature gradient.

Laplace's equation combines the heat conduction theory with the continuity equation to generate a second order partial differential equation:

$$\frac{\delta}{\delta x}\left(-Kt\,\frac{\delta h}{\delta x}\right) + \frac{\delta}{\delta y}\left(-Kt\,\frac{\delta h}{\delta y}\right) + \frac{\delta}{\delta z}\left(-Kt\,\frac{\delta h}{\delta z}\right) = 0$$

(eq. 3)

where: $Kt = Kt\,(x.y.z)$

If the region considered is homogeneous and isotropic then Kt is independent of x,y and z, so that the above equation simplifies to:

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = 0$$

(eq. 4)

Laplace's equation therefore describes heat conduction under steady state conditions. Fourier's law in combination with the continuity equation is solved in one dimension within PERIMOVE so that temperature change through time is described by:

$$C_v \frac{\delta T}{\delta t} = -\frac{\delta}{\delta x}\left(-Kt \frac{\delta T}{\delta x}\right)$$

(eq.5)

where: $C_v$ = volumetric heat capacity of the soil medium

and: **volumetric Heat Capacity** is the amount of heat required to change the temperature of a unit volume of a substance by one degree. The heat capacity of a mixture is equal to the sum of the heat capacities of its components.

This heat exchange with the profile is achieved by specification of Neuman boundary conditions in which the transfers of energy across the surfaces bounding the problem are known.

The thermal response of a soil requires the calculation of volumetric heat capacity. In unfrozen soils the volumetric heat capacity is dependent on dry bulk density of soil, moisture content and specific heat capacity of the constituent mineral matter, (Jumikis, 1966). The relationship can be expressed as:

$$C_v = \gamma d\,(Cs + Cw\,W/100)$$

where:

$C_v$ = volumetric heat capacity ($J\ m^{-3}\ K^{-1}$)
$\gamma d$ = dry bulk density of soil ($g\ m^{-3}$)
$Cs$ = specific heat capacity of dry mineral matter ($J\ g^{-1}\ K^{-1}$)
$Cw$ = specific heat capacity of water ($4.18 J\ g^{-1}\ K^{-1}$)
$W$ = water content (%)

As soil freezes the volumetric heat capacity changes as relative volumes of ice and water change. The equation for partially frozen soil is expressed by:

$$C_v f = \gamma d_f\,(Cs + (Cw\,W/100) + (Ci\,I/100))$$

where:

$\gamma d_f$ = frozen bulk density
$Ci$ = specific heat capacity of ice ($J\ g^{-1}\ K^{-1}$) pure ice = $2.1\ J\ g^{-1}\ K^{-1}$
$I$ = ice content (%)

This assumes that the air phase can be ignored and the specific heats are assumed to be independent of temperature. Bi-modal values of soil bulk density where one value is used for frozen conditions and another for unfrozen conditions are employed in PERIMOVE. This represents a simplification of reality as soil structure changes during repeated freezing and thawing events producing corresponding changes in bulk density values. It may well be necessary to incorporate this continual change in bulk density at a later stage especially if the model is particularly sensitive to this.

## *Processes of Phase Change in Freezing and Thawing Soils*

Phase change of water to ice and ice to water takes place over a range of temperatures in soils. As an example, fine-grained silt/clay soils can still contain a liquid moisture content at temperatures as low as -20°C. Therefore it is not sufficient to consider the freezing process occurring at a single interface (i.e. the 0°C isotherm). Phase changes in cooling and warming soils are determined by heat flux and water content of the cell.

### *Phase change in freezing soils*

The heat budget for a uniform volume of soil can be described by:

$$\Delta Q = La\frac{\delta\theta}{\delta T}.\,\Delta T - C_V\delta\Delta T \qquad \text{(eq. 6)}$$

where:

| | |
|---|---|
| $La\ \delta\theta/\delta T.\Delta T$ | is the energy released due to phase change of moisture to ice, termed the **hydrological component.** |
| $C_V\delta\Delta T$ | is the energy release due to thermal capacity of soil medium, termed the **thermal component.** |

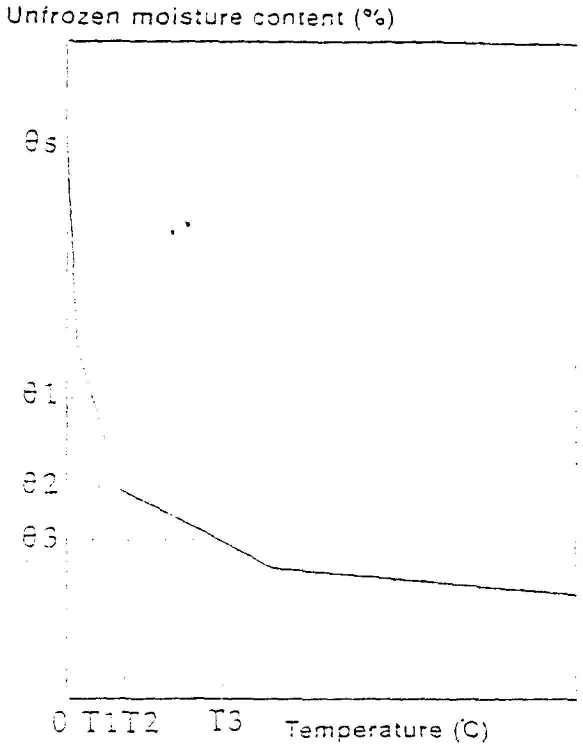
$\Delta Q$ = change in energy of the system
La = latent heat of fusion ($J\ g^{-1}$)
$\theta$ = volumetric soil moisture content (%)
$C_V$ = volumetric heat capacity ($J\ m^{-3}\ K^{-1}$)
V = volume (of cell) ($m^{-3}$)
T = temperature (K)

Use is made of the characteristic freezing curve for a soil which is an experimentally determined curve which describes the percentage of liquid water which remains unfrozen at a given temperature below 0°C

The characteristic freezing curve for the specified soil, the soil liquid water content and the soil temperature are used to determine the quantity of ice formed for a given drop in temperature. The operation of the curve in the PERIMOVE model is described in figure 3.

## Characteristic Freezing Curve

The characteristic freezing curve for a soil defines the relationship between liquid water content and temperatures below 273.15K (0°C). The curve can be determined experimentally and an example of a characteristic freezing curve is given below.



If the soil is initially saturated ($\theta_S$) then as the soil temperature begins to drop below 0°C the liquid water content will fall such that at temperature $T_1$ the liquid water content will be $\theta_1$ and at $T_3$ the corresponding liquid water content will be $\theta_3$. The fall in liquid water content with temperature is equivalent to the water equivalent volume of ice formed.

If, however, the soil is unsaturated at the start of the freezing process, for example $\theta_2$ then ice formation will not be initiated until the soil temperature falls below $T_2$ (the temperature corresponding to a liquid water content of $\theta_2$). Until this point is reached the liquid water content will be super-cooled. Once temperature $T_2$ is reached the falling liquid water content will follow the pattern of the characteristic curve.

This curve is used in subroutine FREEZE to determine a liquid water content given the soil temperature (as calculated in HEATRANS).

**Figure 3: Operation of the characteristic freezing curve within the PERIMOVE model.**

On freezing three possible thermo-hydrodynamic conditions are considered.

1) $La \dfrac{\delta\theta}{\delta T} \Delta T > C_V \Delta T$ $\quad\therefore$ $\Delta Q$ is positive and isothermal phase change occurs

The energy generated from the phase change of water into ice is greater than the temperature decline controlled by ambient temperature change, heat conduction through the soil and heat capacity of the soil (thermal component). The soil temperature remains unchanged as the temperature decline due to soil heat capacity and temperature gradient is compensated for by energy release from phase change. Excess $\Delta Q$ is assumed to be lost from the system.

2) $La \dfrac{\delta\theta}{\delta T} \Delta T = C_V \Delta T$ $\quad\therefore$ $\Delta Q$ is zero

The energy losses due to the thermal component are equivalent to the energy gain due to water phase change. The soil temperature remains constant as the gains/losses are compensatory.

3) $La \dfrac{\delta\theta}{\delta T} \Delta T < C_V \Delta T$ $\quad\therefore$ $\Delta Q$ is negative, non-isothermal phase change occurs

The energy loss from the thermal component is greater than can be compensated for by release of energy which occurs as the soil cools below freezing. There is a drop in soil temperature as phase change cannot release sufficient energy. $\Delta Q$ is negative and no energy is lost from the soil system as all hydrological latent heat is used in compensating for thermal losses.

**Thawing Soils**:

The logic of phase change for thawing soils is based on the assumption that energy input to a cell is partitioned between:

(1) temperature change - the **thermal component**
(2) phase change of ice to water - the **hydrological component**

A thaw temperature is specified (normally 273.15K) and all energy input into a cell is used to raise the cell temperature until the thaw temperature is reached. Once the thaw temperature is reached the energy transferred into a cell is used to satisfy the energy requirements of the phase change from ice to liquid water. Once the cell is ice free the incoming energy is again used to raise the cell temperature. These can be expressed as three conditions.

1) if the cell temperature is less than the set thaw temperature then all the energy entering the cell is used to raise the cell temperature.

$$\Delta T = \Delta Q / C_V \delta \Delta T$$

2) if cell temperature is at thaw temperature and ice is present then the energy entering the cell is used to satisfy the latent heat requirement of melting ice. The incoming energy determines the volume of ice which can be melted. The temperature remains at the thaw temperature until all the cell ice is melted.

$$\Delta\theta = \frac{\Delta Q / La\,\delta\theta}{\delta T} \,.\, \Delta T$$

3) if the cell temperature is at or greater than thaw temperature and there is no ice present all the incoming energy is used to raise the cell temperature.

$$\Delta T = \Delta Q / C_v \delta \Delta T$$

### *Processes of Water Transfer Through the Profile*

In the current version of PERIMOVE only vertical movement of water is incorporated.
Darcy's law provides the basic equation for water flow through soils and for vertical movement the equation can be written as:

$$q_y = -K \frac{\delta H}{\delta y} = -K \frac{\delta}{\delta y} (H_p - y)$$

(eq. 7)

where:

$q_y$ = water flux
$H$ = total hydraulic head
$H_p$ = pressure head (m)
$y$ = vertical distance component (in PERIMOVE scheme)
$K$ = hydraulic conductivity (m $s^{-1}$)

In unsaturated soils $H_p$ is negative and can be expressed as a suction head:

$$q_y = K \frac{\delta\psi}{\delta y} + K$$

Combining the above equation with the continuity equation yields:

$$\frac{\delta h}{\delta t} = \frac{\delta}{\delta y}\left(K \frac{\delta H}{\delta y}\right) = \frac{-\delta}{\delta y}\left(\frac{K\delta\psi}{\delta y}\right) - \frac{\delta K}{\delta y}$$

(eq. 8)

As soil moisture content and suction head are uniquely related the left hand side of the equation can be written as:

$$\frac{\delta\theta}{\delta t} = \frac{\delta\theta}{\delta\psi} \cdot \frac{\delta\psi}{\delta t}$$

Substituting this relationship into the above equation produces:

$$C\frac{\delta\psi}{\delta t} = \frac{\delta}{\delta y}\left( K\frac{\delta\psi}{\delta y} \right) + \frac{\delta K}{\delta y}$$

(eq. 9)

where: C is the specific water capacity describing the change in water content of a unit volume of soil per unit change of matric suction.

Equations 8 and 9 are forms of the Richards equation. Conventionally these are developed for flow in isothermal saturated and unsaturated flow within ice free soil water systems.

Extension of this equation to situations where ice formation occurs within the soil is possible because of the similarity between air/water systems and ice/water systems. As temperatures fall to the point of ice nucleation a single crystal forms in the centre of a water filled pore. If this crystal is regarded as analogous to an air bubble then the flow solution can be assumed similar to that for unsaturated flow. The growth of an ice crystal can be compared to the growth of an air bubble in unsaturated soils and relationships developed for drying soils can be used to describe the hydraulic properties of freezing soils (Burt and Williams, 1976).

As ice begins to form in the upper soil layers the liquid moisture content of these layers falls. This results in significant soil water suctions developing in these cells and allows for water to be drawn up into the freezing zone and fuel the development of ice quantities which can cause profile expansion. Soil conductivity, moisture availability and rate of freezing control the extent to which water will be drawn up the profile.

The hydraulic conductivity curve with moisture content is derived using the Millington-Quirk procedure within the PERIMOVE model.

### *Volume change and mass movement in the PERIMOVE model*

The incorporation of volume expansion and the movement of water through the profile is essential if volume expansion during freezing and subsequent supersaturation of the soil profile and loss of soil strength following thawing are to be modelled. It is known that volume expansion of soil undergoing freezing is not due solely to the volume change that occurs when liquid water becomes ice within the soil pore system. Continued migration of water towards the freezing front as liquid water is converted to ice results in the formation of segregation ice lenses and additional expansion. On thawing this excess water is often prevented from draining away due to the frozen state of lower profile layers. The supersaturation of the soil material that results creates conditions which can lead to solifluction because of the reduction in soil strength.

For inclusion in the PERIMOVE model it is assumed that the change from liquid water to ice is accompanied by a 9% increase in volume. Within each cell the ice formation proceeds until the sum of the liquid water and ice contents exceeds the porosity of the soil. When this situation is reached the new volume of the cell and the change in cell depth (all expansion is assumed to take place in the vertical dimension) is calculated. Following this the new volumetric percentages of soil particles, liquid water and ice are calculated.

The new values are then transferred to the mass transfer calculation section of the program and transfers are made based on the hydraulic gradients between cells.

Previously the movement of water between cells was limited by the cell porosity as water could not move into a cell which had been 'filled'. This check has been removed to allow continued upward migration of water to fuel freezing and volume expansion.

The volume expansion of a cell also effects the operation of the suction-moisture curve and the characteristic freezing curves.

### Characteristic freezing curve

In normal operation the characteristic freezing curve is used to determine the liquid water content of a cell at a given temperature and determine if water is available in the cell for the freezing process to proceed. With volume expansion the assumption is made that the liquid water at a given temperature is an absolute volume calculated on the basis of the original cell volume. When volume change occurs the characteristic freezing curve is used to look up the water content for the given temperature and a value for volumetric water content value is returned. In the program the value is then transformed to a value in $m^3$ for the freezing calculations. If the volume change is not accounted for in this calculation then the volume in $m^3$ will be overestimated. To avoid this the value of liquid water obtained form the characteristic freezing curve is divided by the total volume change that has occurred over the simulation.

### Suction moisture curve

The suction moisture curve is used to 'look-up' values of m suction for a given soil moisture content. The curve is derived for liquid moisture contents so as ice forms in a cell liquid moisture contents fall and suctions increase.

As volume expansion occurs the same m3 volume of water will be equivalent to a reduced volumetric water content and return a higher suction value from the suction-moisture curve. However, this interpretation may be satisfactory as an equivalent absolute volume in a larger cell volume will lead to a reduced connectivity in pore space water and thus a higher suction. This is the approach that is being taken in the current version of the PERIMOVE model.

### Conductivity

The Millington-Quirk relationship is used to derive a conductivity-moisture curve from the suction-moisture curve. The conductivity-moisture curve is then used to 'look-up' the value of conductivity for a given volumetric moisture content in the mass transfer section of the program. If volume expansion has occurred the volumetric liquid water content will be lower for a given absolute volume of water and a lower conductivity will be returned than for the same liquid volume pre-expansion. This reflects the decrease in connectivity that will result when a cell expands so the values extracted from the curve are used directly in the model.

### *Summary*

The above sections have described the model structure and equations. Figure 4 illustrates the sequence in which the processes described above are modelled within each time step of the PERIMOVE model.

The other factors to be considered in this section are the data sources that have been assembled to help construct and validate the model.

## ii) Soil type driven data preparation scheme

An important part of the model development plan was that the model would successfully reproduce the differences in moisture redistribution and freezing of different soil types. To facilitate the derivation of data files for this the Soil Type Essential Property Selector (STEPS) program was written. This is based on the model written by Cochrane and Anderson (1988) and generates soil property files when given a soil class from the standard USDA soil triangle. The original model and database have been expanded to include selection of soil thermal properties and characteristic freezing curves. This provides a quick and user friendly way of selecting soil properties for the PERIMOVE model and introduces the option of wide applicability without elaborate testing of soils.

## iii) Validation data sources

Two major data sources have been used in the model development and validation. They are derived from two areas of collaboration that have been established during the project.

A) **Collaboration with the Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire.** A range of experiments conducted there have been useful in development and testing for the PERIMOVE model.

CRREL has conducted many laboratory tests to derive characteristic freezing curves. In a visit made there the various sample results were collated and soil type information matched with the relevant curves to augment the data preprocessing program STEPS described above.

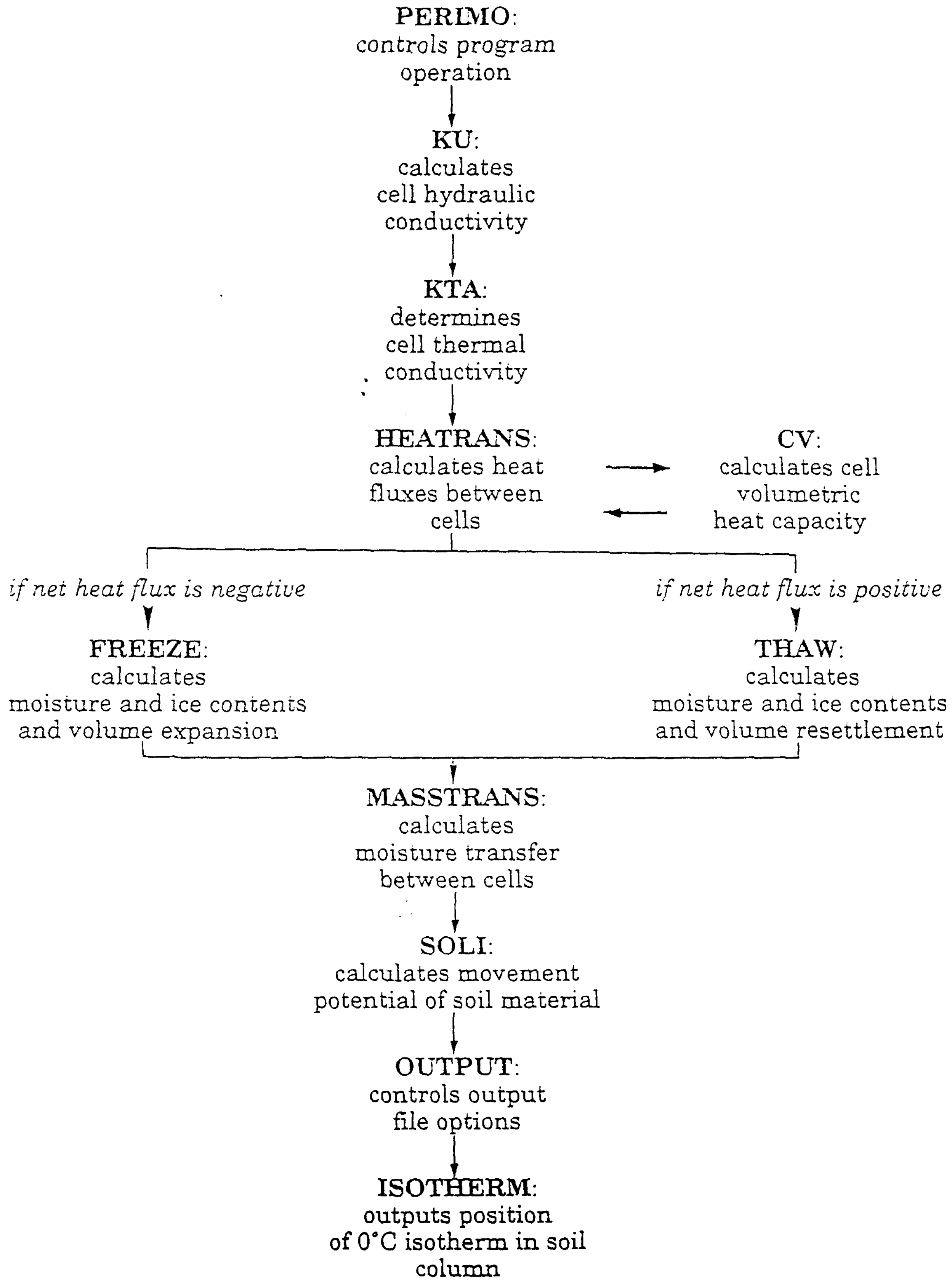


Figure 4: Sequence of operation of the subroutines within the PERIMOVE model.

Shoop (1989) describes the results of an experiment performed within the Frost Effects Research Facility (FERF) at CRREL. The FERF building is an environmentally controlled building and contains a series of test cells measuring around 20ft square and 12 ft deep. Soil freezing is instigated by placing freezing panels on the soil surface and thawing is produced by either heating the building or opening the building to the ambient air temperature. The data which was made available was collected during a freeze/thaw cycle for a silty sand. Profile temperatures were monitored and measurement of total soil heave made at the end of the freeze cycle. Moisture content was measured using tensiometers (although these cease working once freezing commences) and gravimetric moisture determinations were made on samples of the profile removed at the end of the freeze cycle. As such the data provides a good source for validating temperature and moisture movement within the profile.

An additional data source that was used more in the early development of the model was data collected from some plot experiments conducted at CRREL. Two outdoor plots - one containing a sandy soil type and the other a loam soil type were monitored over two winter seasons. The data consists predominantly of temperature data and this was used in the early development of the model before other data sources were available. The second season has some moisture data and may be used at a later date.

**B) The second source of data has come from collaboration with Harris *et al* (1993)** *who* conducted a large scale experiment using a constructed slope within a refrigerated container (some results of which are described in section 1) using different soil types at the C.N.R.S. Centre de Géomorphologie in Caen, France. The results from this study include temperature profiles and heave measurements for a suite of freeze/thaw cycles. The heave measurements can be used to indicate the moisture redistribution occurring during freezing within different soil types and the temperature profiles to compare with model simulated temperatures. In addition measurements were made of the relative amounts of downslope movement of material that could be attributed to creep and gelifluction processes for each of the soils types. This gives an extremely good data set against which soil strength, soil supersaturation on thawing and soil movement can be calibrated within the model.

## 3 PROGRESS IN RELATION TO SCHEDULE OF WORK

At the current stage of development the model can be used to investigate the nature and extent of 2-dimensional movement of material downslope although as stated in section (1) the current model is pseudo 2-dimensional in structure because of the intense computational difficulties in defining a 2-dimensional deforming mesh structure. The continued development of finite element techniques will mean that it should be possible in the future to have a fully integrated 2-dimensional simulation capacity.

The collation of the range of data sources for model validation and testing has been an important part of the project and a larger part than originally anticipated however, the collection and use of these data sources has meant the model development and validation has been more rigourous than originally planned.

## 4 SUMMARY OF RESULTS AND DATA TO DATE

The results summary is presented in three sections and each section highlights a particular area of results from the model. The results follow a progression through the validation and application development of the model. The first section looks at the general performance and behaviour of the model by summarising the results of the sensitivity analysis of model parameter values. The second and third sections concentrate on the application of the model to the two test data sources looking first at the application to the FERF building study which concentrates mostly on heat movement within the profile and total column heave. The extension of the application of the model to consider heave and potential for downslope movement is looked at with the application of the model to the CAEN data set.

A variety of means of handling the data output from the model have been investigated and the results presented here are created using cricket graph and UNIRAS.

### *I) Sensitivity Analysis*

A sensitivity analysis provides an opportunity to discover the most significant parameters in determining model results and also to investigate if the model is responding to changes in parameter values in the manner that one would expect.

To perform the sensitivity analysis a test profile was created which was 50cm deep and input files were used for a silty loam soil type. A short freeze/thaw cycle was used as input to allow for a short simulation duration and permit many runs to be made. With the sensitivity analysis made here only one parameter was altered at any one time. This is very useful in giving a general idea of how the model is operating under different circumstances but means that interrelationships between parameter values which inevitably exist are not considered. An analysis of the combinations of timestep and cell size were made. As cell size is increased timestep can be increased. The time-step and cell size limits are also influenced by the hydraulic conductivities set as these have a strong influence in controlling the mass transfers which will cause instability if they are too great within any time-step length.

The functioning of the hydrological component of the model is of great importance as this is highly significant in determining water migration and therefore the major influence on the occurrence and extent of creep and gelifluction processes. If volume change in a profile occurred only because of the in situ change of water to ice then only a small quantity of heave would result. In many cases the freezing of water in the upper soil layers reduces the liquid water content of the soil and creates a hydraulic gradient sufficient to pull water up through the profile. This process continues until the pore connectivity reduces so that the transfer rates are so slow that movement is effectively halted. In certain silts ice contents can lead to cell volumes doubling.

As expected the value of the hydraulic conductivity was important. The value for saturated conductivity is supplied to the model and this is then used to create the conductivity with liquid moisture content curve within the PERIMOVE program. An increase in hydraulic conductivity reduces the depth to which the freezing front penetrates and increases the total heave and the excess ice contents in the upper soil layers. For the test profile the conductivity range of $1\times10^{-6}$ $ms^{-1}$ to $1\times10^{-8}$ $ms^{-1}$ produced the corresponding range in heave values of 33.8mm to 1.2mm. The slowing of frost penetration with increasing conductivity occurs as a result of the increased volumes of water in the upper cells requiring a greater time period to freeze. Figure 5 illustrates the sensitivity of output to variations in hydraulic conductivity.

The value of saturated moisture content was varied. The major effect of this was in the soil heave values. As the saturated moisture content is used to calculate soil porosity the effect of increasing the saturated moisture content whilst holding the initial profile moisture contents fixed is to reduce heave as greater volumetric change in cell moisture content is required before heave can commence. As the derivation of the conductivity-moisture curve utilizes the value of saturated moisture content the conductivities for corresponding moisture contents are reduced and rate of water movement is slowed.

Bulk densities (both frozen and dry) were altered although the impact of altering these did not result in a straightforward relationship. The most significant impact was to increase the depth of frost penetration with increasing bulk densities. Therefore the impact was mostly in the thermal energy transfer component.

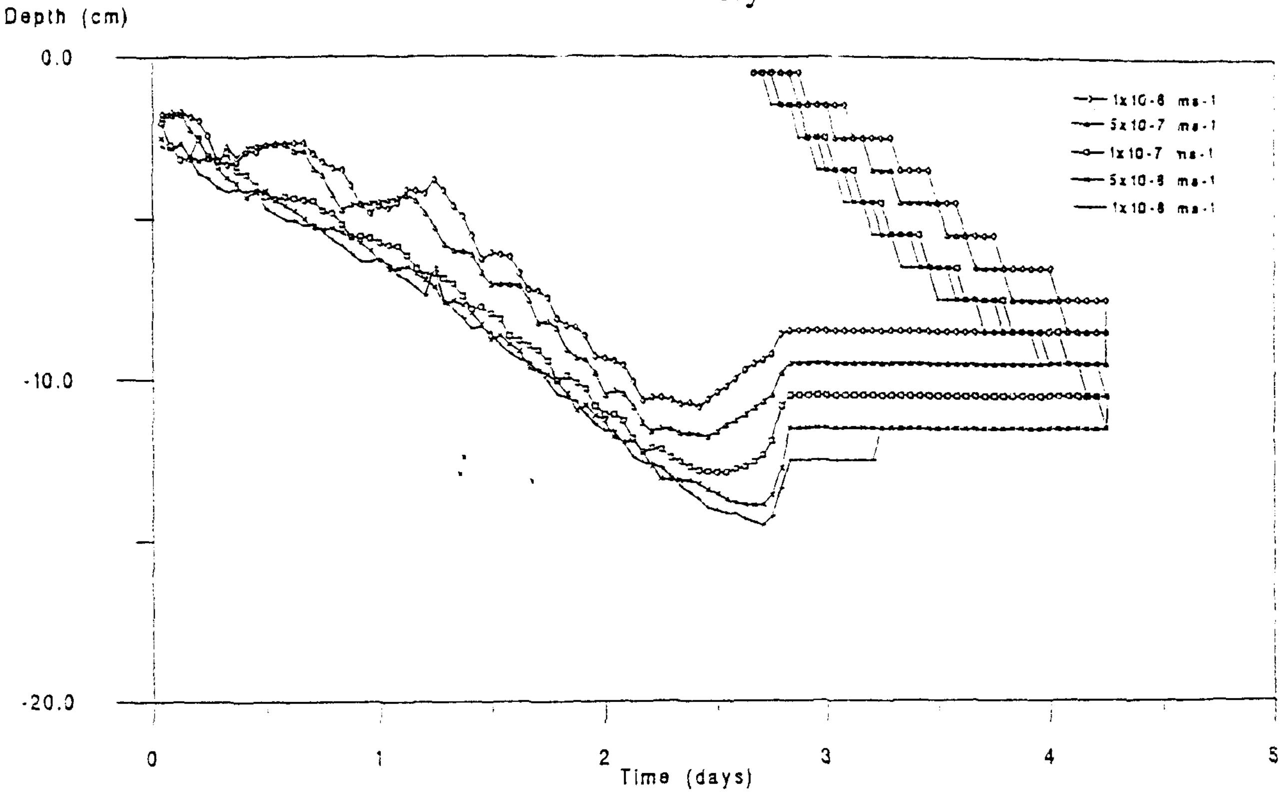
The soil particle conductivity is very significant impact on the thermal component of the model although not greatly influencing the hydrological response. Increasing the thermal conductivity increases the rate and thereby the depth of thaw penetration. Soil heave is reduced a little which probably reflects the slight reduction in water movement caused by the profile freezing earlier and therefore water migration routes being severed sooner.

The sensitivity analysis has identified the implications of parameter changes to model operation and has also providing a guide to the temporal and spatial time-step limitations of the model. This knowledge can be used to aid the application of the model to laboratory data and test the extend the model validation to practical examples.

## *II) FERF Building Simulations*

The FERF building simulations concentrated on the simulation of profile temperatures and total

Sensitivity of 0oC isotherm to hydraulic conductivity



Sensitivity of soil heave to hydraulic conductivity

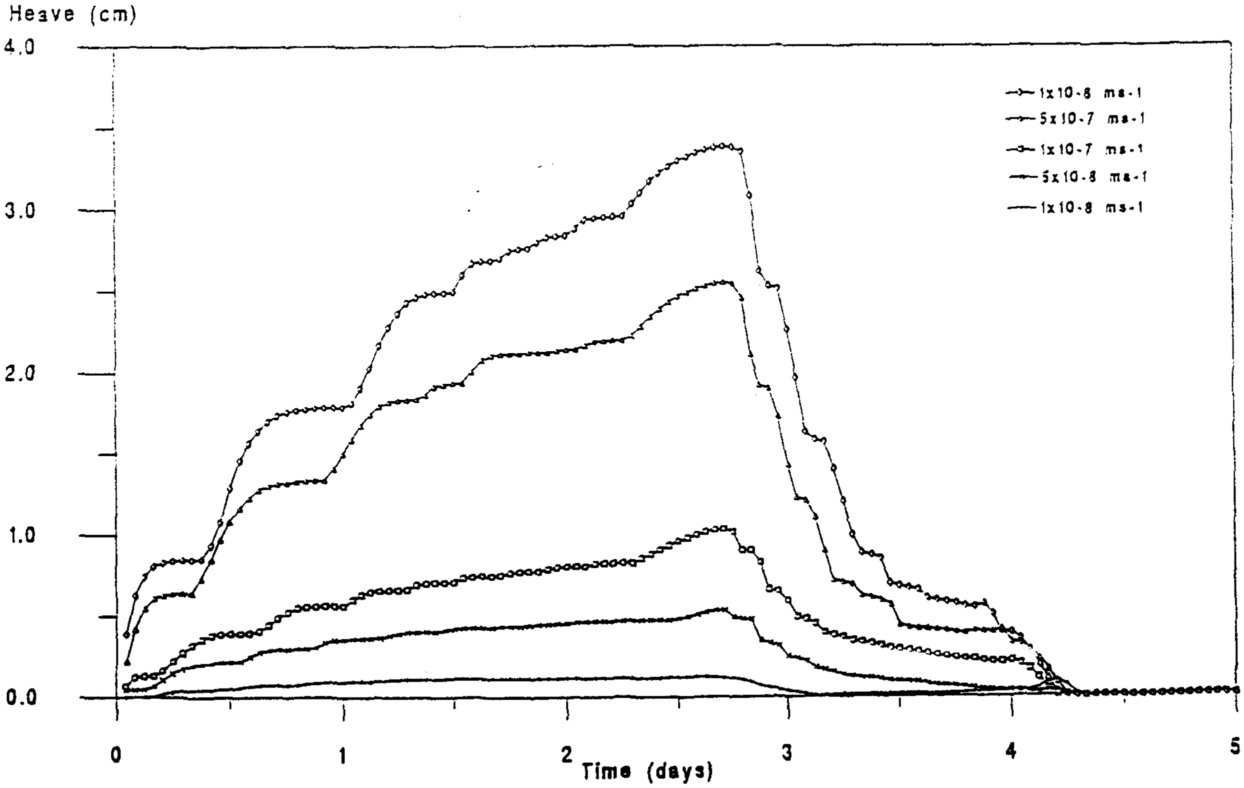


Figure 5: Sensitivity of 0 C isotherm and soil heave to changes in hydraulic conductivity parameter values in the PERIMOVE model.

soil heave values. For the simulation a test profile was created with 1cm deep cells in the upper 10cm of the profile and 2cm deep cells in the remaining 80cm to create a total depth of 90cm. An example simulation is shown in figure 6. The parameter used to indicate the depth of the frost/thaw front is the 0°C isotherm. With the model this is the temperature at which ice can begin to form but, as is also true for the observed situation, does not always indicate that ice forms a significant volumetric portion of the cell.

The soil heave predicted by the model is within the range observed for the study which was from 2.5cm to 11cm and the heave extent can be used as an indicator of the migration of water up through the profile to create the observed ice contents and the excess total water contents. The simulation shown uses the data files established for a silty loam soil type. A certain amount of model calibration was made by adjusting input parameter values (mostly thermal conductivities) to achieve the simulation shown and the basal temperature boundary condition was also used as an additional factor in the calibration. The depth of the profile used in the FERF building study was 1m with an underlying layer of gravelly sand of a further 2m and so the lower zone of the profile would have acted as a heat store to counter frost penetration.

## *III) CAEN Laboratory Simulations*

The CAEN study provides additional sources of data for model development and validation. The laboratory investigation looked at the response to freezing and thawing of four soil types. For this investigation two of those soil types were selected to see if the model could successfully reproduce the differences between the soil types. The physical properties of the two soil types selected are summarised in table 1. The data was collected over a suite of freezing and thawing cycles and one of the cycles was selected for the modelling program. The ambient temperature conditions and the observed position of the 0°C isotherm are shown on figure 7. It appears that the sandy soil freezes slower than the silty soil which is not what one would expect however this may have been due to the production of large quantities of needle ice in the upper few centimetres of the profile which greatly slowed the initial frost penetration. The thaw penetrates the sandy soil faster which is as one would expect. Plots of the observed and simulated depths of the 0°C isotherm, soil heave and estimates of downslope movement of material are shown in figure 8 for the silt soil types. Figure 9 shows an alternative method of displaying the temperature profiles over time using a UNIRAS program. Water, ice and other model output can also be displayed in this way.

Because the CAEN experiment used a series of freeze/thaw cycles it will be possible to model alternative cycles with the parameter sets derived for the cycle modelled (cycle 7) to give an indication of how much calibration of input data is required and if data sets that reproduce the observed patterns over a range of cycles can be determined. In addition further work will look at the differences between soil type responses.
Heave values are calculated assuming soil expansion due to freezing occurs orthogonal to the slope and resettlement values by assuming gravitational resettlement of the heaved material.

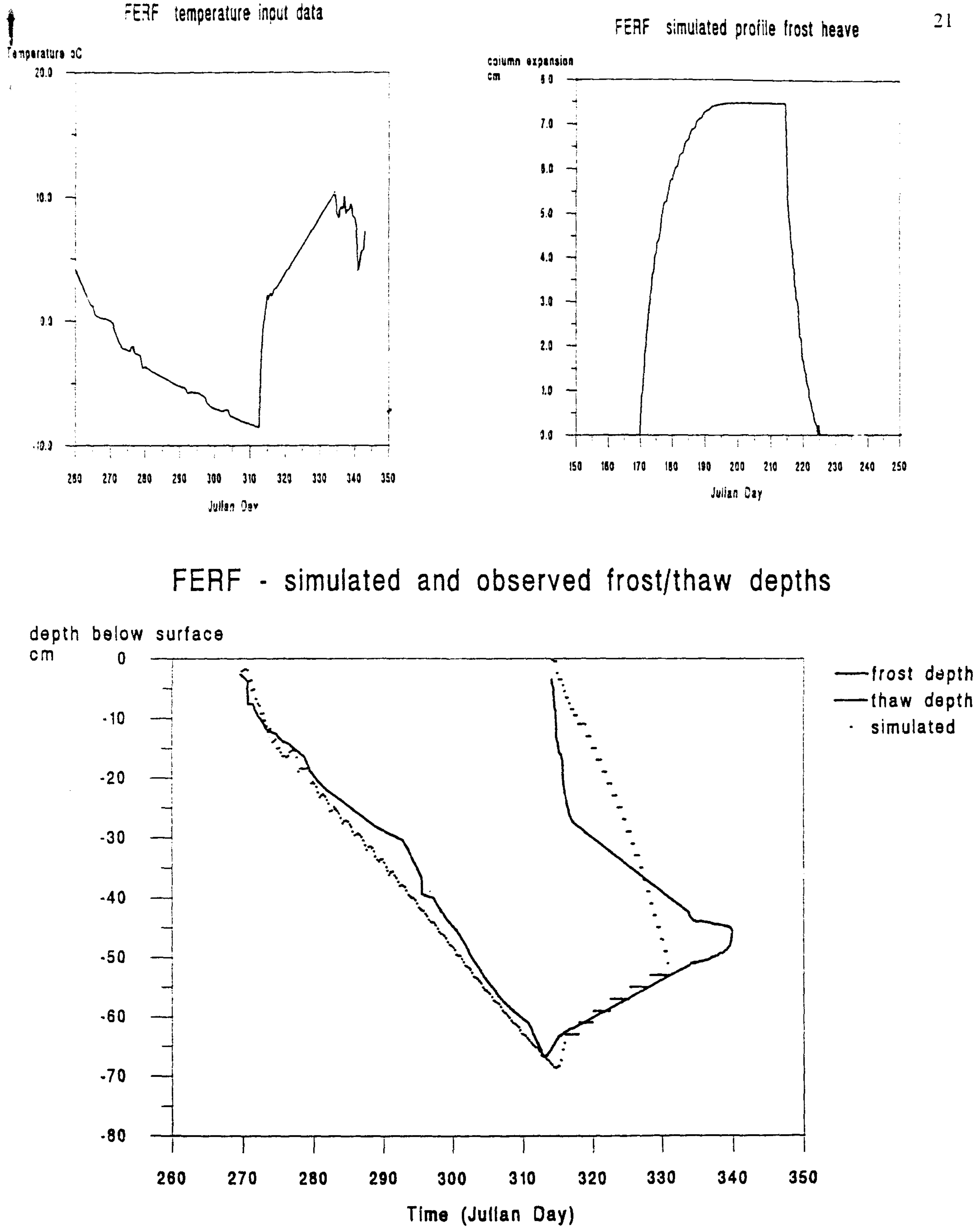


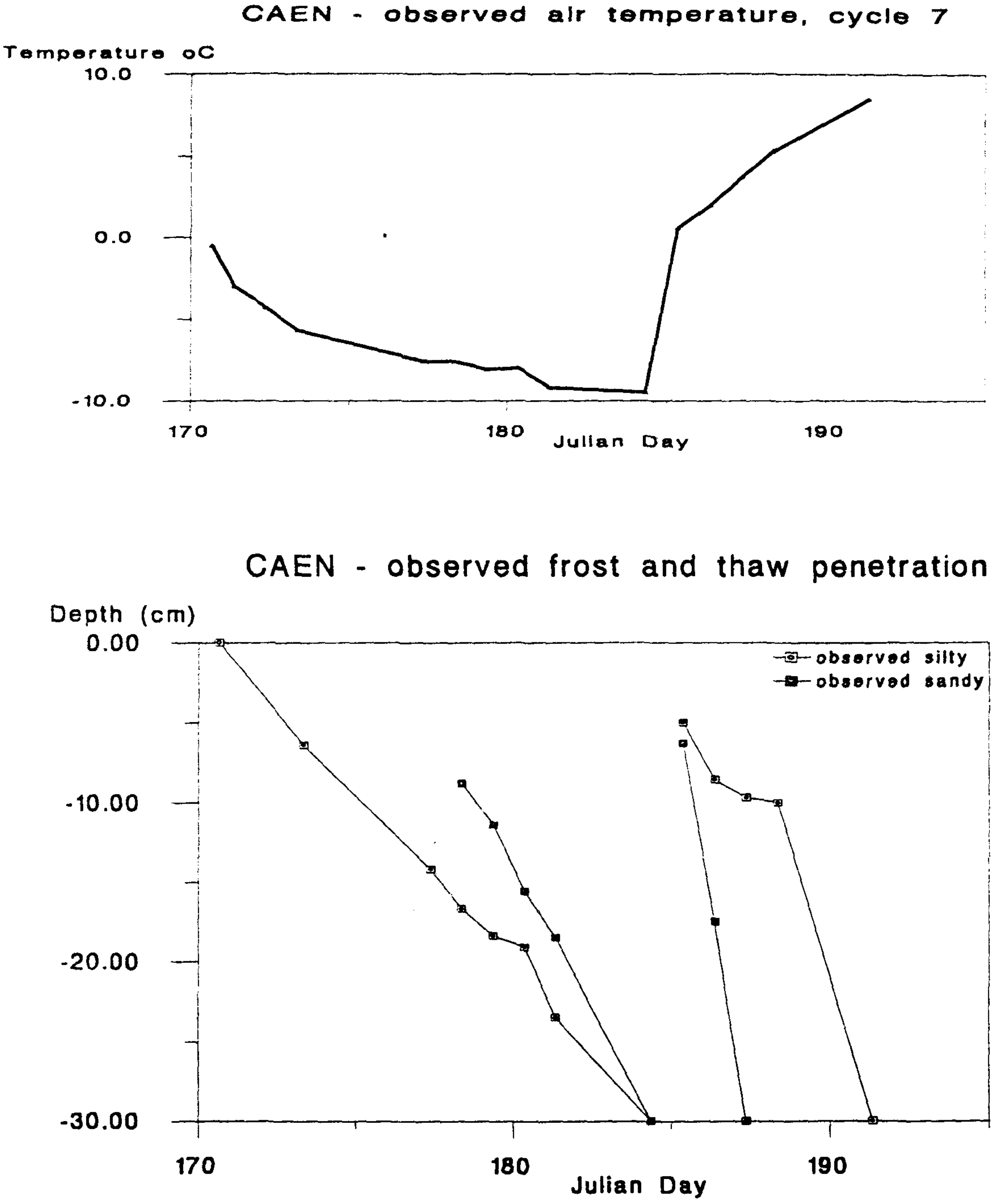
Figure 6: Example simulation of FERF building experiment using the PERIMOVE model.

| | %Clay | %Silt | %Sand | %Gravel | Plastic limit | Liquid limit | c' kPa | O' degrees |
|---|---|---|---|---|---|---|---|---|
| Granite | 6 | 8 | 75 | 11 | - | 34 | 0 | 38 |
| Slate | 7 | 50 | 38 | 5 | 31 | 34 | 0 | 34 |

**mean per cycle rates of downslope soil transport**

| | |
|---|---|
| Granite | 5.8 $cm^3$ per cm width of slope |
| Slate | 31.2 $cm^3$ per cm width of slope |

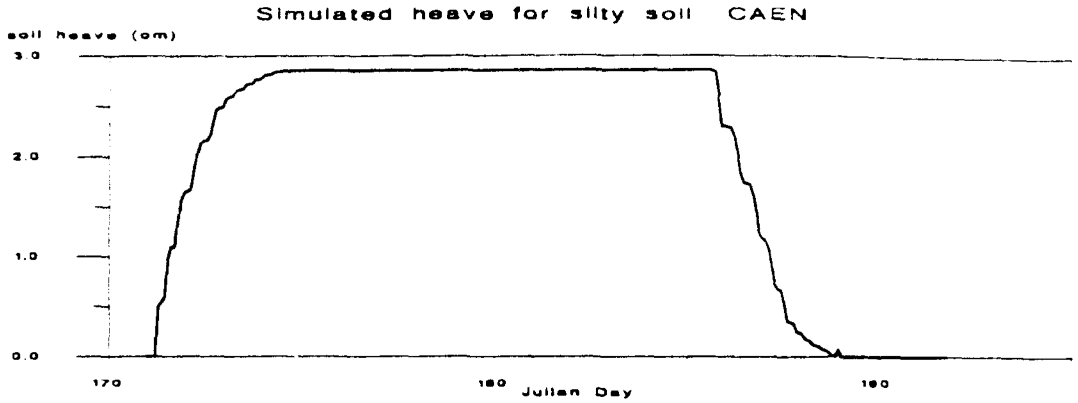
Table 1: Summary of physical properties of soil used in CAEN experiment

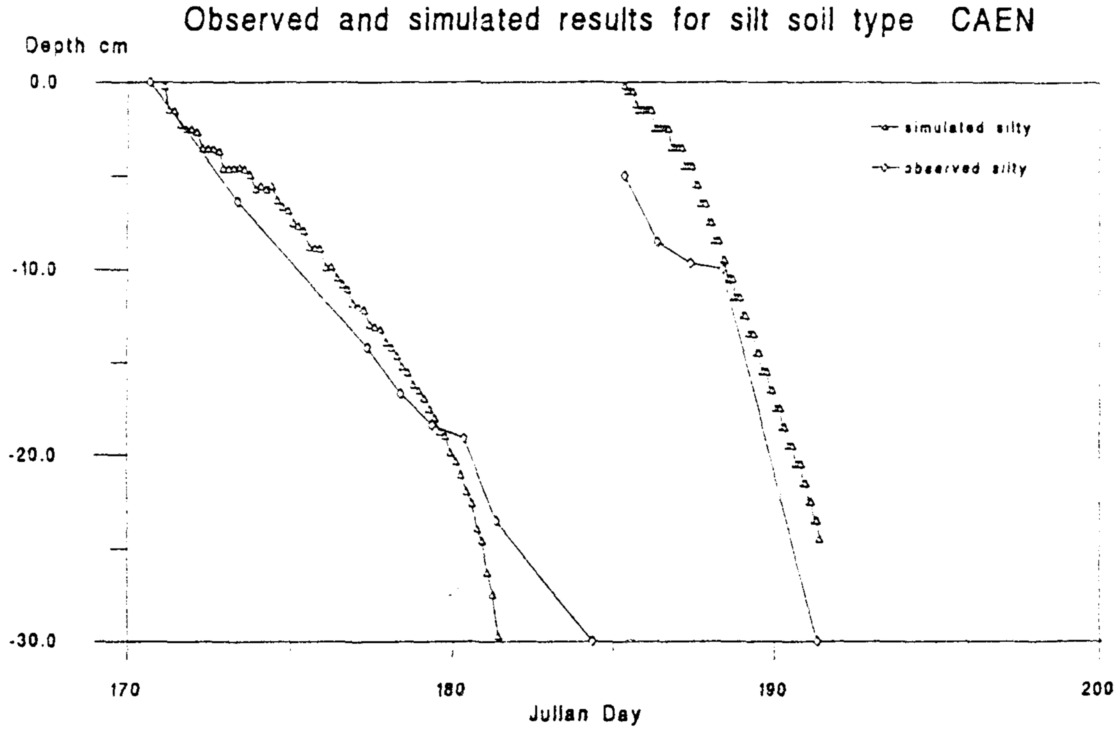


CAEN - observed air temperature, cycle 7

CAEN - observed frost and thaw penetration

Figure 7: Observed ambient temperature and frost thaw depths for the CAEN laboratory experiment





| | |
|---|---|
| Downslope movement at the surface due to creep: | 0.6 cm |
| Downslope movement at the surface due to gelifluction: | 3.6 cm |
| Total downslope movement at surface for freeze/thaw cycle: | 4.2 cm |

Figure 8: Results from simulation of silt soil type for the CAEN experiment

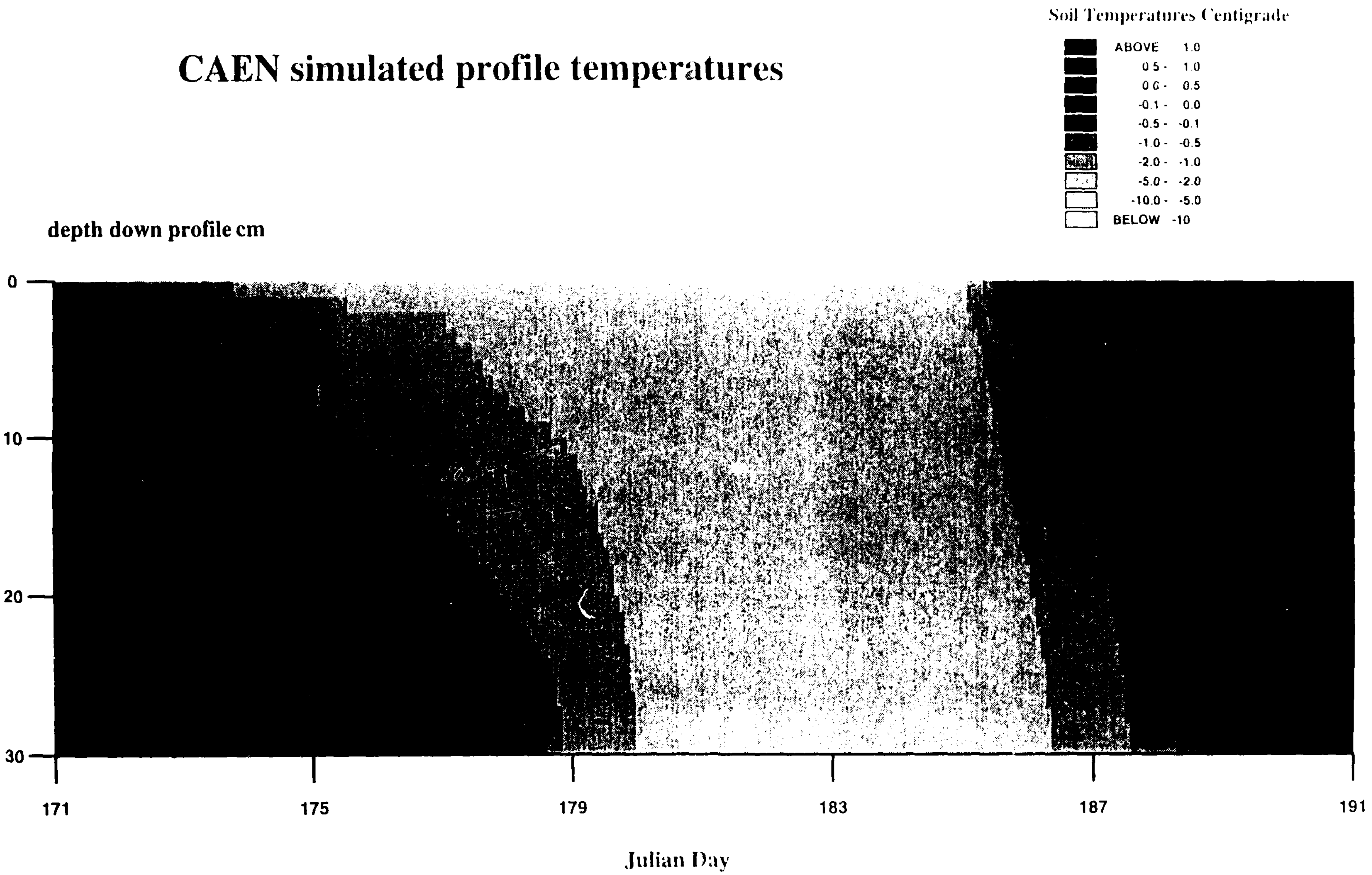


Figure 9: UNIRAS output showing profile temperatures over simulation period for CAEN silt soil.

For the CAEN study the slope angle was 12°. It is not really possible to compare observed and simulated values since the results from the CAEN study were used to determine relationships between excess water contents, soil heave and movement due to gelifuction. Further comparison with other cycles and additional data sources will help to ensure that relationships developed are general in nature.

## 5 CONCLUSIONS REACHED

- The PERIMOVE model is a complex model which is capable of simulating the important processes governing moisture and heat transfer through soils, soil heave and solifluction. The model operation and responses to changes in parameters and input data are as expected.
- very good simulations of observed data have been achieved with the model for a range of experimental conditions.
- Data collection in soil freezing and thawing environments is difficult but new techniques are being developed and many of these concentrate on methods for measuring liquid moisture contents within the soil environment. The collection of further 'internal' data will place further constraints on model validation and ensure that the model is behaving in the desired manner. Routes for further interaction with experimental projects have been identified.
- The PERIMOVE model can also be viewed as a tool to investigate the influence of changing the controlling factors governing freezing, thawing and mass movement to asses the influence of these.

## 6 FUTURE LINES OF RESEARCH ARISING FROM THE PROJECT

Two main lines of further research can be identified which would enhance the capability and applicability of the model. They divide into further improvement to the structure of the model and extensions to the testing and application of the model in association with experimental results.

Firstly to be considered is the extension to a fully 2-dimensional scheme incorporating a constantly deforming grid element structure. These are highly complex to program as model equations must then incorporate a term which includes the velocity due to the movement of the grid as well as the velocity due to the heat or water exchanges. The structure of such schemes has been investigated and a connection made with Mary Albert at CRREL (see for example Albert, 1984 and Albert and O'Neill 1986). Figure 10 shows diagrams of a deforming mesh from Albert (1984) where the movement of the phase boundary was modelled for a drum filled with

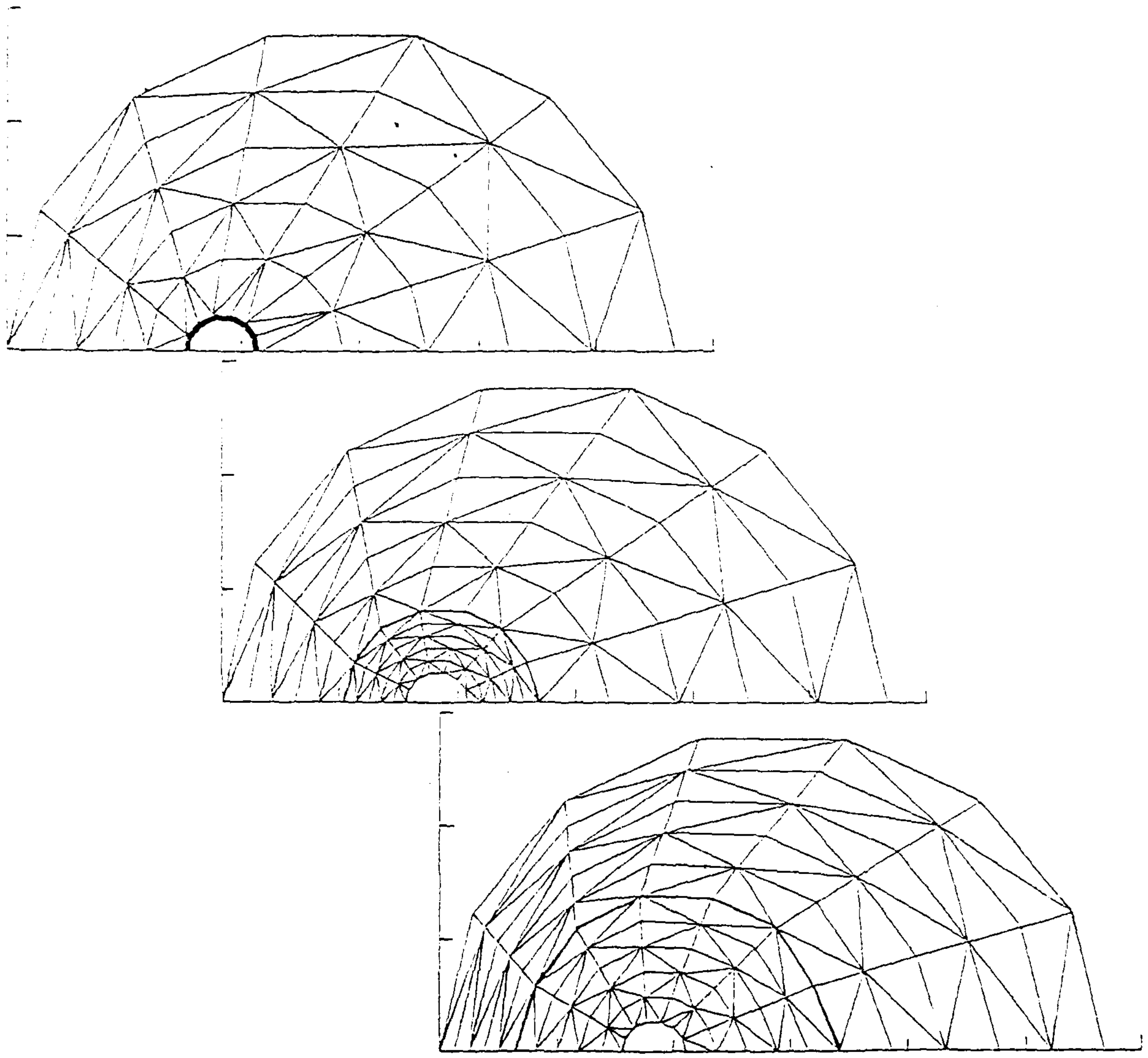


Figure 10: Stages in finite element mesh movement during simulation of freezing around a pipe. The dark line shows the phase front. Albert (1984).

saturated sand in which freezing was instigated by the passage of cold ethylene glycol through a vertical copper pipe situated off-centre within the drum. It may be possible that with the continued development of finite element programming and automatic mesh generation techniques it will eventually be possible to obtain standard deforming grid packages to which the model can be linked. Alternatively, the connections established at CRREL may provide the basis for the development of a scheme to directly link in with the current model.

Secondly, as mentioned in the previous section is the desire to enhance the model by further interaction with observed data sources. Harris *et al* (1993) are continuing the project based at CAEN with a further series of freeze/thaw experiments planned in 1994. Additional data on soil moisture status during freezing will be collected then and the aim is to collect a more comprehensive data set particularly with regard to internal profile conditions during freezing and thawing. They aim to concentrate on two different soil types to highlight the differences between coarse grained sandy soils and finer grained silty soils.

In addition to the use of the model to simulate specific experimental conditions it should be possible to extend the use of the model as a tool in investigating controlling factors on slope movement and development in cold climates. This could be to investigate movements in current cold regions or to try to unravel climatic conditions which could have led to the formation of certain geomorphological features.

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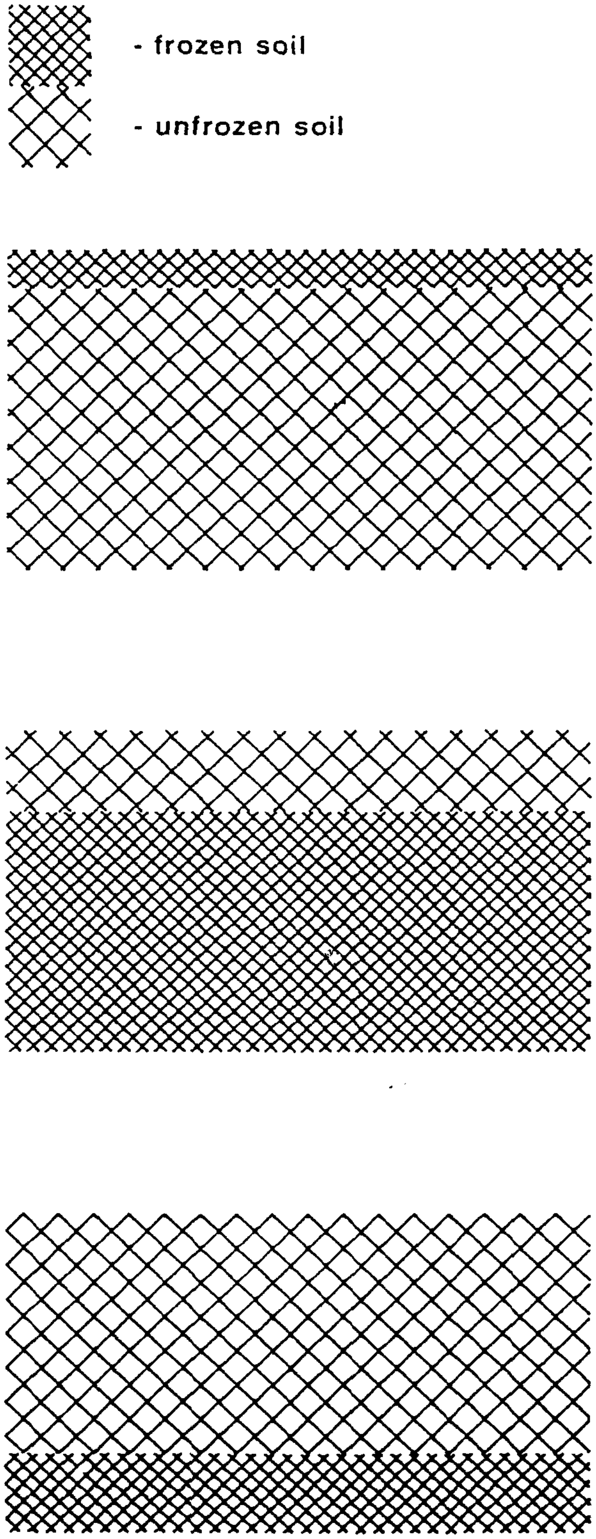

CONDITION (1)

critical depth of frozen soil which will support chosen vehicle

CONDITION (2)

critical depth of unfrozen ('slippery') layer where traction is too low. If tires reach frozen layer then zone may be trafficable.

CONDITION (3)

soil moisture status is critical for determining trafficability. The frozen layer is too far down the profile to give support and acts to impede drainage.

Figure 11: Summary diagram of critical soil trafficability conditions in freeze/thaw environments.

# APPENDIX 1

## Input files required to run PERIMOVE and parameter definitions.

# GUIDE TO THE INPUT FILES REQUIRED TO RUN PERIMOVE

---

The input files are listed in alphabetical order. All inputs are in free format unless otherwise stated.

INDEX:

| | |
|---|---|
| Ambient1.data | initial ambient temperature and number of temperature changes in simulation. |
| Ambt.data | array of ambient temperatures for simulation. |
| Cvin.data | soil freezing parameter data. |
| Hydro.data | soil hydrological property data. |
| InitialH.data | soil hydrological condition at start of simulation. |
| InitialT.data | soil temperature condition at start of simulation. |
| Kcurve.data | ice charateristic curve data. |
| Out.data | output option controls. |
| SM.data | data for suction/moisture curve. |
| *Soli.data* | data for solifluction potential. |
| Struc.data | cell configuration and definition of computational points. |
| TW.data | data for temperature/water curve. |
| Temporal.data | controls for length of simulation. |
| Ttsec.data | time of each temperature change. |

## **Ambient1.data** (unit 49)

| | | |
|---|---|---|
| L1 | | NOTC, STAMBT, BTEMP |
| | NOTC | number of temperature changes in run. |
| | STAMBT | initial ambient temperature (K). |
| | BTEMP | basal boundary temperature (K). |

## **Ambt.data** (unit 48)

| | | |
|---|---|---|
| L1 | | AMBT(NOTC) |
| | AMBT | ambient temperature (K). |

* L1 is repeated NOTC times.

### **Cvin.data** (unit 59)

| | | |
|---|---|---|
| L1 | | UDENS, FDENS, SHCSOIL, CW, CI |
| | UDENS | unfrozen soil bulk density g $m^{-3}$. |
| | FDENS | frozen dry bulk density g $m^{-3}$. |
| | SHCSOIL | specific heat capacity of soil J $g^{-1}$ $K^{-1}$. |
| | CW | specific heat capacity of soil water J $g^{-1}$ $K^{-1}$. |
| | CI | specific heat capacity of ice J $g^{-1}$ $K^{-1}$. |

### **Hydro.data** (unit 57)

| | | |
|---|---|---|
| L1 | | STCON1, STCON2 |
| | STCON1 | saturated soil hydraulic conductivity for soil layer 1 m $s^{-1}$. |
| | STCON2 | saturated soil hydraulic conductivity for soil layer 2 m $s^{-1}$. |
| L2 | | ASR1, ASR2 |
| | ASR1 | saturated soil moisture content for soil layer 1 $m^3$ $m^{-3}$. |
| | ASR2 | saturated soil moisture content for soil layer 2 $m^3$ $m^{-3}$. |
| L3 | | (HYDG(I), I=1,NC) |
| | HYDG | hydraulic gradient under saturated flow - based on slope angle. |
| | NC | number of columns in simulation. |
| L4 | | (ORES1, I=1,NC) |
| | ORES1 | residual soil moisture content for layer 1. |
| L5 | | (ORES2, I=1,NC) |
| | ORES2 | residual soil moisture content for layer 2. |

### **InitialH.data** (unit 54)

| | | |
|---|---|---|
| L1 | | (ATHESP(I,J), J=1,M) |
| | ATHESP | initial soil moisture contents $m^3$ $m^{-3}$. |
| | M | number of cells in column. |

* L1 is repeated NC times.

| | | |
|---|---|---|
| L2 | | (VATHET(I,J), J=1,M) |
| | VATHET | *ice content or potential volume of moisture available for release* on thaw m$^3$ m$^{-3}$. |

## InitialT.data (unit 53)

| | | |
|---|---|---|
| L1 | | (sltp(I,J), J=1,M) |
| | sltp | initial soil temperature (K) for each cell. |
| | M | number of cells in column. |

* L1 is repeated NC times (I=1,NC).

## Kcurve.data (unit 58)

| | | |
|---|---|---|
| L1 | | NKI |
| | NKI | number of values on thermal conductivity of ice with temperature curve (KtI/T). |
| L2 | | (KI(I), I=1,NKI) |
| | KI | thermal conductivity of ice on KtI/T curve W m$^{-1}$ K$^{-1}$. |
| L3 | | (TKI(I), I=1,NKI) |
| | TKI | temperature values on KtI/T curve K. |
| L4 | | NKO |
| | NKO | number of values on thermal conductivty of water with temperature curve (Ktθ/T). |
| L5 | | (KO(I), I=1,NKO) |
| | KO | thermal conductivity of water on Ktθ/T curve W m$^{-1}$ K$^{-1}$. |
| L6 | | (TKO(I), I=1,NKO) |
| | TKO | temperature values on Ktθ/T curve °K. |
| L7 | TDEP | temperature at which ice starts to melt |
| L8 | (KS(I,J), J=1,NNL(I)) | |
| | KS | intrinsic thermal conductivity of soil particles W m$^{-1}$ K$^{-1}$. |

| | | |
|---|---|---|
| | NNL | number of cells in column |

* L8 repeated for each column (I=1,NC).

## **Out.data** (unit 61)

| | | |
|---|---|---|
| L1 | | outmin, nops |
| | outsec | iteration period for output of data (minutes). |
| | nops | number of output data options. |
| L2 | | (option(I), I=1,nops) |
| | option | output data option codes. (see key below) |
| L3 | | nslices |
| | nslices | number of columns for which graphics data are to be written out. |
| L4 | | (slice(K), K=1,nslices) |
| | slice | column for which graphics data is to be written out. |
| L5 | NOCOP | number of cells for which output is required |
| L6 | | (CELLOP(I), I=1,NOCOP) |
| | | cell numbers for which output is required |

*L5 and L6 are repeated for each column (NC times)

| | | |
|---|---|---|
| L7 | outstart | minute from which output is produced |

### Key to PERIMO output options.

Numerical data files with captions.

| OPTION | FILE NAME | FORTRAN UNIT NO. | DATA |
|---|---|---|---|
| 1 | sltp.data | 81 | sltp |
| 2 | ice.data | 82 | VATHET |
| 3 | water.data | 83 | ATHESP |
| 4 | nhflux.data | 84 | NHFLUX |
| 5 | hflux.data | 85 | HFLUX |
| 6 | heatcap.data | 86 | VHC |
| 7 | thermcon.data | 87 | APKT |
| 8 | hydcon.data | 88 | KU |
| 9 | suction.data | 89 | sct |
| 10 | fcum.data | 90 | FCUM |
| 11 | fmax.data | 91 | FMAX |
| 12 | fmin.data | 92 | FMIN |
| 13 | fs.data | 93 | FS |

| | | | |
|---|---|---|---|
| 14 | ath1.data | 94 | ATH1 |
| 15 | vath1.data | 95 | VATH1 |
| 16 | atemp.data | 96 | ATEMP |
| 17 | btflux.data | 97 | BTFLUX |
| 40 | move.data | 40 | GDISP+HDISP |

Graphical data files

| OPTION | FILE NAME | FORTRAN UNIT NO. | DATA |
|---|---|---|---|
| 20 | Gsltp.data | 70 | sltp |
| 21 | Gice.data | 72 | VATHET |
| 22 | Gwater.data | 73 | ATHESP |
| 23 | Gsuction.data | 73 | sct |
| 24 | Ghycond.data | 74 | KP |
| 25 | gtemp.data | 75 | ATEMP |
| 26 | Gkt.data | 76 | KT |
| 27 | Gapkt.data | 77 | APKT |
| 28 | Gfs.data | 78 | FS |
| 29 | Gnhflux.data | 79 | NHFLUX |
| 30 | Ghflux.data | 80 | HFLUX |
| 33 | Gexp.data | 33 | COLHT, COLHT-DEPTHP |
| 34 | Gcelexp.data | 34 | EXP |
| 35 | fort.300-400 | (isotherm position) | ISO,KKK |
| | e.g. fort.302 contains ISO and KKK data for column 2 | | |
| 36 | Gsoilp.data | 36 | SOILP |
| 37 | Gexwat.data | 37 | EXWAT |
| 38 | Gdisplace.data | 38 | HDISP, GDISP |

## **SM.data** (unit 56)

| | | |
|---|---|---|
| L1 | | NQ1, NQ2, KQ |
| | NQ1 | number of observations on suction/moisture curve for hydrological layer 1. |
| | NQ2 | number of observations on suction/moisture curve for hydrological layer 2. |
| | KQ | number of observations on hydraulic conductivity/moisture curve. |
| L2 | | (X1(I), I=1,NQ1) |
| | X1 | moisture values on suction/moisture curve for layer 1 $m^3$ $m^{-3}$. |
| L3 | | (Y1(I), I=1,NQ1) |
| | Y1 | suction values on suction/moisture curve for layer 1 m. |

* lines L2 and L3 are repeated for layer 2 for X2 and Y2.

## **Soli.data** (unit 60)

| | | |
|---|---|---|
| L1 | | GAMMAS, GAMMAU |
| | GAMMAS | saturated unit weight of soil g $m^{-3}$. |
| | GAMMAU | unsaturated unit weight of soil g $m^{-3}$. |
| L2 | | (BETA(I), I=1,NC) |
| | BETA | slope angle in degrees |
| L3 | | (C(I,J), J=1,M) |
| | C | cohesion KPa for each cell (J=1,M). |
| | * L3 is repeated for each column. | |
| L4 | | (PHI(I,J), J=1,M) |
| | PHI | internal friction angle in radians. |
| | * L4 is repeated for each column. | |
| L5 | GELRAT | heave:gelifluction ratio for soil type |

## **Structural.data** (unit 51)

| | | |
|---|---|---|
| L1 | | NC, NOC, LENGTH, BDT |
| | NC | number of columns in simulation |
| | NOC | number of cells in first column of the profile |
| | LENGTH | cell length (m). |
| | BDT | breadth of cell (m) |
| L2 | | (NNL(I), I=1,NC) |
| | NNL | number of cells in each column of the profile. |
| L3 | | (CDEPTH(I,J), dcp(I,J), I=1,NC, J=1,NNL(I)) |
| | CDEPTH | cell depth (m) |
| | dcp | depth to computation point in cell(m) |
| L4 | | (DEPTHP(I), I=1,NC) |
| | DEPTHP | depth of profile in each column (m). |
| L5 | | (HT(I,J), J=1,M) |

| | | |
|---|---|---|
| | HT | height of each computation point above the profile base. |

* L3 is repeated for each column

| | | |
|---|---|---|
| L6 | | (LC1(I), I=1,NC) |
| | LC1 | position (j) of last cell in hydrological layer 1. |
| L7 | | (FC2(I), I=1,NC) |
| | FC2 | position (j) of first cell in hydrological layer 2. |
| L8 | | (TTCOM(I,J), J=1,M) |

depth of cell computation point from surface (m).

* line L8 is repeated for each column.

**TW.data** (unit 55)

| | | |
|---|---|---|
| L1 | | TF |
| | TF | number of observations on characteristic freezing curve. |
| L2 | | (TEMCV(I), I=1,TF) |
| | TEMCV | temperature values on characteristic freezing curve, K (highest first). |
| L3 | | (WATECV(I), I=1,TF) |
| | WATECV | moisture values on characteristic freezing curve ($m^3$ $m^{-3}$). |

**Temporal.data** (unit=50)

| | | |
|---|---|---|
| L1 | | IP, NOSECR |
| | IP | iteration period (seconds). |
| | NOMINR | number of minutes in simulation. |

**Ttsec.data** (unit=52)

| | | |
|---|---|---|
| L1 | | TTSEC(JJJ) |
| | TTSEC | time from start of simulation to temperature change input to PERIMO model (minutes). |
| | JJJ | number of temperature changes during simulation (NOTC). |

# DEFINITIONS OF VARIABLES FOR PERIMOVE

| | |
|---|---|
| AMBT | ambient temperature K. |
| APKT | apparent thermal conductivity W $m^{-1}$ $K^{-1}$ . |
| ASR1 | saturated moisture content for soil type 1 $m^3$ $m^{-3}$. |
| ASR2 | saturated moisture content for soil type 2 $m^3$ $m^{-3}$. |
| ATEMP | Ambient temperature (K). |
| ATH1 | volume of water in cell. |
| ATHESP | soil water content $m^3$ $m^{-3}$. |
| ATHESP1 | soil water volume $m^3$. |
| ATHET | volumetric water content derived from T/0 curve. |
| ATHET1 | water content derived from T/0 curve, $m^3$. |
| AVK | averge hydraulic conductivity m $s^{-1}$. |
| AVKT | Average thermal conductivity across cell boundary. |
| BDT | cell breadth m. |
| BETA | slope angle. |
| BFLUX | volume of flux through base of profile. |
| BISO | depth of basal isotherm. |
| BWFLUX | basal flux. |
| C | cohesion. |
| CDEPTH | Depth (size) of cells (m). |
| CELVOL | cell volume. |
| CH | Temperature change. |
| CHPERC | Temperature change expected given net input or loss of energy on phase change. Calculated per cell. |
| COLHT | height of each soil column. |
| cmdt | Thermal component of energy budget for dT. |
| CVGR | curve gradient on T/0 curve. |
| dcp | depth to computation point in cell. |
| deltaT | Change in temperature during iteration period. |
| deltaw | Change in moisture during iteration period. |
| DEPTHP | depth of profile in each column. |
| DISO | depth from surface at which 273.15K isotherm occurs. |
| EXP | expansion of cell in vertical from original volume. |
| EXSAT | change in moisture content due to saturated flow. |
| EXWAT | excess water content expelled from cell on thawing. |
| FC2 | position (j) of first cell in layer 2. |
| FCUM | cumulative factor of safety per column. |
| FDENS | frozen dry bulk density (g $m^{-3}$). |
| FDMAX | depth of max. FS. |
| FDMIN | depth of min. FS. |
| FLUX | soil water flux between cells, volume. |
| FMAX | maximum factor of safety per column. |
| FMIN | minimum factor of safety per column. |
| FS | factor of safety. |
| G1, G2 | average incremental gradients on suction/moisture curve,layers 1 and 2. |
| GAMMAS | saturated unit weight of soil. |
| GAMMAU | unsaturated weight of soil. |
| GZ1, GZ2 | average incremental gradients on K/0 curve. |
| HFLUX | Heat flux across cell boundary. |
| HPOT | hydraulic potential. |
| HT | height of each computation point above profile base. |
| HYDG | hydraulic gradient sat. flow, ie. slope angle. |
| IKG | incremental gradient on Ktl/T curve. |
| IP | iteration period secs. |
| ISO | depth from previous compn. point at which 273.15K isotherm occurs. |

| | |
|---|---|
| ITT | count for iterations. |
| KI | thermal conductivity of ice, KtI/T curve. |
| KIK | thermal conductivity of ice at given temp. |
| KO | thermal conductivity of water, Kt0/T curve. |
| KOK | thermal conductivity of water at given temp. |
| KP | cell hydraulic conductivity, m $s^{-1}$. |
| KQ | number of observations on K/0 curve. |
| KS | intrinsic thermal conductivity of soil solids. |
| LA | Latent heat of fusion. |
| LAO | hydrological component of energy release for dT. |
| LC1 | position (j) of last cell in layer 1. |
| LENGTH | cell length, m. |
| MORES | Mean residual moisture contents. |
| NC | no. of columns. |
| NEWVOL | updated cell volume followind expansion or resettlement. |
| NFLUX | net water flux of cell. |
| NHFLUX | net heat flux W $m^{-3}$ $s^{-1}$. |
| NKI | number of values on KtI/T curve. |
| NKO | number of values on Kt0/T curve. |
| NNL | number of cells in each column of profile. |
| NNLMAX | maximum number of cells in any of the columns. |
| NOC | number of cells in first column of the profile. |
| NOIT | number of iterations in simulation. |
| NOMINR | number of minutes in run. |
| NOSECR | number of seconds in run. |
| NOTC | number of temperature changes. |
| NQ1, NQ2 | number of observations on suction/moisture curve, layers 1 and 2. |
| NSEIT | number of seconds passed by end of iteration. |
| nslices | number of columns for which graphics data are written. |
| OKG | incremental gradient of Kt0/T curve. |
| option | output data options. |
| ORES1, ORES2 | residual soil moisture content, layer 1 & 2. |
| ORIVOL | cell volume at start of simulation. |
| OUTMIN | iteration period for output data, minutes. |
| OUTSEC | iteration period for output, minutes. |
| OUTSTART | control for start time for output, minutes. |
| PHI | internal friction angle of soil. |
| sct | soil suction in each cell. |
| SEC | difference between nseit and ttsec input. |
| SFI | shape factor ice. |
| SFO | shape factor water. |
| SFS | shape factor solids. |
| SHCSOIL | specific heat capacity of soil (J $m^{-3}$ $K^{-1}$). |
| NC | number of columns. |
| slice | column for which graphics data is to be output. |
| sltp | soil temp. (K). |
| sltpt2 | soil temp calculated by heatrans.f on basis of changing ambient temp. |
| SOILP | percentage volume of soil particles per cell. |
| SOILV | volume of soil solids, $m^{-3}$. |
| STAMBT | starting ambient temperature. |
| STCH | ambient temperature. |
| STCON1 STCON2 | saturated hydraulic conductivity m $s^{-1}$. |
| TEMCV | temperature values on T/0 curve. |
| TEMCV | Temperature values on T/0 curve (K). |
| TF | number of observations on T/0 curve. |
| tgrad | temperature gradient across frozen fringe. |
| TKI | temperature values om KtI/T curve. |
| TKO | temperature values on Kt0/T curve. |

| | |
|---|---|
| TQ | number of observations on Ts/0 curve. |
| TTCOM | depth of cell computation point from surface. |
| TTMIN | time(minutes) from start of run to temperature change. |
| TTSEC | time from start of run for temperature change. |
| UDENS | unfrozen dry bulk density (g m-3). |
| VADFAC | volume adjustment factor for cell expansion/contraction. |
| VATH1 | volume of ice in cell. |
| VATHET | ice content m3 m-3. |
| VOLCH | ratio of volume to original cell volume. |
| VHC | volumetric heat capacity of cell (J m$^{-3}$ K$^{-1}$). |
| WATECV | Moisture values on T/0 curve m$^{3}$ m$^{-3}$. |
| X1, X2 | moisture values on suction moisture curve, layers 1 & 2. |
| Y1, Y2 | suction values on suction moisture curve, layers 1 & 2. |
| Z1, Z2 | conductivity values on conductivity moisture curve, layers 1 & 2. |

# APPENDIX 2

## PERIMOVE model code.

# PERIMOVE FORTRAN CODE

```
c        Program PERIMOVE.f
c
c        ************************************************************
c                   PERIMOVE.F
c        ************************************************************
c        Program to predict the volume of ice present in a soil profile during
c        freezing and thawing.  The program also predicts heave and resettlement
c        of the soil profile and volumetric water excesses following thawing.
c
c        The program calculates the soil temperature at depth, through
c        time, modifies the temperature for transfer of latent heat
c        and updates soil moisture content accordingly.

c        ***************************************************************
c        program PERI
        program perimove
c        ***************************************************************
c        DECLARATION OF VARIABLES
c        ***************************************************************
        DOUBLE PRECISION TTCOM(5,60), HT(5,60),COLHT(5)
        DOUBLE PRECISION LENGTH, CDEPTH(5,60), BDT,CELVOL(5,60)
        DOUBLE PRECISION dcp(5,60),ORIVOL(5,60),VADFAC(5,60)
        DOUBLE PRECISION DEPTHP(5),SOILP(5,60),EXP(5,60),CDEP(5,60)
        DOUBLE PRECISION ATHET(5,60), VATHET(5,60),ATHESP(5,60)
        DOUBLE PRECISION ORES1(50), ORES2(50), X1(50), X2(50)
        DOUBLE PRECISION Y1(50), Y2(50) ,STCON1, STCON2
        DOUBLE PRECISION ASR1, ASR2, sltp(5,60), sltpt2(5,60)
        DOUBLE PRECISION KP(5,60),sct(5,60),EXWAT(5,60)
        DOUBLE PRECISION LA, VHC(5,60), G1(50), G2(50)
        DOUBLE PRECISION Z1(50), Z2(50), GZ1(50), GZ2(50)
        DOUBLE PRECISION FLUX(5,60), NFLUX(5,60), HPOT(5,60)
        DOUBLE PRECISION BWFLUX(50), STATH(5,60), STVATH(5,60)
        DOUBLE PRECISION AVK(5,60), HYDG(50)
        DOUBLE PRECISION TEMCV(50), WATECV(50), CVGR(50),TDEP
        DOUBLE PRECISION APKT(5,60), KT(5,60)
        DOUBLE PRECISION HFLUX(5,60), NHFLUX(5,60)
        DOUBLE PRECISION AMBT(525600), ATEMP(1468800)
        DOUBLE PRECISION STAMBT,BTEMP
        DOUBLE PRECISION FS(5,60), FMIN(50), FMAX(50)
        DOUBLE PRECISION FDMAX(50), FDMIN(50), FCUM(50)
        DOUBLE PRECISION EXSAT(50),ISO(5,60),SOIL1(5,60)
        DOUBLE PRECISION SHATHET(5,60), SHVATHET(5,60)
        DOUBLE PRECISION HTHETAC(50),KI(20),TKI(20),KS(5,60)
        DOUBLE PRECISION KO(20),TKO(20),OKG(20),IKG(20)
        DOUBLE PRECISION C(5,60), BETA(5),MAXCOLHT(5),HDISP(5)
        DOUBLE PRECISION GAMMAS, GAMMAU,GELRAT,GDISP(5)
        DOUBLE PRECISION PHI(5,60)

c       Integers
        INTEGER NC, NNL(5), NOC
        INTEGER NNLMAX, col(50), ncol
        INTEGER SEC(525600)
        INTEGER outsec
        real outmin
        INTEGER NQ1, NQ2, KQ, TF
        INTEGER LC1(50), FC2(50)
        INTEGER option(50)
        INTEGER IP
```

```
      INTEGER NOTC
      INTEGER NSEIT(1468800), ITT, NOIT
      INTEGER NOSECR,NOMINR,TTSEC(525600),TTMIN(525600)
      INTEGER slice(50), nslices
      INTEGER isocol(50), isoncol
      INTEGER  NKO, NKI,KKK
      INTEGER NOCOPV,NNLMA,CELL
      INTEGER NOCOP(30),CELLOP(5,60)
      INTEGER OUTSTART,OUTTIM

      COMMON DUMMY(5,60)
c
c      *************************************************************
c      OPEN STATEMENTS
c      *************************************************************
      open(unit=20, file='DATAIN/Mb.data', status='old')
      rewind 20

      open(unit=21, file='DATAIN/Iso.data', status='old')
      rewind 21

c       open(unit=32, file='DATAIN/massbal.data',status='unknown')
c      rewind 32

     open(unit=48, file='DATAIN/Ambt.data', status='old')

     open(unit=49,file='DATAIN/Ambient1.data',status='old')
     rewind 49

     open(unit=50, file='DATAIN/Temporal.data',status='old')
     rewind 50

     open(unit=51, file='DATAIN/Struc.data', status='old')
     rewind 51

     open(unit=52,file='DATAIN/Ttsec.data',status='old')

     open(unit=53,file='DATAIN/InitialT.data', status='old')
     rewind 53

      open(unit=54,file='DATAIN/InitialH.data',status='old')
      rewind 54

      open(unit=55,file='DATAIN/TW.data',status='old')
      rewind 55

      open(unit=56,file='DATAIN/SM.data',status='old')
      rewind 56

      open(unit=57,file='DATAIN/Hydro.data',status='old')
      rewind 57

      open(unit=58 , file='DATAIN/Kcurve.data', status='old')
      rewind 58

      open(unit=59, file='DATAIN/Cv.data', status='unknown')
      rewind 59
```

```
        open(unit=60, file='DATAIN/Soli.data',status='old')
        rewind 60

        open(unit=61, file='DATAIN/Out.data', status='old')
        rewind 61

        OUTTIM=1
c       ************************************************************
c       TEMPORAL.data   unit 50
c       ************************************************************
c       Read iteration time and no. of minutes in run.
        read(50,*)IP, NOMINR
c       convert no. of minutes in run to no of seconds
        NOSECR=NOMINR*60

c       ************************************************************
c       STRUCTURAL.data    unit 51
c       ************************************************************
c       Space dimensions.
        READ(51,*)NC, NOC, LENGTH, BDT

c       Number of cells in each column
        READ(51,*)(NNL(I),I=1,NC)

c       calculate volume of each cell and store in ORIVOL for volume
c       change calculations.  Initialise volume adjustment factors.
        DO 16 I=1,NC
           DO 17 J=1,NNL(I)
           READ(51,*) CDEPTH(I,J),dcp(I,J)
           CELVOL(I,J)=LENGTH*BDT*CDEPTH(I,J)
           ORIVOL(I,J)=CELVOL(I,J)
           VADFAC(I,J)=1.0
           EXP(I,J)=0.0
           CDEP(I,J)=CDEPTH(I,J)
17      CONTINUE
16      CONTINUE
c

c
        NNLMAX=0
        DO 1 I=1,NC
        IF(NNL(I).GT.NNLMAX)THEN
        NNLMAX=NNL(I)
        ENDIF
1       CONTINUE
c
c       Depth of profile in each column.
        READ(51,*)(DEPTHP(I),I=1,NC)
c
c       Height of computation point above profile base.
        DO 2 I=1,NC
        M=NNL(I)
        READ(51,*)(HT(I,J),J=1,M)
2       CONTINUE
c
c       Define LC1 and FC2.
        READ(51,*)(LC1(I),I=1,NC)
        READ(51,*)(FC2(I),I=1,NC)
```

```
c
c     Depth of each computation point from surface.
      DO 3 I=1,NC
      M=NNL(I)
      READ(51,*)(TTCOM(I,J),J=1,M)
3      CONTINUE
      do 3012 I=1,NC
      write(39,*)depthp(i)
      MAXCOLHT(I)=DEPTHP(I)
      do 3013 J=1,M
      WRITE(39,*)I,J,HT(I,J),TTCOM(I,J),CELVOL(I,J)
3013    CONTINUE
3012    CONTINUE

c     ************************************************************
c     INITIALT.data
c     ************************************************************
c     Starting soil temperatures.
      DO 4 I=1, NC
      M=NNL(I)
      READ(53,*)(sltp(I,J),J=1,M)
4      CONTINUE
c     ************************************************************
c     INITIALH.data     unit 54
c     ************************************************************
c     Starting moisture conditions
      DO 5 I=1,NC
      M=NNL(I)
      read(54,*)(ATHESP(I,J),J=1,M)
5      continue

c     Starting ice content
      DO 60 I=1,NC
      M=NNL(I)
      read(54,*)(VATHET(I,J),J=1,M)
60     continue
c     ************************************************************
c     TW.data       unit 55
c     ************************************************************
c     Number of values on soil water characteristic curve for temps
c     below 273.15K. (Temperature and moisture values)
c     Ambient thermal conductivity
      READ(55,*)TF

c     Values on soil water characteristic curve.
      READ(55,*)(TEMCV(I),I=1,TF)
      READ(55,*)(WATECV(I),I=1,TF)

c     ************************************************************
c      Ktcurve.data     unit
c     ************************************************************
c     Read no. of values on KI/T curve
      read(58,*)NKI

c     Read KI and T values on KI/T curve
      read(58,*)(KI(I),I=1,NKI)
      read(58,*)(TKI(I),I=1,NKI)
```

```
c      Read no. of values on KO/T curve
       read(58,*)NKO

c      Read KO and T values on KO/T curve
       read(58,*)(KO(I),I=1,NKO)
       read(58,*)(TKO(I),I=1,NKO)

c      Read thaw initiation temperature TDEP
       read(58,*)TDEP

c      Read values for intrinsic thermal conductivity of soil particles
       do 25 I=1,NC
       read(58,*)(KS(I,J),J=1,NNL(I))
25       continue


c      Establish thermal conductivity of water
c      Incremental gradients on K/0 curve
       do 26 I=1,NKO-1
       OKG(I)=(KO(I+1)-KO(I))/(TKO(I+1)-TKO(I))
26       continue

c      Incremental gradients on K/I curve
       do 27 I=1,NKI-1
       IKG(I)=(KI(I+1)-KI(I))/(TKI(I+1)-TKI(I))
27       continue


c      *************************************************************
c      SM.data   unit 56
c      *************************************************************
c      Number of observations on suction moisture curve, Ku/moisture
c      curve.
       READ(56,*)NQ1, NQ2, KQ


c      Values of moisture and suction on suction moisture curve.
       READ(56,*)(X1(I),I=1,NQ1)

       READ(56,*)(Y1(I),I=1,NQ1)

       READ(56,*)(X2(I),I=1,NQ2)

       READ(56,*)(Y2(I),I=1,NQ2)
c      ****************************************************************
c      HYDRO.data       unit 57
c      ****************************************************************
c      Saturated hydraulic conductivity
       READ(57,*)STCON1, STCON2

c      Saturated moisture content for layers 1 and 2, and hydraulic gradient
c      (slope angle)
       READ(57,*)ASR1, ASR2
       READ(57,*)(HYDG(I),I=1,NC)
c      Initialise starting volumetric contents of soil solids
       DO 591 I=1,NC
```

```
        M=NNL(I)
        DO 592 J=1,M
          if(J.LE.LC1(I))SOILP(I,J)=1.0-ASR1
          if(J.GE.FC2(I))SOILP(',J)=1.0-ASR2
          SOIL1(I,J)=SOILP(I,J)*CELVOL(I,J)
592     continue
591     continue
c
c      Residual soil moisture content for layers 1 and 2.
       READ(57,*)(ORES1(I),I=1,NC)
       READ(57,*)(ORES2(I),I=1,NC)
c      ************************************************************
c        READ IN STABILITY DATA
c      ************************************************************
        READ(60,*)GAMMAS, GAMMAU

        READ(60,*)(BETA(I),I=1,NC)

        DO 40 I=1,NC
        M=NNL(I)
        READ(60,*)(C(I,J),J=1,M)
40        CONTINUE

        DO 41 I=1,NC
        M=NNL(I)
        READ(60,*)(PHI(I,J),J=1,M)
41        CONTINUE

        DO 42 I=1,NC
        M=NNL(I)
        READ(60,*)GELRAT
42        CONTINUE

c      ************************************************************
c      OUT.data       unit 61
c      ************************************************************
c      Iteration period of output, number of data sets.
       read(61,*)outmin,nops
c      convert iteration period to seconds
       outsec=outmin*60
c      Data set definitions
       read(61,*)(option(I),I=1,nops)
c      Graphics, column data to sent to graphics files.
       read(61,*)nslices
       read(61,*)(slice(K),K=1,nslices)

       do 598 I=1,NC
       READ(61,*)NOCOP(I)
       NOCOPV=NOCOP(I)
       READ(61,*)(CELLOP(I,M),M=1,NOCOPV)
598      CONTINUE

       do 601 I=1,NC
       M=1
       CELL = CELLOP(I,M)
       NNLMA=NNL(I)
        DO 602  J=1,NNLMA
        IF(CELL.EQ.J)THEN
```

```
        DUMMY(I,J)=1
        M=M+1
        CELL=CELLOP(I,M)
         ELSE
        DUMMY(I,J)=0
        ENDIF
602      CONTINUE

601      CONTINUE
c       read time in minutes at which output is to start
        READ(61,*) OUTSTART
        OUTSTART=OUTSTART*60


c      ************************************************************
c      Mb.data
c      ************************************************************
c      Number of columns for which mass balance data is to be written
       read(20,*)ncol

c      Column numbers for which mass balance data is to be written
       do 350 I=1,ncol
       read(20,*)col(I)
350      continue
c      ************************************************************
c      iso.data
c      ************************************************************
c      Number of columns for which isotherm is to be identified
       read(21,*)isoncol

c      Column numbers  for which isotherm is to be identified
       do 351 I=1,isoncol
       read(21,*),isocol(I)
351      continue
c      ************************************************************
c      INITIAL SECTION
c      ************************************************************
c      MILLINGTON and QUIRK method is used  to calculate
c      hydraulic  conductivity for each layer from a given
c      soil moisture characteristic curve.
c
       NQJ=NQ1
c
c      Layer 1
       DO 6 I=1,NQJ
       IIJ=NQJ-I+1
       XII=X1(IIJ)
       TOPS=0.0
       BOTS=0.0
       DO 7 J=1,NQJ
       JF=NQJ-J+1
       YJJ=Y1(JF)
7      BOTS=((2*J-1)*YJJ**(-2))+BOTS
       II=I
       DO 8 J=II,NQJ
       JF=NQJ-J+1
       YJJ=Y1(JF)
8      TOPS=((2*J+1-2*I)*YJJ**(-2))+TOPS
```

```
      JT=NQJ-I+1

      Z1(JT)=STCON1*(XII/ASR1)*TOPS/BOTS
      open(unit=2,file='zval',status='unknown')
6      write(2,*)JT,Z1(JT),XII

c      Layer 2
      NQJ=NQ2
      DO 9 I=1,NQJ
      IIJ=NQJ-I+1
      XII=X2(IIJ)
      TOPS=0.0
      BOTS=0.0
      DO 10 J=1,NQJ
      JF=NQJ-J+1
      YJJ=Y2(JF)
10     BOTS=((2*J-1)*YJJ**(-2))+BOTS
      II=I
      DO 11 J=II,NQJ
      JF=NQJ-J+1
      YJJ=Y2(JF)
11     TOPS=((2*J+1-2*I)*YJJ**(-2))+TOPS
      JT=NQJ-I+1

9     Z2(JT)=STCON2*(XII/ASR2)*TOPS/BOTS

c     Calculate gradients on suction/moisture curves, K/moisture
c     curve, and T/moisture characteristic curve.

c     Calculate average incremental gradients of suction-moisture
c     and K-moisture curves.
c     Layer 1
      DO 12 I=1,NQ1-1
      G1(I)=(Y1(I+1)-Y1(I))/(X1(I+1)-X1(I))
      GZ1(I)=(Z1(I+1)-Z1(I))/(X1(I+1)-X1(I))
12     CONTINUE

c      Layer 2
      DO 13 I=1,NQ2-1
      G2(I)=(Y2(I+1)-Y2(I))/(X2(I+1)-X2(I))
      GZ2(I)=(Z2(I+1)-Z2(I))/(X2(I+1)-X2(I))
13     CONTINUE

c     T/0 curve.
      DO 14 I=1,TF-1
      CVGR(I)=(WATECV(I+1)-WATECV(I))/(TEMCV(I+1)-TEMCV(I))
14     CONTINUE
c     ****************************************************************
c     SET PARAMETERS
c     ****************************************************************
c     Latent heat of fusion, units J g-1
      LA=333.2852
c     ****************************************************************
c     DYNAMIC SECTION
c     ****************************************************************
c     Set number of iterations
c     Iterations = no. of seconds in run/ iteration period
```

```
      NOIT=NOSECR/IP

      read(49,*)NOTC,STAMBT,BTEMP


      DO 600 KKK=1,NOIT
      ITT=KKK

        DO 650 I=1,NC
        M=NNL(I)
        DO 651 J=1,M
        STATH(I,J)=ATHESP(I,J)
        STVATH(I,J)=VATHET(I,J)
651       CONTINUE
650       CONTINUE

c      Second marking the end of iteration
      NSEIT(KKK)=ITT*IP

      JJJ=0

c      Set up loop for the number of temp. changes in data set.
      DO 500 JJJ=1,NOTC
         if(JJJ.eq.1)then
          rewind 52
          rewind 48
         endif

c      read in time in minutes of next temperature change
      read(52,*)TTMIN(JJJ)
c      convert this value to seconds
      TTSEC(JJJ)=TTMIN(JJJ)*60
      read(48,*)AMBT(JJJ)

c      ------------------------------------------------------------------
      if(TTSEC(JJJ).gt.NSEIT(KKK))then

      if(KKK.eq.1)then
      SEC(JJJ)=TTSEC(JJJ)
      ATEMP(KKK)=STAMBT+(((AMBT(JJJ)-STAMBT)/SEC(JJJ))
     &  *IP)
      endif

      if(KKK.gt.1)then
      ATEMP(KKK)=ATEMP(KKK-1)+(((AMBT(JJJ)-ATEMP(KKK-1))
     &  /(TTSEC(JJJ)-NSEIT(KKK-1)))*IP)
      endif

        do 900 NN=1,nops
         if(option(NN).eq.31)then
         open(unit=8, file='atemp.data', status='unknown')
         rewind 8
         open(unit=9, file='Gatemp.data', status='unknown')
         rewind 9
        write(8,*)'ATEMP=',ATEMP(KKK),'KKK=',KKK
        write(9,*)ATEMP(KKK),KKK
        endif
900       continue
```

```
        goto 700
       endif

c      -----------------------------------------------------------
         if(TTSEC(JJJ).eq.NSEIT(KKK))then
         ATEMP(KKK)=AMBT(JJJ)
          do 1000 NN=1,nops
           if(option(NN).eq.31)then
            open(unit=8,file='atemp.data',status='unknown')
            rewind 8
            open(unit=9, file='Gatemp.data', status='unknown')
            rewind 9
            write(8,*)'ATEMP=',ATEMP(KKK),'KKK=',KKK
            write(9,*)ATEMP(KKK),KKK
          endif
1000        continue
         goto 700
         endif

       if(TTSEC(JJJ).lt.NSEIT(KKK))goto 500


500     continue

700     call ku(NC, LC1, FC2, KQ, ATHESP,
   &    X1, X2, Z1, Z2, GZ1, GZ2, KP)

       call kta(VATHET, ATHESP, CELVOL,
   &    sltp, NNLMAX, NC, NNL, ASR1, ASR2, LA,
   &    APKT, KT,KI,NKI,KO,NKO,TKI,TKO,KS,OKG,IKG,SOILP)

       call heatrans(ATEMP, CDEPTH, sltp, sltpt2,
   &   VATHET, NC, NNL, VHC, LENGTH, option,
   &   ATHESP, NNLMAX, BDT, TEMCV, WATECV,
   &   TF, LA, ORES1, ORES2, CVGR, ATHET, HFLUX, NHFLUX,
   &   APKT, STAMBT, IP, KKK, LC1, FC2, ASR1, ASR2,
   &   SHVATHET,CELVOL,ORIVOL,VADFAC,SOILP,SOIL1,TDEP,BTEMP,EXWAT)

       call masstrans(NC,LC1,NQ1,ATHESP,X1,Y1,G1,FC2,NNL,
   &        Y2,G2,HT,KP,KQ,Z1,GZ1,Z2,GZ2,CDEPTH,LENGTH,
   &        sct,HPOT,AVK,FLUX,NFLUX,HYDG,IP,DEPTHP,TTCOM,dcp,
   &        BDT, X2, NQ2, STCON1, STCON2, ASR1, ASR2,
   &        EXSAT, BWFLUX, HTHETAC, SHATHET,VATHET,COLHT,
   &        CDEP,EXP,vadfac,MAXCOLHT)


c      call massbal(ATHESP, VATHET, NC, NNL, STATH, STVATH,
c  &        NFLUX, KKK, EXSAT, NSEIT, BWFLUX, HTHETAC,
c  &        SHATHET, SHVATHET, col, ncol, nops, option)


       call soli(NC, NNL, NNLMAX, TTCOM, sct, FS, FDMAX, FDMIN,
   &       FMAX, FMIN, FCUM,GAMMAS,GAMMAU,BETA,C,PHI,maxcolht,
   &       DEPTHP,HDISP,GELRAT,GDISP)

       if(mod(NSEIT(KKK),outsec).eq.0.and.NSEIT(KKK).ge.OUTSTART)
   &   call doutput(outsec,nops,
   &   option,NC,sltp,VATHET,ATHESP,sct,KP,NHFLUX,HFLUX,
```

```
     &  VHC,FCUM,FMIN,FDMIN,FMAX,FDMAX,FS,APKT,KKK,NNLMAX,
     &  NOTC, ATH1, VATH1, TTSEC, ATEMP, BTFLUX, KT, nslices,
     &  slice,OUTTIM,DEPTHP,COLHT,EXP,SOILP,HDISP,EXWAT,GDISP)


       do 888 NN=1,nops
       if(option(NN).eq.35)then
       if(mod(NSEIT(KKK),outsec).eq.0)call isotherm(NC, sltp,
     &  TTCOM,dcp,KKK,NNL,ATEMP,ISO,outsec,isocol,isoncol,
     &  nops,option)
       endif
888     continue



600    continue

      DO I=1,NC
      write(40,*)'total downslope displacement at surface'
      write(40,*)'column ',I, (GDISP(I)+HDISP(I))*100,' cm'
      enddo
c
c
c
     stop
     end
```

```
c     Subroutine Cv.f
c
c     Calculates volumetric heat capacity of a soil cell given
c     intrinsic thermal properties of soil mineralogy, and relative
c     proportions of soil ice and water.
c
c     DEFINITIONS
c     Volumetric heat capacity (Cv) is the amount of heat required to change
c     the temperature of a unit volume of a substance by 1K.
c     Units = KJ / m-3 . K
c
c     For unfrozen soil
c     Cvu = d(Cs + Cw W/100)
c
c     For frozen soil
c     Cvf = df(Cs + Cw W/100 + Ci I/100)
c
c       Cvu = volumetric heat capacity of unfrozen soil (J m-3 K-1)
c       Cvf = volumetric heat capacity of frozen soil (m-3 K-1)
c         d = dry bulk density of unfrozen soil (g m-3)
c        df = dry bulk density of frozen soil (g m -3)
c        Cs = specific heat capacity of dry mineral matter (J g-1 K-1)
c        Cw =   "     "     "    " water (J g-1 K-1)
c        Ci =   "     "     "    " ice (J g -1 K -1)
c         W = water (volumetric %)and W/100 is unit % ie. ATHESP
c         I = ice (volumetric %) and I/100 is unit % ie. VATHET
c
c     **************************************************************
      subroutine Cv(NC,NNL,VHC,ATHESP,VATHET,TT,NNLMAX)
c     **************************************************************
c     DECLARATION OF VARIABLES
c     **************************************************************
      DOUBLE PRECISION UDENS, FDENS, SHCSOIL, VHC(5,60)
      DOUBLE PRECISION CW, CI, ATHESP(5,60),VATHET(5,60)

      INTEGER NC, NNL(5), TT, NNLMAX

c     **************************************************************
c     OPEN STATEMENTS
c     **************************************************************
      open(unit=59, file='DATAIN/Cvin.data', status='unknown')
      rewind 59
c     **************************************************************
c     READ DATA INPUT FILE
c     **************************************************************
      READ(59,*)UDENS, FDENS, SHCSOIL., CW, CI
c     **************************************************************

c     DYNAMIC SECTION
c     **************************************************************

c     Values of ice and water transferred from main program are already in
c     % volumetric terms.
c     Determine whether soil cell contains ice.
      DO 1 I=1,NC
      M=NNL(I)
```

```
        DO 2 J=1,M
c        Frozen soil. VHC units = J m -3 K-1.
        IF(VATHET(I,J).GT.0.0)VHC(I,J)=FDENS*
     &  (SHCSOIL+(CW*ATHESP(I,J))+(CI*VATHET(I,J)))

c        Unfrozen soil. VHC units = J m -3 K-1.
        IF(VATHET(I,J).LE.0.0)VHC(I,J)=UDENS*(SHCSOIL+
     &  (CW*ATHESP(I,J)))


2       CONTINUE
1       CONTINUE
        return
        end
```

```
c       Subroutine freeze.f

c       ************************************************************
c       Program freeze.f
c       ************************************************************
c       freeze is entered if the net heat flux for a cell is negative
c       as calculated in heatrans.f

       subroutine freeze(ATHESP, TEMCV, WATECV, NC,
     & TF, sltp, sltpt2, CVGR, VHC, LA, TT, LENGTH, CDEPTH,
     & VATHET, BDT, ORES1, ORES2, ATHET, option, I, J, KKK,
     & ASR1, ASR2,CELVOL,VADFAC,SOILP)

c       DECLARATION OF VARIABLES
c       ************************************************************
       DOUBLE PRECISION ATHESP(5,60), ATHET(5,60)
       DOUBLE PRECISION ATHESP1(5,60), ATHET1(5,60)
       DOUBLE PRECISION VATHET(5,60),VATADD(5,60)
       DOUBLE PRECISION TEMCV(50), WATECV(50)
       DOUBLE PRECISION sltpt2(5,60), sltp(5,60), CVGR(50)
       DOUBLE PRECISION deltaT(5,60), deltaW(5,60), cmdt(5,60)
       DOUBLE PRECISION LAO(5,60), VHC(5,60), LA
       DOUBLE PRECISION CH(5,60),VADFAC(5,60),NEWVOL(5,60)
       DOUBLE PRECISION LENGTH, CDEPTH(5,60), BDT
       DOUBLE PRECISION ORES1(50), ORES2(50), MORES(50)
       DOUBLE PRECISION CHPERC(5,60), TEMPCH(5,60),SOILP(5,60)
       DOUBLE PRECISION ASR1, ASR2, ADFAC(5,60),CELVOL(5,60)


       INTEGER NC, TF, TFMAX,  option, I, J, KKK

       ADFAC(I,J)=1.0

c       ************************************************************
c       DYNAMIC SECTION
c       ************************************************************
c       Freezing conditions in cell?
       IF((sltpt2(I,J)-273.15).LT.1.0e-10)GOTO 12
       IF(sltpt2(I,J).LE.273.15)GOTO 12
       IF((sltpt2(I,J)-273.15).GT.1.0e-10)THEN
       sltp(I,J)=sltpt2(I,J)
        GOTO 2
        ENDIF


c       New soil temperature at end of iteration has been calculated by
c       heatrans.f, (sltpt2), using the 0/T characteristic curve.
c       Establish corresponding soil moisture content for temperature
c       sltpt2.
c       The value returned from the O/T curve is adjusted by the volume
c       change factor for the cell.  This means that the absolute volume of
c       water at a given temperature is the same whilst the volumetric
c       percentage will be decreased if expansion has taken place.

c       Calculate dt deltaT, for iteration period. (K)
12      IF(sltp(I,J).GT.273.15)deltaT(I,J)=273.15-sltpt2(I,J)
       IF(sltp(I,J).LE.273.15)deltaT(I,J)=sltp(I,J)-sltpt2(I,J)
```

```
      IF(deltaT(I,J).EQ.0.0D-10)THEN
         GOTO 2
         ENDIF
      IF(sltpt2(I,J).GE.TEMCV(1))ATHET(I,J)=WATECV(1)
      TFMAX=TF
      IF(sltpt2(I,J).LE.TEMCV(TFMAX))ATHET(I,J)=WATECV(TFMAX)

      DO 4 K=1,TF-1
      IF(sltpt2(I,J).LE.TEMCV(K).AND.sltpt2(I,J).GT.TEMCV(K+1))
     & ATHET(I,J)=WATECV(K)+CVGR(K)*(sltpt2(I,J)-TEMCV(K))
4      CONTINUE
      ATHET(I,J)=ATHET(I,J)/VADFAC(I,J)
c     ------------------------------------------------------------------

c      Calculate dW deltaW.
c      Calculate mean residual moisture content and adjust for any volume
c      change that has occurs based on the absolute residual moisture
c      content being unchanged.
      MORES(I)=((ORES1(I)+ORES2(I))/2)/VADFAC(I,J)

c      Balance checks, ATHESP must not fall below residual moisture content
c      adjusted for cell volume.  The assumption is made that the residual
c      moisture content for a cell is an absolute volume and not a unit
c      percentage so it is adjusted for any change in volume.

      IF(DABS(ATHESP(I,J)-MORES(I)).LT.1.0D-10)ATHESP(I,J)=MORES(I)
c      .........no further freezing unless water migrates to cell.

      IF(ATHESP(I,J).LT.MORES(I))ATHESP(I,J)=MORES(I)
c      .........no further freezing unless water migrates to cell.

c      Convert ATHESP from %volume to volume m3.
      ATHESP1(I,J)=CELVOL(I,J)*ATHESP(I,J)


c      Balance checks , ATHET must not fall below residual moisture content.
      IF(DABS(ATHET(I,J)-MORES(I)).LT.1.0D-10)ATHET(I,J)=MORES(I)

      IF(ATHET(I,J).LT.MORES(I))ATHET(I,J)=MORES(I)

c      Convert ATHET from %volume to volume m3.
      ATHET1(I,J)=CELVOL(I,J)*ATHET(I,J)

c      d0, deltaW m3
      deltaW(I,J)=ATHESP1(I,J)-ATHET1(I,J)

c      *****************************************************************
c      cmdt, thermal component of energy budget. J (m-3 K-1).
      cmdt(I,J)=((VHC(I,J)*CELVOL(I,J))*deltaT(I,J))

c      LAO, hydrological component of energy budget. J (m-3).
      LAO(I,J)=(LA*1000000.0)*deltaW(I,J)
c      *****************************************************************
c      PHASE CHANGE LOGIC

c      dQ = La d0  dt - cmdt
c           dt
c      *****************************************************************
```

```
c     If change in moisture content is negative, (given the predicted
c     temperature change and isothermal nature of pase change in previous
c     iteration), phase change cannot occur. Energy is therefore not
c     released as a hydrological response to transient thermal conditions
c     and thus has no effect on the temperature of the cell.

      IF(deltaW(I,J).LE.0.0)THEN
c     .........no further change in 0 or I
      sltp(I,J)=sltpt2(I,J)
      GOTO 2
      ENDIF

c     ****************************************************************
c     LAO = cmdt

      IF(DABS(LAO(I,J)-cmdt(I,J)).LT.1.0D-10)THEN
c     ........isothermal phase change occurs.

c     Temperature
c     ........reset temperature to that before heat transfer, i.e. temp
c     processes.

c     Ice
c      VATHET(I,J)=VATHET(I,J)+(ATHESP(I,J)-ATHET(I,J))
      VATADD(I,J)=(ATHESP(I,J)-ATHET(I,J))*1.09
      VATHET(I,J)=VATHET(I,J)+VATADD(I,J)

c     Moisture
      ATHESP(I,J)=ATHET(I,J)
c     ........where ATHET is defined by the characteristic curve for
c     sltpt2.

c     determine if new volumetric total exceeds unity
      NEWVOL(I,J)=VATHET(I,J)+ATHESP(I,J)+SOILP(I,J)
      IF(NEWVOL(I,J).GT.1.0)THEN
       ADFAC(i,j)=NEWVOL(I,J)
       VATHET(I,J)=VATHET(I,J)/ADFAC(I,J)
       ATHESP(I,J)=ATHESP(I,J)/ADFAC(I,J)
       SOILP(I,J)=SOILP(I,J)/ADFAC(I,J)
       CDEPTH(I,J)=CDEPTH(I,J)*ADFAC(I,J)
       CELVOL(I,J)=CELVOL(I,J)*ADFAC(I,J)
      endif

      GOTO 2
      ENDIF

c     COMMENT
c     Moisture content is set to ATHET on characteristic curve as defined
c     by sltpt2, however after phase change release of energy, the temp.
c     returns to sltp. Therefore at the beginning of the next time step,
c     soil water and temperature are not in accordance with the
c     characteristic curve. ie. the soil moisture content is less than
c     normally expected given the cell temperature. 0 in next iteration
c     is set to ATHET->ATHESP.
c     ----------------------------------------------------------------
c     LAO<cmdt
c       NEW IF STATEMENT
      IF(deltaW(I,J).GE.0.0)THEN
```

```
c       IF(LAO(I,J).LT.cmdt(I,J))THEN

c       ........no isothermal phase change, cell cools. Energy released by
c       cooling of cell (thermal component), is partially compensated by
c       phase change energy release. Temperature is not maintained at
c       273.15 K, rather the cell cools by an amount equivalent to LAO given
c       the volumetric heat capacity of the soil mixture.
c       Temperature
c       Calculate the temperature change expected by an input of 1J.
       TEMPCH(I,J)=1.0/VHC(I,J)

c       Temperature change given the cell volume.
       CHPERC(I,J)=TEMPCH(I,J)/CELVOL(I,J)
       CH(I,J)=LAO(I,J)*CHPERC(I,J)
       sltp(I,J)=sltpt2(I,J)+CH(I,J)

c      Isothermal ???
       if(sltp(I,J).gt.273.15)sltp(I,J)=273.15

       VATADD(I,J)=(ATHESP(I,J)-ATHET(I,J))*1.09
       VATHET(I,J)=VATHET(I,J)+VATADD(I,J)
c        VATHET(I,J)=VATHET(I,J)+(ATHESP(I,J)-ATHET(I,J))
       ATHESP(I,J)=ATHET(I,J)

c      determine if new volumetric total exceeds unity
       NEWVOL(I,J)=VATHET(I,J)+ATHESP(I,J)+SOILP(I,J)
       if(NEWVOL(I,J).GT.1.0)THEN
        ADFAC(i,j)=NEWVOL(I,J)
        VATHET(I,J)=VATHET(I,J)/ADFAC(I,J)
        ATHESP(I,J)=ATHESP(I,J)/ADFAC(I,J)
        SOILP(I,J)=SOILP(I,J)/ADFAC(I,J)
        CDEPTH(I,J)=CDEPTH(I,J)*ADFAC(I,J)
        CELVOL(I,J)=CELVOL(I,J)*ADFAC(I,J)
       endif

       ENDIF
c      ****************************************************************
2       return
       end
```

```
c       Subroutine heatrans.f

c      Subroutine calculates flux of heat energy in one dimension on basis
c      of thermal conductivity of medium and temperature gradient.
c      Temperature of cells are updated given the volumetric heat capacity
c      of the medium, modified on each iteration for changing ice and water
c      content.
c
c
c        C dT  = -d ( k dT )
c          dt    dx    dx
c
c       where
c         C = volumetric heat capacity     J m -3 K -1
c         x = depth                        m
c         t = time                         sec
c         k = thermal conductivity         Jsec m -1 K-1
c         T = temperature                  K
c
c       and
c         1 W = 1 J sec
c
c
c
c         Subroutine contains time element for thermal conductivity
c         Kt. W m-1 K-1    where 1W = 1 J sec
c             i.e. multiply thermal conductivity entered in input file
c               by iteration period in seconds.
c      *****************************************************************

      subroutine heatrans(ATEMP, CDEPTH, sltp, sltpt2,
   &   VATHET, NC, NNL, VHC, LENGTH, option,
   &   ATHESP, NNLMAX, BDT, TEMCV, WATECV, TF, LA,
   &   ORES1, ORES2, CVGR, ATHET, HFLUX, NHFLUX, APKT,
   &   STAMBT,IP, KKK, LC1, FC2, ASR1, ASR2,
   &   SHVATHET,CELVOL,ORIVOL,VADFAC,SOILP,SOIL1,TDEP,BTEMP,EXWAT)

       *****************************************************************
c
c      DECLARATION OF VARIABLES
c      *****************************************************************
      DOUBLE PRECISION ATEMP(1468800), sltp(5,60), sltpt2(5,60)
      DOUBLE PRECISION CDEPTH(5,60), VATHET(5,60), AVKT(5,60)
      DOUBLE PRECISION NHFLUX(5,60), BTFLUX(50), HFLUX(5,60)
      DOUBLE PRECISION LENGTH, TCHA(5,60),CELVOL(5,60)
      DOUBLE PRECISION ATHESP(5,60), ATHET(5,60), BDT
      DOUBLE PRECISION VHC(5,60), WATTS(5,60)
      DOUBLE PRECISION TEMCV(50), WATECV(50), LA, CVGR(50),TDEP
      DOUBLE PRECISION ORES1(50), ORES2(50),EXWAT(5,60)
      DOUBLE PRECISION APKT(5,60), STAMBT,BTEMP
      DOUBLE PRECISION ASR1, ASR2,SOILP(5,60),SOIL1(5,60)
      DOUBLE PRECISION SHVATHET(5,60),VADFAC(5,60),ORIVOL(5,60)


      INTEGER NC, NNL(5), option, NNLMAX
      INTEGER LC1(50), FC2(50)
      INTEGER TF, I, J, IP, KKK

c      *****************************************************************
```

```
c     DYNAMIC SECTION
c     ****************************************************************

c     Call subroutine Cv.f for calculation of volumetric heat capacities
c     in each cell of matrix.
      call Cv(NC,NNL,VHC,ATHESP,VATHET,TT,NNLMAX)

      DO 666 I=1,NC
      M= NNL(I)
      DO 667 J=1,M
      SHVATHET(I,J)=VATHET(I,J)
c     calculate volume adjustment factor (VADFAC) before going through
c     heatrans and on to thaw or freeze
      VADFAC(I,J)=CELVOL(I,J)/ORIVOL(I,J)
667     CONTINUE
666     CONTINUE

c     SURFACE BOUNDARY CONDITIONS

c     Mean thermal conductivity across surface interface.
      DO 1 I=1,NC
      J=1
      AVKT(I,J)=APKT(I,J)

c     Surface boundary heat flux.
c     Divide by 0.5 x cell depth.

      HFLUX(I,J)=((AVKT(I,J)*IP)*((ATEMP(KKK)-sltp(I,J))/
     & (0.5*CDEPTH(I,J))))*(LENGTH*BDT)
1     CONTINUE

c     PROFILE HEAT FLUX
c     Mean thermal conductivities across cell boundaries.
      DO 2 I=1,NC
      M=NNL(I)
      DO 3 J=2,M
      AVKT(I,J)=((APKT(I,J)*CDEPTH(I,J))+(APKT(I,J-1)*
     &        CDEPTH(I,J-1)))/(CDEPTH(I,J)+CDEPTH(I,J-1))


c     Heat flux across cell boundaries. Jsec cm-3 -K.
      HFLUX(I,J)=((AVKT(I,J)*IP)*((sltp(I,J-1)-sltp(I,J))/
     &         ((CDEPTH(I,J)+CDEPTH(I,J-1))/2)))*(LENGTH*BDT)

3     CONTINUE
2     CONTINUE

c     Basal heat flux. Jsec m-3 -K
      DO 4 I=1,NC
      J=NNL(I)

c     btemp set as input basal temperature
c     also possible to set btflux to zero if do not want basal heat supply
      btflux(i)=((avkt(i,j)*ip)*((sltp(i,j)-btemp)/cdepth(i,j)))*
     &        (length*bdt)
4     CONTINUE

c     Net heat flux across all cell boundaries. J cm-3 -K.
```

```
      DO 5 I=1,NC
      M=NNL(I)
      DO 6 J=1,M

c      Net flux of heat across all boudaries
      IF(J.NE.NNL(I))NHFLUX(I,J)=HFLUX(I,J)-HFLUX(I,J+1)

c      Basal cell net heat flux.
      IF(J.EQ.NNL(I))NHFLUX(I,J)=HFLUX(I,J)-BTFLUX(I)

6      CONTINUE
5      CONTINUE

c      Temperature change of all cells in matrix
      DO 7 I=1,NC
      M=NNL(I)
      DO 8 J=1,M

c      Calculate Joules required to change temperature by 1K
      WATTS(I,J)=1.0/VHC(I,J)

c      Temperature change.
      TCHA(I,J)=(WATTS(I,J)/(LENGTH*CDEPTH(I,J)*BDT))*NHFLUX(I,J)

c      New soil temperature.
      sltpt2(I,J)=sltp(I,J)+TCHA(I,J)

8      CONTINUE
7      CONTINUE

c      ****************************************************************
208      DO 888 I=1,NC
      M=NNL(I)
      DO 999 J=1,M

        IF(NHFLUX(I,J).GT.0.0)THEN
        call thaw(sltpt2, TF, LENGTH,
     &   CDEPTH, BDT, ATHESP, VATHET, VHC, sltp, NC, LA,
     &   NHFLUX, I, J, KKK,CELVOL,VADFAC,SOILP,ORIVOL,SOIL1,
     &   ASR1,ASR2,LC1,FC2,TDEP,EXWAT)
        ENDIF
c
        IF(NHFLUX(I,J).LE.0.0)THEN
        call freeze(ATHESP, TEMCV, WATECV, NC, TF, sltp,
     &   sltpt2, CVGR, VHC, LA, TT, LENGTH, CDEPTH, VATHET,
     &   BDT, ORES1, ORES2, ATHET, option, I, J, KKK,
     &   ASR1, ASR2,CELVOL,VADFAC,SOILP)
        ENDIF


999    CONTINUE
888    CONTINUE

c      ****************************************************************
      return
      end
```

```
c         subroutine isotherm.f
c        ************************************************************
c        This subroutine defines and writes out the depth of the 273.15K
c        isotherm to a file which may then be converted into a graphical
c        plot.
c
c        ************************************************************
         subroutine isotherm(NC, sltp, TTCOM, dcp,
     &    KKK, NNL, ATEMP,ISO,outsec,isocol,isoncol,
     &    nops,option)

c         DECLARATION OF VARIABLES

         DOUBLE PRECISION sltp(5,60), ATEMP(1468800)
         DOUBLE PRECISION TTCOM(5,60), dcp(5,60)
         DOUBLE PRECISION ISO(5,60), DISO(5,60)
         DOUBLE PRECISION SISO(5,60),TCH(5,60),TG(5,60)
c         DOUBLE PRECISION TISO(525600), BISO(525600)



         INTEGER KKK, NC, NNL(5)
         INTEGER outsec, MM
         INTEGER isoncol, isocol(50)
         INTEGER nops, option(50)


c        ************************************************************
c        SURFACE CELLS
c        Does 273.15K isotherm lie between surface and first compn. point?
         DO 1 I=1,isoncol


         M=NNL(I)
         DO 2 J=1,M

           II=isocol(I)

            if(J.eq.1)then
            if(sltp(II,J).le.273.15.and.ATEMP(KKK).gt.273.15)then

c        Temperature gradient
         TG(II,J)=(ATEMP(KKK)-sltp(II,J))/dcp(II,j)

c        What is the temperature difference between surface and 273.15K?
         TCH(II,J)=ATEMP(KKK)-273.15

c        At what depth from the surface does the isotherm occur?
         ISO(II,J)=TCH(II,J)/TG(II,J)

              if(ISO(II,J).le.0.0)goto 140

c        Write isotherm data to files with suffix 300-399

         do 506 NN=1,nops
           if(option(NN).eq.35)then
         MM=(II+300)
```

```
          write(MM,*)ISO(II,J),KKK
            endif
506         continue

140               endif


c         ---------------------------------------------------------------
            if(sltp(II,J).gt.273.15.and.ATEMP(KKK).le.273.15)then
          TG(II,J)=(sltp(II,J)-ATEMP(KKK))/dcp(II,j)
          TCH(II,J)=273.15-ATEMP(KKK)
          SISO(II,J)=TCH(II,J)/TG(II,J)
          ISO(II,J)=SISO(II,J)

              if(ISO(II,J).le.0.0)goto 150


c         Write isotherm data to files with suffix 300-400
          do 501 NN=1,nops
            if(option(NN).eq.35)then
          MM=(II+300)
          write(MM,*)ISO(II,J),KKK
          endif
501         continue

150             endif

          endif


c         ***************************************************************
c         PROFILE CELLS


            if(J.gt.1)then

c         Does 273.15K isotherm lie between computation points of cells
c         J-1 and J.
          if(sltp(II,J).le.273.15.and.sltp(II,J-1).gt.273.15)then

c         Temperature gradient
          TG(II,J)=(sltp(II,J-1)-sltp(II,J))/(dcp(II,J)+dcp(II,J-1))


c         What is the temperature difference between cell J-1 and 273.15?
          TCH(II,J)=sltp(II,J-1)-273.15

c         At what depth from compn. point of cell J-1 does 273.15 isotherm
c         occur?
          DISO(II,J)=TCH(II,J)/TG(II,J)

c         Depth of isotherm from surface.
          ISO(II,J)=TTCOM(II,J-1)+DISO(II,J)

              if(ISO(II,J).le.0.0)goto 160


          do 502 NN=1,nops
```

```
           if(option(NN).eq.35)then
         MM=(II+300)
         write(MM,*)ISO(II,J),KKK
           endif
502        continue


160          endif
c        ------------------------------------------------------------
        if(sltp(II,J).gt.273.15.and.sltp(II,J-1).le.273.15)then
        TG(II,J)=(sltp(II,J)-sltp(II,J-1))/(dcp(II,J)+dcp(II,J-1))
        TCH(II,J)=273.15-sltp(II,J-1)
        DISO(II,J)=TCH(II,J)/TG(II,J)
        ISO(II,J)=TTCOM(II,J)+DISO(II,J)

          if(ISO(II,J).le.0.0)goto 170


         do 503 NN=1,nops
           if(option(NN).eq.35)then
         MM=(II+300)
         write(MM,*)ISO(II,J),KKK
           endif
503        continue


170        endif


         endif


2     continue
1     continue


        return
        end
```

```
c     Subroutine kta.f

c     Sub routine kta.f calculates temperature dependent thermal
c     conductivity (W m-1 K-1) for each cell of profile. The system is
c     assumed to comprise three phases, soil solids, water and ice.


      subroutine kta(VATHET, ATHESP,CELVOL,
   &  sltp, NNLMAX, NC, NNL, ASR1, ASR2, LA,
   &  APKT,KT,KI,NKI,KO,NKO,TKI,TKO,KS,OKG,IKG,SOILP)

c     ***************************************************************
c     DECLARATION OF VARIABLES
c     ***************************************************************
      DOUBLE PRECISION KI(20),TKI(20),KO(20),TKO(20)
      DOUBLE PRECISION VATHET(5,60), ATHESP(5,60),CELVOL(5,60)
      DOUBLE PRECISION KS(5,60), sltp(5,60), SOILV(5,60)
      DOUBLE PRECISION KOK(5,60), KIK(5,60), ASR1, ASR2
      DOUBLE PRECISION VATH1(5,60), ATH1(5,60),SOILP(5,60)
      DOUBLE PRECISION SFI(5,60), SFO, SFS(5,60)
      DOUBLE PRECISION KT(5,60), APKT(5,60),LA,IKG(20),OKG(20)


     INTEGER NKI, NKO, NC, NNL(5), NNLMAX, NKOMAX, NKIMAX

c     ***************************************************************
c     DYNAMIC SECTION
c     ***************************************************************
c     Derive volume of soil soilds per cell
     DO 10 I=1,NC
      M=NNL(I)
       DO 20 J=1,M
       SOILV(I,J)=CELVOL(I,J)*SOILP(I,J)

c     Derive volume of ice per cell
       VATH1(I,J)=CELVOL(I,J)*VATHET(I,J)

c     Derive volume of water per cell
       ATH1(I,J)=CELVOL(I,J)*ATHESP(I,J)

20       continue
10      continue


c     Extrapolation from curve
c     Water
     DO 40 I=1,NC
     M=NNL(I)
     DO 41 J=1,M
     if(sltp(I,J).GE.TKO(1))KOK(I,J)=KO(1)
     NKOMAX=NKO
     if(sltp(I,J).LE.TKO(NKOMAX))KOK(I,J)=KO(NKOMAX)
     do 4 K=1,NKO-1
     if(sltp(I,J).LE.TKO(K).AND.sltp(I,J).GT.TKO(K+1))
   &  KOK(I,J)=KO(K)+OKG(K)*(sltp(I,J)-TKO(K))
4    continue
41    continue
40    continue
```

```
c     Ice
      DO 60 I=1,NC
      M=NNL(I)
      DO 70 J=1,M
      if(sltp(I,J).GE.TKI(1))KIK(I,J)=KI(1)
      NKIMAX=NKI
      if(sltp(I,J).LE.TKI(NKIMAX))KIK(I,J)=KI(NKIMAX)

      do 5 K=1,NKI-1
      if(sltp(I,J).LE.TKI(K).AND.sltp(I,J).GT.TKI(K+1))
     & KIK(I,J)=KI(K)+IKG(K)*(sltp(I,J)-TKI(K))
5     continue

70    continue
60    continue
c     Derive shape factor for water
      SFO=1.0D00

c     Derive shape factor for ice
      DO 50 I=1,NC
      M=NNL(I)
      DO 51 J=1,M
      SFI(I,J)=(1.0D00/3.0D00)
     & *((1.0D00/(1.0D00+((KIK(I,J)/KOK(I,J))-1.0D00)*0.125))
     & +(1.0D00/(1.0D00+((KIK(I,J)/KOK(I,J))-1.0D00)*0.125))
     & +(1.0D00/(1.0D00+((KIK(I,J)/KOK(I,J))-1.0D00)*0.750)))

c     Derive shape factor for soil solids
      SFS(I,J)=(1.0D00/3.0D00)
     & *((1.0D00/(1.0D00+((KS(I,J)/KOK(I,J))-1.0D00)*0.125))
     & +(1.0D00/(1.0D00+((KS(I,J)/KOK(I,J))-1.0D00)*0.125))
     & +(1.0D00/(1.0D00+((KS(I,J)/KOK(I,J))-1.0D00)*0.750)))

c     Calculate thermal conductivity of the cell W m-1 K-1
      KT(I,J)=((ATH1(I,J)*KOK(I,J)*SFO)
     & +(VATH1(I,J)*KIK(I,J)*SFI(I,J))
     & +(SOILV(I,J)*KS(I,J)*SFS(I,J)))
     & /((ATH1(I,J)*SFO)+(VATH1(I,J)*SFI(I,J))
     & +(SOILV(I,J)*SFS(I,J)))


      APKT(I,J)=KT(I,J)


51    continue
50    continue

      return
      end
```

```
c     Subroutine ku.f

c     Subroutine ku.f calculates hydraulic conductivity
c     for all cells in the profile


      subroutine ku(NC, LC1, FC2, KQ, ATHESP,
     &   X1, X2,Z1, Z2, GZ1, GZ2, KP)

c     Z1  Z2...........curve gradients on suction/moisture curve.

      DOUBLE PRECISION ATHESP(5,60),X1(50),X2(50)
      DOUBLE PRECISION Z1(50),Z2(50),GZ1(50),GZ2(50),KP(5,60)

      INTEGER NC, KQ, LC1(50), FC2(50)

c     ****************************************************************
c     DYNAMIC SECTION
c     ****************************************************************

      DO 1 I=1,NC
      M=LC1(I)
      DO 2 J=1,M
      if(KQ.gt.20)write(428,*)KQ,athesp(i,j),i,j,kp(i,j)
      DO 3 K=1,KQ-1
      IF(ATHESP(I,J).GT.X1(K).AND.ATHESP(I,J).LE.X1(K+1))
     & KP(I,J)=Z1(K)+GZ1(K)*(ATHESP(I,J)-X1(K))
      IF(ATHESP(I,J).LE.X1(1))KP(I,J)=Z1(1)
      IF(ATHESP(I,J).GT.X1(20))KP(I,J)=Z1(20)
3     CONTINUE
2     CONTINUE
1     CONTINUE

      DO 4 I=1,NC
      M=LC1(I)
      N=FC2(I)
      DO 5 J=M,N
      DO 6 K=1,KQ-1
      IF(ATHESP(I,J).GT.X2(K).AND.ATHESP(I,J).LE.X2(K+1))
     & KP(I,J)=Z2(K)+GZ2(K)*(ATHESP(I,J)-X2(K))
      IF(ATHESP(I,J).LE.X2(1))KP(I,J)=Z2(1)
      IF(ATHESP(I,J).GT.X2(20))KP(I,J)=Z2(20)
6     CONTINUE
5     CONTINUE
4     CONTINUE

      return
      end
```

```
c       Subroutine masstrans.f

c       Subroutine masstrans.f, is used to reasses the distribution of
c       water in the soil profile after freezing or thawing have occurred,
c       on the basis of Darcy's Law.

c
        subroutine masstrans(NC,LC1,NQ1,ATHESP,X1,Y1,G1,FC2,NNL,
     &       Y2,G2,HT,KP,KQ,Z1,GZ1,Z2,GZ2,CDEPTH,LENGTH,
     &       sct,HPOT,AVK,FLUX,NFLUX,HYDG,IP[illegible]TTCOM,dcp,
     &       BDT, X2, NQ2, STCON1, STCON2, [illegible], EXSAT,
     &       BWFLUX, HTHETAC, SHATHET,VATHET,COLHT,CDEP,EXP,
     &       VADFAC,MAXCOLHT)
c
c
        DOUBLE PRECISION SHATHET(5,60),ASR1,ASR2,ATHESP(5,60)
        DOUBLE PRECISION ATHESPT(5,60),VATHET(5,60)
        DOUBLE PRECISION STCON1, STCON2
        DOUBLE PRECISION Y1(50),Y2(50),G1(50),G2(50),X1(50),X2(50)
        DOUBLE PRECISION sct(5,60), HPOT(5,60),CDEP(5,60),EXP(5,60)
        DOUBLE PRECISION HT(5,60),CDEPTH(5,60),LENGTH,BDT
        DOUBLE PRECISION AVK(5,60),KP(5,60),GZ1(50),GZ2(50)
        DOUBLE PRECISION FLUX(5,60), NFLUX(5,60),BWFLUX(5)
        DOUBLE PRECISION COLHT(5),CUMHT,MAXCOLHT(5)
        DOUBLE PRECISION Z2(50), Z1(50),vadfac(5,60)
c
        INTEGER NC, LC1(50), FC2(50), NQ1, NQ2, KQ, NNL(5),IP
c
c       UNSATURATED FLOW
c       Soil water pressure (suction)
c       Layer 1
        DO 20 I=1,NC
        M=LC1(I)
        DO 30 J=1,M
c       is saturated set suction to zero
        IF (ATHESP(I,J).GE.ASR1)THEN
        SCT(I,J)=0.0
        ELSEIF(ATHESP(I,J).LT.X1(1))THEN
        SCT(I,J)=Y1(1)
        ELSE
        K=NQ1-1
        DO 40 L=1,K
        IF(ATHESP(I,J).GE.X1(L).AND.ATHESP(I,J).LT.X1(L+1))THEN
        sct(I,J)=Y1(L)+G1(L)*(ATHESP(I,J)-X1(L))
        ENDIF
40       CONTINUE
        ENDIF
30       CONTINUE
20       CONTINUE
c
c
c       Layer 2
        DO 50 I=1,NC
        M=FC2(I)
        N=NNL(I)
        DO 60 J=M,N
        IF (ATHESP(I,J).GE.ASR2)THEN
        SCT(I,J)=0.0
```

```
      ELSEIF(ATHESP(I,J).LT.X2(1))THEN
      SCT(I,J)=Y2(1)
      ELSE
      K=NQ2-1
      DO 70 L=1,K
      IF(ATHESP(I,J).GE.X2(L).AND.ATHESP(I,J).LT.X2(L+1))THEN
      sct(I,J)=Y2(L)+G2(L)*(ATHESP(I,J)-X2(L))
      ENDIF
70     CONTINUE
      ENDIF
60     CONTINUE
50     CONTINUE
c
c
c      calculate cell mid-point heights, total column height
c      and volume expansion of each cell
      DO 151  I=1,NC
      M=NNL(I)
      CUMHT=0.0
      COLHT(I)=0.0
        DO 152  J=M,1,-1
c      find height of midpoint of cell
        CUMHT=CUMHT+(CDEPTH(I,J)/2.0)
c       cell expansion calculated as value in mm
        EXP(I,J)=(CDEPTH(I,J)-CDEP(I,J))*1000
        HT(I,J)=CUMHT
c       convert CUMHT to height of column so far
        CUMHT=CUMHT+(CDEPTH(I,J)/2.0)
        COLHT(I)=COLHT(I)+CDEPTH(I,J)
152      CONTINUE
      IF(COLHT(I).GT.MAXCOLHT(I))MAXCOLHT(I)=COLHT(I)
151    CONTINUE

c      Hydraulic potential
      DO 80 I=1,NC
      DO 90 J=1,NNL(I)
      HPOT(I,J)=sct(I,J)+HT(I,J)
90     CONTINUE
80     CONTINUE
c
c
c      Hydraulic conductivity
c      Layer 1
      DO 100 I=1,NC
      M=LC1(I)
      DO 110 J=1,M
      IF(ATHESP(I,J).GE.ASR1) THEN
      KP(I,J)=STCON1
      ELSEIF(ATHESP(I,J).LT.X1(1))THEN
      KP(I,J)=Z1(1)
      ELSE
      DO 120 K=1,KQ-1
      IF(ATHESP(I,J).GE.X1(K).AND.ATHESP(I,J).LT.X1(K+1))
     & KP(I,J)=Z1(K)+GZ1(K)*(ATHESP(I,J)-X1(K))
120    CONTINUE
      ENDIF
110    CONTINUE
100    CONTINUE
```

```
c
c
c        Layer 2
         DO 130 I=1,NC
         M=FC2(I)
         N=NNL(I)
         DO 140 J=M,N
         IF(ATHESP(I,J).GE.ASR2)THEN
         KP(I,J)=STCON2
         ELSEIF(ATHESP(I,J).LT.X2(1))THEN
         KP(I,J)=Z2(1)
         ELSE
         DO 150 K=1,KQ-1
         IF(ATHESP(I,J).GE.X2(K).AND.ATHESP(I,J).LT.X2(K+1))
   &     KP(I,J)=Z2(K)+GZ2(K)*(ATHESP(I,J)-X2(K))
150        CONTINUE
         ENDIF
140        CONTINUE
130        CONTINUE
c
c
c        Mean hydraulic conductivity for surface cells
         DO 1401 I=1,NC
         J=1
         AVK(I,J)=KP(I,J)
c         write(6,*) 'kp',KP(I,J),'avk', AVK(I,J)
1401       CONTINUE


c        Mean hydraulic conductivity for profile cells
         DO 160 I=1,NC
         DO 170 J=2,NNL(I)
c        if freezing has started use upper cell conductivity as average
c        conductivity as a guide to ability to draw up water
          IF(VATHET(I,J-1).GT.0.0)THEN
          AVK(I,J)=KP(I J-1)
             ELSE
         AVK(I,J)=((KP(I,J-1)*CDEPTH(I,J-1))+(KP(I,J)*CDEPTH(I,J)))/
   &             (CDEPTH(I,J-1)+CDEPTH(I,J))
          ENDIF
170       CONTINUE
160       CONTINUE
c
c
c        Convert hydraulic conductivity, m sec-1 into m IP-1
          DO 600 I=1,NC
          M=NNL(I)
          DO 601 J=1,M
         AVK(I,J)=AVK(I,J)*IP
601        CONTINUE
600        CONTINUE

c        Calculate flux across surface boundary
         DO 302 I=1,NC
         J=1
        FLUX(I,J)=0.0
302       CONTINUE
```

```
c      Calculate flux between cells, (vol m-3 hr)
       DO 180 I=1,NC
       M=NNL(I)
       DO 190 J=2,M
       FLUX(I,J)=(((HPOT(I,J-1)-HPOT(I,J))*AVK(I,J))/((CDEPTH(I,J-1)
    &   +CDEPTH(I,J))/2))*(LENGTH*BDT)
c      approach to stemming downward flux if cell below is
c      saturated with water or water+ice.
      if(flux(i,j).gt.0.0.and.vadfac(i,j+1).gt.1.0)flux(i,j)=0.0
190      CONTINUE
180      CONTINUE
c
c
c      Basal water flux
       DO 303 I=1,NC
       J=NNL(I)
       BWFLUX(I)=(AVK(I,J)*(0.5*CDEPTH(I,J)))*(LENGTH*BDT)
303     CONTINUE

c      Calculate net flux for each cell
       DO 200 I=1,NC
       M=NNL(I)
       DO 210 J=1,M

c      Profile net water flux.
         if(J.NE.NNL(I))NFLUX(I,J)=FLUX(I,J)-FLUX(I,J+1)
c      Basal net water flux.
         if(J.EQ.NNL(I))NFLUX(I,J)=FLUX(I,J)-BWFLUX(I)
210     CONTINUE
200     CONTINUE
c
c
c      Calculate new soil moisture conditions
       DO 220 I=1,NC
       DO 230 J=1,NNL(I)
       ATHESPT(I,J)=ATHESP(I,J)+(NFLUX(I,J)/(CDEPTH(I,J)*LENGTH
    &          *BDT))
       ATHESP(I,J)=ATHESPT(I,J)
230     CONTINUE
220     CONTINUE
c
c
       DO 240 I=1,NC
       M=NNL(I)
       DO 241 J=1,M
       SHATHET(I,J)=ATHESP(I,J)
241     CONTINUE
240     CONTINUE

       return
       end
```

```
c      Subroutine output.f

c      Subroutine OUTPUT.F writes data to files according to
c      selection of option(I).


       subroutine doutput(outsec, nops, option, NC,
     & sltp, VATHET, ATHESP, sct, KP, NHFLUX, HFLUX, VHC,
     & FCUM, FMIN, FDMIN, FMAX, FDMAX, FS, APKT, KKK,NNLMAX,
     & NOTC, ATH1, VATH1, TTSEC, ATEMP, BTFLUX, KT,nslices,
     & slice,OUTTIM,DEPTHP,COLHT,EXP,SOILP,HDISP,EXWAT,GDISP)

c      *******************************************************
c      DECLARATION OF VARIABLES
c      *******************************************************
       DOUBLE PRECISION sltp(5,60), VATHET(5,60), ATHESP(5,60)
       DOUBLE PRECISION sct(5,60), KP(5,60), NHFLUX(5,60)
       DOUBLE PRECISION HFLUX(5,60), VHC(5,60),SOILP(5,60)
       DOUBLE PRECISION FCUM(50), FMIN(50), FDMIN(50)
       DOUBLE PRECISION FMAX(50), FDMAX(50), FS(5,60)
       DOUBLE PRECISION APKT(5,60)
       DOUBLE PRECISION ATH1(5,60), VATH1(5,60), KT(5,60)
       DOUBLE PRECISION BTFLUX(50),DEPTHP(5),COLHT(5),EXP(5,60)
       DOUBLE PRECISION ATEMP(1468800),HDISP(5),GDISP(5),EXWAT(5.60)

       INTEGER NC,  outsec, nops, option(50)
       INTEGER KKK, NNLMAX
       INTEGER TTSEC(525600)
       INTEGER nslices, slice(50),OUTTIM
       COMMON DUMMY(5,60)
c      *******************************************************
       IF(OUTTIM.EQ.1)THEN
       do 100 NN=1,nops
       if(option(NN).eq.1)then
       open(unit=81, file='sltp.data',status='unknown')
       rewind 81
       endif

       if(option(NN).eq.2)then
       open(unit=82, file='ice.data',status='unknown')
       rewind 82
       endif

       if(option(NN).eq.3)then
       open(unit=83, file='water.data', status='unknown')
       rewind 83
       endif

       if(option(NN).eq.4)then
       open(unit=84, file='nhflux.data', status='unknown')
       rewind 84
       endif

       if(option(NN).eq.5)then
       open(unit=85, file='hflux.data', status='unknown')
       rewind 85
       endif
```

```
if(option(NN).eq.6)then
open(unit=86, file='heatcap.data', status='unknown')
rewind 86
endif

if(option(NN).eq.7)then
open(unit=87, file='thermcon.data', status='unknown')
rewind 87
endif

if(option(NN).eq.8)then
open(unit=88, file='hydcon.data', status='unknown')
rewind 88
endif

if(option(NN).eq.9)then
open(unit=89, file='suction.data', status='unknown')
rewind 89
endif

if(option(NN).eq.10)then
open(unit=90, file='fcum.data', status='unknown')
rewind 90
endif

if(option(NN).eq.11)then
open(unit=91, file='fmax.data', status='unknown')
rewind 91
endif

if(option(NN).eq.12)then
open(unit=92, file='fmin.data', status='unknown')
rewind 92
endif

if(option(NN).eq.13)then
open(unit=93, file='fs.data', status='unknown')
rewind 93
endif

if(option(NN).eq.14)then
open(unit=94, file='ath1.data', status='unknown')
rewind 94
endif

if(option(NN).eq.15)then
open(unit=95, file='vath1.data', status='unknown')
rewind 95
endif

if(option(NN).eq.16)then
open(unit=96, file='atemp.data', status='unknown')
rewind 96
endif

if(option(NN).eq.17)then
open(unit=97,file='btflux.data', status='unknown')
```

```
rewind 97
endif

if(option(NN).eq.20)then
open(unit=70, file='Gsltp.data', status='unknown')
rewind 70
endif

if(option(NN).eq.21)then
open(unit=71, file='Gice.data', status='unknown')
rewind 71
endif

if(option(NN).eq.22)then
open(unit=72, file='Gwater.data', status='unknown')
 rewind 72
endif

if(option(NN).eq.23)then
open(unit=73, file='Gsuction.data', status='unknown')
rewind 73
endif

if(option(NN).eq.24)then
open(unit=74, file='Ghycond.data', status='unknown')
rewind 74
endif

if(option(NN).eq.25)then
open(unit=75, file='gtemp.data', status='unknown')
rewind 75
endif

if(option(NN).eq.26)then
open(unit=76, file='Gkt.data',status='unknown')
rewind 76
endif

if(option(NN).eq.27)then
open(unit=77, file='Gapkt.data',status='unknown')
rewind 77
endif

if(option(NN).eq.28)then
open(unit=78,file='Gfs.data',status='unknown')
rewind 78
endif

if(option(NN).eq.29)then
open(unit=79,file='Gnhflux.data',status='unknown')
rewind 79
endif

if(option(NN).eq.30)then
open(unit=80,file='Ghflux.data',status='unknown')
rewind 80
endif
```

```
      if(option(NN).eq.33)then
      open(unit=33,file='Gexp.data',status='unknown')
      rewind 33
      endif

      if(option(NN).eq.34)then
      open(unit=34,file='Gcelexp.data',status='unknown')
      rewind 34
      endif

      if(option(NN).eq.36)then
      open(unit=36,file='Gsoilp.data',status='unknown')
      rewind 36
      endif

      if(option(NN).eq.37)then
      open(unit=37,file='Gdisplace.data',status='unknown')
      rewind 37
      endif

      if(option(NN).eq.38)then
      open(unit=38,file='Gexwat.data',status='unknown')
      rewind 38
      endif

100     continue
      OUTTIM=OUTTIM+1
      endif

      do 103 NN=1,NOPS

c        OUTPUT OPTIONS

c       ***  SLTP  ***
      if(option(NN).eq.1)then
      write(81,11)KKK
11      format(//'Soil temperature, sltp.  K',/,
     &  'Iteration = ',i8)

      call sieve(sltp,81,NC,NNLMAX)

      endif
c       ----------------------------------------------------------------
c       *** ICE ***
      if(option(NN).eq.2)then

      write(82,13)KKK
13      format(//'Soil ice content m3 m-3',/,
     &  'Iteration = ',i8)

      call sieve(VATHET,82,nc,nnlmax)

      endif
c       ----------------------------------------------------------------
c       ***  WATER  ***
      if(option(NN).eq.3)then

      write(83,14)KKK
```

```
14       format(//'Soil moisture content m3 m-3',/,
   &    'Iteration = ',i8)

        call sieve(ATHESP,83,NC,nnlmax)

        endif
c       ----------------------------------------------------------------
c       ***  NET HEAT FLUX  ***
        if(option(NN).eq.4)then

        write(84,16)KKK
16       format(//'Net heat flux W m-3 K-1',/,
   &    'Iteration = ',i8)

        call sieve(NHFLUX,84,nc,nnlmax)

        endif
c       ----------------------------------------------------------------
c       ***  HEAT FLUX  ***
        if(option(NN).eq.5)then

        write(85,18)KKK
18       format(//'Heat flux W m-3 K-1',/,
   &    'Iteration = ',i8)

        call sieve(HFLUX,85,nc,nnlmax)

        endif
c       ----------------------------------------------------------------
c       *** VOLUMETRIC HEAT CAPACITY ***
        if(option(NN).eq.6)then

        write(86,20)KKK
20       format(//'Volumetric heat capacity J m-3 K-1',/,
   &    'Iteration = ',i8)


        call sieve(VHC,86,nc,nnlmax)

        endif
c       ----------------------------------------------------------------
c       ***  THERMAL CONDUCTIVITY  ***
        if(option(NN).eq.7)then

        write(87,22)KKK
22       format(//'Thermal conductivity W m-3 sec-1 K-1',/,
   &    'Iteration = ',i8)

        call sieve(APKT,87,nc,nnlmax)

        endif
c       ----------------------------------------------------------------
c       ***  HYDRAULIC CONDUCTIVITY  ***
        if(option(NN).eq.8)then

        write(88,24)KKK
24       format(//'Hydraulic conductivity  m sec-1',/,
   &    'Iteration = ',i8)
```

```
        call sieve(KP,88,nc,nnlmax)

        endif
c       ---------------------------------------------------------------
c       ***  SUCTION  ***
        if(option(NN).eq.9)then

        write(89,26)KKK
26       format(//'Soil suction   m',/,
     &  'Iteration = ',i8)

        call sieve2(sct,89,nc,nnlmax)

        endif
c       ---------------------------------------------------------------
c       ***  CUMULATIVE "F" RATIO  ***
        if(option(NN).eq.10)then

        write(90,28)KKK
28       format(//'Cumulative F ratio per column',/,
     &  'Iteration = ',i8)

        write(90,*)(FCUM(I),I=1,NC)
        endif
c       ---------------------------------------------------------------
c       ***  MAXIMUM "F" RATIO  ***
        if(option(NN).eq.11)then

        write(91,29)KKK
29       format(//'Maximum F ratio per column',/,
     &  'Iteration = ',i8)
        write(91,*)(FMAX(I),I=1,NC)
        write(91,30)
30       format(//'Depth of maximum F ratio from surface  m'//)
        write(91,*)(FDMAX(I),I=1,NC)
        endif
c       ---------------------------------------------------------------
c       ***  MINIMUM "F" RATIO  ***
        if(option(NN).eq.12)then

        write(92,31)KKK
31       format(//'Minimum F ratio per column',/,
     &  'Iteration = ',i8)
        write(92,*)(FMIN(I),I=1,NC)

        write(92,32)
32       format(//'Depth of minimum F ratio from surface  m'//)
        write(92,*)(FDMIN(I),I=1,NC)
        endif
c       ---------------------------------------------------------------
c       *** FACTOR OF SAFETY ***
        if(option(NN).eq.13)then

        write(93,33)KKK
33       format(//'Factor of Safety ',/,
     &  'Iteration = ',i8)
```

```
        call sieve(FS,93,nc,nnlmax)

        endif
c       ----------------------------------------------------------------
c       ***  ATH1  ***
        if(option(NN).eq.14)then

        write(94,200)KKK
200       format(//'Soil water content, volume m3',/,
     &    'Iteration=', i8)

        call sieve(ATH1,94,nc,nnlmax)
        endif
c       ----------------------------------------------------------------
c       ***  VATH1  ***
        if(option(NN).eq.15)then

        write(95,202)KKK
202       format(//'Soil ice content, volume m3',/,
     &    'Iteration=', i8)

        call sieve(VATH1,95,nc,nnlmax)
        endif
c       ---------------------------------------- - ------------  --   -- -
c       ***  ATEMP  ***
        if(option(NN).eq.16)then

        write(96,204)KKK
204       format(//'Ambient temperature change and time',/,
     &    'Iteration=',i8)

        write(96,*)ATEMP(I),TTSEC(I)

        endif
c       ----------------------------------------------------------------
c       ***  BTFLUX  ***
        if(option(NN).eq.17)then
        write(97,206)KKK
206       format('Basal heat flux W m-3 s-1',/,
     &    'Iteration =', i8)

        write (97,*)(BTFLUX(I),I=1,NC)
        endif
c       ****************************************************************
c       GRAPHICS
c       ****************************************************************
c       *** Gsltp ***

c       *******    change this for correct output    *******
        do 800 K=1,nslices
        if(option(NN).eq.20)then

c        do 35 J=1,NNLMAX
c        I=slice(K)
c        call sieve(70,*) KKK, sltp(I,J)
        call sieve(sltp,70,nc,nnlmax)
c        call sieve(112,*)  atemp(kkk)
35       continue
```

```
      endif
c     --------------------------------------------------------------
c      *** Gice ***
      if(option(NN).eq.21)then

      call sieve(VATHET,71,nc,nnlmax)
      endif
c     --------------------------------------------------------------
c      *** Gwater ***

      if(option(NN).eq.22)then
      call sieve(ATHESP,72,nc,nnlmax)
      endif

c     --------------------------------------------------------------
c      *** Gsuction ***
      if(option(NN).eq.23)then

      call sieve2(sct,73,nc,nnlmax)
      endif
c     --------------------------------------------------------------
c      *** Ghycond ***
      if(option(NN).eq.24)then

      call sieve2(KP,74,nc,nnlmax)
      endif
c     --------------------------------------------------------------
c     ***  gATEMP  ***
      if(option(NN).eq.25)then

      do 220 I=1,NOTC

c      call sieve(75,*)TTSEC(I),ATEMP(I)
220    continue
      endif
c     --------------------------------------------------------------
c     ***  gKT  ***
      if(option(NN).eq.26)then

      call sieve2(KT,76,nc,nnlmax)
      endif
c     --------------------------------------------------------------
c     ***  gAPKT  ***
      if(option(NN).eq.27)then

      do 251 J=1,NNLMAX
      I=slice(K)
c      call sieve(77,*)APKT(I,J)
251    continue
      endif
c     --------------------------------------------------------------
c     ***  FS  ***
      if(option(NN).eq.28)then

      do 252 J=1,NNLMAX
      I=slice(K)
c      call sieve(78,*)FS(I,J)
252    continue
```

```
        endif
c       ---------------------------------------------------------------
c       ***  NHFLUX   ***
        if(option(NN).eq.29)then
c        do 253 J=1,NNLMAX
c        I=slice(K)
        call sieve(NHFLUX,79,nc,nnlmax)
c 253      continue
        endif
c       ---------------------------------------------------------------
c       ***  HFLUX  ***
        if(option(NN).eq.30)then
        do 254 J=1,NNLMAX
        I=slice(K)
c        call sieve(80,*)HFLUX(I,J)
254       continue
        endif
c       ---------------------------------------------------------------
c       ***  COLUMN HEIGHT (CM) ***
        if(option(NN).eq.33)then
        do 255 I=1,NC
        write(33,*)COLHT(I)*100.0,(COLHT(I)-DEPTHP(I))*100.0
255       continue
        endif
c       ---------------------------------------------------------------
c       ***  CELL EXPANSION (MM)  ***
        if (option(NN).eq.34)then
        call sieve(exp,34,nc,nnlmax)
        endif
c       ---------------------------------------------------------------
c       ***  SOIL VOLUMETRIC PERCENTAGE  ***
        if(option(nn).eq.36)then
        call sieve(soilp,36,nc,nnlmax)
        endif

c       ---------------------------------------------------------------
c       ***  SOIL DOWNSLOPE DISPLACEMENT POTENTIAL (cm)***
        if(option(nn).eq.37)then
        do 256 I=1,NC
        write(37,*)HDISP(I)*100.,GDISP(I)*100.,(GDISP(I)+HDISP(I))
   &         *100.
256       continue
        endif

c       ---------------------------------------------------------------
c       ***  EXPELLED EXCESS WATER VOLUMES  ****
        if(option(nn).eq.38)then
        call sieve(exwat,38,nc,nnlmax)
        endif

c       ***  ISOTHERM  ***

800     continue

103     continue
```

```
          return
          end

c         subroutine sieve
c     subroutine sieve sifts the desired arrays and outputs the cells
c     specified in the Out.data file thereby enabling selective output
c     rather than the entire column to be printed.


        subroutine sieve(array, outid,nc,nnlmax)
        integer  nc,nnlmax,outid, counter
        COMMON DUMMY(5,60)
         double precision buffer(60), array(5,60)

        do 1013 i=1,nc
        counter=0
          do 2013 j=1,nnlmax
          if(DUMMY(i,j).eq.1)then
          counter=counter+1
          buffer(counter)=array(i,j)
          endif
2013      continue
        write(outid,'(30f9.4,x)')(buffer(col), col=1,counter)
1013    continue
        return
        end


c     subroutine sieve2


        subroutine sieve2(array, outid,nc,nnlmax)
        integer  nc,nnlmax,outid, counter
        COMMON DUMMY(5,60)
         double precision buffer(60), array(5,60)

        do 1013 i=1,nc
        counter=0
          do 2013 j=1,nnlmax
          if(DUMMY(i,j).eq.1)then
          counter=counter+1
          buffer(counter)=array(i,j)
          endif
2013      continue
c       write(outid,'(30f9.4,x)')(buffer(col), col=1,counter)
        write(outid,*)(buffer(col), col=1,counter)
1013    continue
        return
        end
```

```
c      Subroutine soli.f

c      Subroutine soli.f calculates solifluction movement potential for column cells
c
c
       subroutine soli(NC, NNL, NNLMAX, TTCOM,sct,FS,FDMAX,
     & FDMIN, FMAX, FMIN, FCUM,GAMMAS,GAMMAU,BETA,C,PHI,MAXCOLHT
     & ,DEPTHP,HDISP,GELRAT,GDISP)

c      DECLARATION OF VARIABLES

       DOUBLE PRECISION C(5,60), BETA(5)
       DOUBLE PRECISION GAMMAS, GAMMAU,GELRAT,GDISP(5)
       DOUBLE PRECISION sct(5,60), PHI(5,60), FS(5,60)
       DOUBLE PRECISION TTCOM(5,60), FMAX(50)
       DOUBLE PRECISION FMIN(50), SMAX(50)
       DOUBLE PRECISION FDMAX(50), FDMIN(50),DEPTHP(5)
       DOUBLE PRECISION FCUM(50),MAXCOLHT(5),HDISP(5)

       INTEGER NC, NNL(5), NNLMAX

c      *****************************************************
c      calculate maximum downslope displacement due to heave
c      resettlement using maximum displacement and slope angle

       DO 5 I=1,NC
       HDISP(I)=(MAXCOLHT(I)-DEPTHP(I)) * TAND(BETA(I))
       GDISP(I)=HDISP(I)*GELRAT
5      CONTINUE

c      **************************************************************
c      Set FMAX and FMIN limits
       DO 1 I=1,NC
       FMAX(I)=-20000
       FMIN(I)=20000
       SMAX(I)=-20000
1      CONTINUE

c      Calculation of factor of safety.
       DO 3 I=1,NC
       M=NNL(I)
       DO 4 J=1,M
       IF(sct(I,J).GE.0.0)THEN
       FS(I,J)=(C(I,J)+(GAMMAS*TTCOM(I,J)*(DCOS(BETA(I)))**2
     & -sct(I,J)*9.8)*DTAN(PHI(I,J)))/(GAMMAS*TTCOM(I,J)
     & *DSIN(BETA(I))*DCOS(BETA(I)))
       ENDIF

       IF(sct(I,J).LT.0.0)THEN
       FS(I,J)=(C(I,J)+(GAMMAU*TTCOM(I,J)*(DCOS(BETA(I)))**2
     & -sct(I,J)*9.8)*DTAN(PHI(I,J)))/(GAMMAU*TTCOM(I,J)
     & *DSIN(BETA(I))*DCOS(BETA(I)))
       ENDIF

       IF(FS(I,J).GT.FMAX(I))FMAX(I)=FS(I,J)
                 FDMAX(I)=TTCOM(I,J)
       IF(FS(I,J).LT.FMIN(I))FMIN(I)=FS(I,J)
                 FDMIN(I)=TTCOM(I,J)
```

```
      IF(sct(I,J).GT.SMAX(I))SMAX(I)=sct(I,J)
      FCUM(I)=FCUM(I)+FS(I,J)

4      CONTINUE
3      CONTINUE

      return
      end
```

```
c       Subroutine thaw.f

c       Subroutine thaw.f calculates the partition of energy between
c       two processes:-

c          (i) phase change
c         (ii) thermal change
c                 when NHFLUX is +ve and thaw of soil moisture
c                 is a likely result.


       subroutine thaw(sltpt2, TF, LENGTH,
     &  CDEPTH, BDT, ATHESP, VATHET, VHC, sltp, NC, LA,
     &  NHFLUX, I, J,KKK,CELVOL,VADFAC,SOILP,ORIVOL,SOIL1,ASR1,ASR2,
     &  LC1,FC2,TDEP,EXWAT)
c      **************************************************************
c       DECLARATION OF VARIABLES

       DOUBLE PRECISION sltpt2(5,60), sltp(5,60),ASR1,ASR2
       DOUBLE PRECISION ATHESP(5,60), ATHESP1(5,60)
       DOUBLE PRECISION VATHET(5,60), VATH1(5,60)
       DOUBLE PRECISION LENGTH, CDEPTH(5,60), BDT
       DOUBLE PRECISION deltaW(5,60), deltaT(5,60),Et(5,60)
       DOUBLE PRECISION LA, VHC(5,60),CELVOL(5,60),SOIL1(5,60)
       DOUBLE PRECISION SOILP(5,60),volch(5,60),ORIVOL(5,60)
       DOUBLE PRECISION VADFAC(5,60),TDEP
       DOUBLE PRECISION EXWAT(5,60), WAT(5,60)

       INTEGER LC1(50),FC2(50),TF, NC, I, J, KKK
c      **************************************************************


c       Is energy partition between phase change and thermal heating
c       required, i.e. is ice present.
       IF(VATHET(I,J).LE.0.0D-06.OR.SLTPT2(I,J).LT.TDEP)THEN
       sltp(I,J)=sltpt2(I,J)
       ELSEIF(SLTPT2(I,J).GE.TDEP.AND.VATHET(I,J).GT.0.0)THEN
       sltp(i,j)=tdep
c      **************************************************************
c       Change in temperature for iteration period predicted by heatrans.f
c       this is heat energy that will be used to melt ice
       deltaT(I,J)=sltpt2(I,J)-TDEP

c       calculate thermal energy available for melting ice
       Et(I,J) = ((VHC(I,J)*CELVOL(I,J))*DeltaT(I,J))


c      ------------------------------------------------------------------
c       HYDROLOGY

c       Convert Athesp and Athet from % volume to volume m3
       ATHESP1(I,J)=CELVOL(I,J)*ATHESP(I,J)

c       Volumetric change in moisture content - ice melted (wat equiv) m3
       deltaW(I,J)=Et(i,j)/(LA*1000000.0)

c       Convert VATHET ice content % into a volume m3
       VATH1(I,J)=CELVOL(I,J)*VATHET(I,J)
```

```
c      check that ice is available for melting
       IF(VATH1(I,J).GT.(deltaw(I,J)*1.09))THEN
        VATH1(I,J)=VATH1(I,J)-(deltaW(I,J)*1.09)
       ELSE
        DELTAW(I,J)=VATH1(I,J)/1.09
        VATH1(I,J)=0.0
       ENDIF

       ATHESP1(I,J)=ATHESP1(I,J)+DELTAW(I,J)
       ATHESP(I,J)=ATHESP1(I,J)/CELVOL(I,J)
       VATHET(I,J)=VATH1(I,J)/CELVOL(I,J)


c      calculate if any volume adjustment is required
       IF(VADFAC(I,J).GT.1.0)THEN
        IF(J.LE.LC1(I))WAT(I,J)=ASR1*ORIVOL(I,J)
        IF(J.GE.FC2(I))WAT(I,J)=ASR2*ORIVOL(I,J)
c      include lines to expel water content that is above the original
c      porosity of the soil
         IF(ATHESP1(I,J).GT.WAT(I,J))THEN
           EXWAT(I,J)=EXWAT(I,J)+((ATHESP1(I,J)-WAT(I,J))
     &                /ORIVOL(I,J))
           ATHESP1(I,J)=WAT(I,J)
         ENDIF

        VOLCH(I,J)=CELVOL(I,J)-(ATHESP1(I,J)+VATH1(I,J)+SOIL1(I,J))
        CELVOL(I,J)=CELVOL(I,J)-VOLCH(I,J)
        VADFAC(I,J)=CELVOL(I,J)/ORIVOL(I,J)
        IF(VADFAC(I,J).LT.1.0)THEN
          VADFAC(I,J)=1.0
          VOLCH(I,J)=CELVOL(I,J)-ORIVOL(I,J)
          CELVOL(I J)=ORIVOL(I,J)
        ENDIF
        ATHESP(I,J)=ATHESP1(I,J)/CELVOL(I,J)
        VATHET(I,J)=VATH1(I,J)/CELVOL(I,J)
        SOILP(I,J)=SOIL1(I,J)/CELVOL(I,J)
        CDEPTH(I,J)=CDEPTH(I,J)-(VOLCH(I,J)/(BDT*LENGTH))

        endif
       else
       write(6,*)'slipped out in thaw'

       ENDIF


       return
       end
```