DOCUMENTATION OF COMPUTER PROGRAM VS2DH FOR SIMULATION OF ENERGY TRANSPORT IN VARIABLY SATURATED POROUS MEDIA--MODIFICATION OF THE U.S. GEOLOGICAL SURVEY'S COMPUTER PROGRAM VS2DT

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CONVERSION FACTORS

Multiply	By	To obtain
millimeter	.03937	inch (in)
meter	3.28084	foot (ft)
kilometer	0.6215	mile
square kilometer	0.3861	square mile (mi^2)
cubic meter per second	35.3107	cubic foot per second (ft^3/s)
joule (J)	0.00095	British thermal units (mean) (Btu)
joule (J)	0.2388	calorie
watt per square meter (W/m^2)	0.00529	British thermal unit per square foot per minute ($Btu/ft^2 \cdot min$)
watt per square meter (W/m^2)	0.00142	calorie per square centimeter per minute ($cal/cm^2 \cdot min$)
watt per square meter per kelvin ($W/m^2 \cdot K$)	0.1761	British thermal unit per square foot per hour per degree Fahrenheit ($Btu/ft^2 \cdot h \cdot \cdot °F$)

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ABSTRACT

This report documents computer program VS2DH for solving problems of energy transport in variably saturated porous media. The program is a modification to the U.S. Geological Survey's computer program VS2DT, which simulates water and solute movement through variably saturated porous media. In VS2DH, the advection-dispersion equation for single phase liquid water is used to describe energy transport. The finite difference method is applied to solve that equation. Regions can be simulated in one or two dimensions. Cartesian or radial coordinates can be used. Three test problems are presented to demonstrate the accuracy of the computer program. In addition, the third test problem serves as an example that allows users to compare results after installation on any computer.

INTRODUCTION

Energy transport can be an important component in a variety of hydrologic and environmental processes. Diurnal and annual variations in streamflow loss have been directly linked to diurnal and annual variations in stream water temperature (Lapham, 1989; Constantz and others, 1994). Similarly, strong annual variations in recharge from recharge basins under constant ponding can be attributed to annual water temperature cycles (Nightingale, 1975). Duke (1992) showed that increasing the temperature of irrigation water could dramatically increase the rate of infiltration in an agricultural field. Understanding the role of heat flow on these and other processes can be useful in the study and management of water resources.

This report describes computer program VS2DH, which simulates energy transport in porous media under variably saturated conditions. VS2DH assumes a single, constant-density liquid phase flow. Applications where vapor-phase flow and fluid density variations are negligible are well suited for simulation by VS2DH. Studies where vapor-phase water transport is an important process (such as bare soil evaporation or burial of high-level radioactive waste) would require a model that could account for multiple phases (for example, Milly (1984, 1996)). If variable density liquids are of concern (such as for injection of waste water into a saline aquifer), then models that can account for variable density should be considered (for example, HST 3D (Kipp,1987) or SUTRA (Voss, 1984)).

VS2DH is a modification to the U.S. Geological Survey's computer program VS2DT which simulates water and solute movement under variably saturated conditions. Use of VS2DH requires an awareness of the assumptions and limitations inherent in its development. This report presents a brief description of theory of energy transport and gives details on the numerical implementation of energy transport contained in VS2DH. The energy transport equation is similar to the solute transport equation. As such, there are relatively minor differences between VS2DH and VS2DT (primarily in definitions of parameters that appear in the equations). The descriptions included here are of a somewhat limited scope; before using this program, users should obtain copies of the VS2DT documentations, Lappala and other (1987) and Healy (1990). These references contain necessary information on simulation of water flow and details on parameter defi-

nitions that may not be repeated in this report. To demonstrate the accuracy of VS2DH and illustrate program use, three test problems are presented.

THEORY

Energy Transport Equation

The energy transport equation, which is actually a form of the advection-dispersion equation, is derived by balancing the changes in energy stored within a volume of porous media. Such changes occur due to ambient water of different temperature flowing into the volume, thermal conduction into or out of the volume, and energy dispersion into or out of the volume. The energy transport equation can be written with temperature as the dependent variable:

$$\partial/\partial t\,[\theta C_w + (1-\phi)C_s]\,T = \nabla\cdot K_T(\theta)\,\nabla T + \nabla\cdot\theta\, C_w D_H \nabla T - \nabla\theta C_w\, vT + qC_w\, T^*\,; \qquad (1)$$

where t is time in s; θ is volumetric moisture content; C_w is heat capacity (density times specific heat) of water, in J/m^3°C; ϕ is porosity; C_s is heat capacity of the dry solid, in J/m^3°C; T is temperature, in °C; K_T is thermal conductivity of the water and solid matrix (a tensor), in W/m°C; D_H is hydrodynamic dispersion tensor, in m^2/s; v is water velocity, in m/s; q is rate of fluid source, in s^{-1}; and T^* is temperature of fluid source, in °C. Development of Equation (1) ignores the heat capacity of the air phase in the porous medium when moisture content is less than porosity; however, this heat capacity term is small relative to that of water and should therefore be of little practical concern (Sellers, 1965). Further details on Equation (1) can be obtained from Voss (1984) and Kipp (1987).

The left-hand side of Equation (1) represents the change in energy stored in a volume over time. The first term on the right side of the equation describes energy transport by thermal conduction. The second term represents transport due to thermo-mechanical dispersion (Kipp, 1987). The third term on the right side accounts for advective transport of energy. The last term represents heat sources or sinks.

The advective and dispersive components of energy transport are analogous to those in solute transport. Thermo-mechanical dispersion accounts for energy transport as a result of mixing due to the movement of water. The hydrodynamic dispersion tensor is defined as (Healy, 1990):

$$D_{Hi,j} = \alpha_T|v|\delta_{ij} + (\alpha_L - \alpha_T)v_i v_j / |v|\,, \qquad (2)$$

where α_T is transverse dispersivity of the porous medium, in m; v_i is the i^{th} component of the velocity vector; δ_{ij} is the Kronecker delta and equals 1 if i=j and otherwise is equal to 0; and α_L is longitudinal dispersivity in m; $|v|$ is magnitude of the velocity vector.

Heat conduction can be viewed as a kind of molecular diffusion. The mechanism is also analogous to water flow through porous media, with thermal conductivity being analogous to hydraulic conductivity and the temperature gradient in space being the driving force rather than the head gradient. Thermal conductivity is strongly dependent on moisture content . This dependency is illustrated in Figure 1. Additional information on thermal conductivity can be obtained from Kersten (1949) and Lapham (1989). VS2DH assumes that thermal conductivity varies linearly with moisture content, between residual moisture content and full saturation. Residual moisture content is defined as the moisture content that the medium approaches as the pressure potential decreases towards negative infinity. It can range from as low as about 0.02 for a sand up to values exceeding 0.2 for clays. Typical values for residual moisture content can be found in Table 1 on page 20 of Lappala and others (1987).

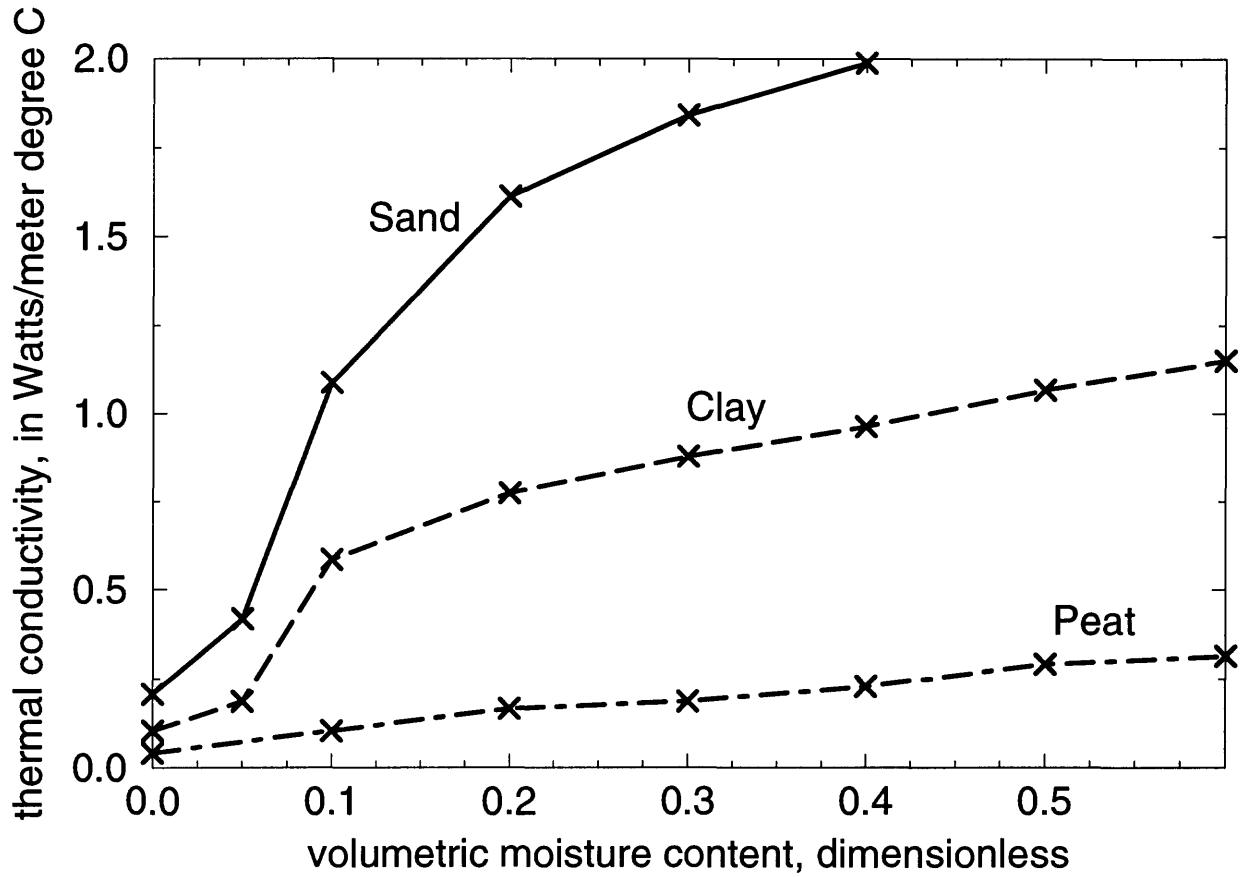

Figure 1. Thermal conductivity of three soils as a function of moisture content (data from van Duin, 1963).

Advection accounts for energy transport by the movement of water of different temperatures. As such, the mechanism is identical to that for solute transport.

Source/sink terms account for energy introduced to or removed from the domain by the movement of water into or out of the domain. These terms are represented by the last term in equation (1). Typically these take the form of injection or withdrawal wells.

Boundaries can be assigned as fixed heat fluxes or fixed temperature. In addition, the temperature of any inflowing water from a fluid-flow boundary must be specified. When water flows out of the domain through a flow boundary, the program sets the temperature of that water equal to the temperature in the finite difference cell where the water is exiting.

Flow Equation

The flow equation solved by VS2DH is identical to that given by Equation 9 on page 7 of Lappala and others (1987) with one exception. Because of the temperature dependency of viscosity, saturated hydraulic conductivity, K, is now treated as a function of temperature:

$$K = \rho g k / \mu(T) \qquad (3)$$

where ρ is density, in kg/m^3; g is gravity, in m/s^2; k is intrinsic permeability, in m^2; and μ is viscosity, in Ns/m^2. Viscosity is calculated according to the empirical formula (Kipp, 1987):

$$\mu(T) = 0.00002414 \times 10^{[247.8/(T+133.16)]} \qquad (4)$$

Although the density of water is also dependent on temperature, it is treated as a constant in VS2DH because its dependence is much less than that of viscosity over the range of pore-water pressures and temperatures typically encountered under variably saturated field conditions.

The van Genuchten equations are used to represent moisture content, specific moisture capacity, and relative hydraulic conductivity as functions of pressure head. Use of alternate equations is described in Lappala and others (1987).

COMPUTER PROGRAM STRUCTURE

Development of VS2DH required substantial modification to subroutine VTSETUP in VS2DT, minor modifications to VSEXEC, and the addition of function subroutine THERMC for calculating thermal conductivity as a function of volumetric moisture content. A copy of the FORTRAN version of the program can be obtained from the address shown on page ii.

The revised structure of the program requires that three new global variables be introduced: NIT3, EPS2, and VMAX, whose values are explained in the following sentences. Because temperature is a variable within both the flow and transport equations, the two equations could be solved simultaneously. However, VS2DT is set up to solve the equations sequentially. VS2DH maintains the sequential solution algorithm, necessitating iterative solution of both equations within each time step. The flow equation is solved first, assuming a temperature equal to that at the previous time step. Next the transport equation is solved to update the value of temperature. The flow equation is then resolved with the updated temperature. This iterative process is continued within the time step until the change in velocity between subsequent solutions of the flow equation (VMAX) is less in magnitude than EPS2 at every node. The total number of iterations is NIT3. Experience has shown that NIT3 rarely exceeds a value of 4 or 5. At the completion of every time step, the energy flux into and out of the system, as well as the change in energy stored in the system is calculated in subroutine VSFLUX.

A few options pertaining to solute transport that were available in VS2DT are not allowed in VS2DH. These include solute decay, adsorption, and cation exchange. The user is also cautioned against using the bare soil evaporation or plant transpiration options without careful analysis. These processes are in reality highly temperature dependent, but the program does not treat them as such.

Input-data formats are described in Appendix 1. The formats are quite similar to those in VS2DT (Healy, 1990). A value is now required for EPS2 and the definitions of several of the parameters contained in array HT are modified. Also, SI units must now be used for all data; time must be in seconds, length in meters, temperature in degrees Centigrade, and mass in kilograms. The program assumes a reference temperature of 20°C. Input data values for saturated hydraulic conductivity should correspond to this refer-

ence temperature.

MODEL VERIFICATION

Three problems are presented to evaluate the accuracy of the new program. In addition the third test problem also serves as an example that allows users to compare program output after installation on any computer.

One-Dimensional Saturated Flow and Heat Transport Problem

This test problem simulates heated water flowing into a one-dimensional saturated column of cool water. It is intended to demonstrate the ability of VS2DH to match an analytical solution to a hypothetical laboratory experiment. The problem is based on example problem 6 presented in documentation for the U.S. Geological Survey computer program HST3D (Kipp, 1987, p. 244). Model parameters are:

$K = 1.389 \times 10^{-4}$ m/s;

$\phi = \theta = 0.50$;

$\alpha_L = \alpha_T = 10$ m;

$C_s = 2.08 \times 10^6$ J/m^3°C;

$K_T(\phi) = 1.8$ W/m°C;

$C_w = 4.2 \times 10^6$ J/m^3°C;

Initial column temperature $T_o = 20$°C; and

Influent water temperature $T_{inj} = 21$°C.

An interstitial velocity of 2.778×10^{-4} m/s was imposed through the column by orienting the column in a vertical direction and specifying a constant pressure head boundary condition of 1 m at each end of the column.

The domain was modeled using a series of increasingly finer discretizations in both space and time. The discretization was centered in space and time. With a spatial discretization of 1.0 m and a time discretization of 107.65 s (approximately 0.03 hr), the temperatures predicted by VS2DH were in very close agreement with the analytical solution of Ogata and Banks (1961). Table 1 compares normalized temperatures predicted by VS2DH to the analytical solution at a time of 10765 s.

Table 1. Analytical and numerical results for test problem 1 in terms of normalized temperature, $(T - T_o) / (T_{inj} - T_o)$.

	Normalized Temperature	
Distance along column, in meters	**Analytical result**	**VS2DH result**
0	1.00000	1.00000
8	0.29815	0.29891
16	0.02441	0.02548
24	0.00047	0.00058
32	0.00000	0.00000
56	0.00000	0.00000

Radial Saturated Flow and Heat Transport Problem

The second test problem simulates heated water injected into an aquifer. The problem is based on example problem 3 presented in documentation for the U.S. Geological Survey computer program SUTRA (Voss, 1984, p. 186) and is intended to demonstrate the ability of VS2DH to simulate typical field applications. Axial symmetry is assumed, so radial coordinates are used. Model parameters are:

$K = 1.0 \times 10^{-4}$ m/s;

$\phi = \theta = 0.20$;

$\alpha_L = \alpha_T = 10$ m;

$C_s = 2.225 \times 10^6$ J/m^3°C;

$K_T(\phi) = 2.92$ W/m°C;

$C_w = 4.182 \times 10^6$ J/m^3°C;

$T_o = 20$°C;

$T_{inj} = 21$°C; and

Injection rate, $Q = 0.3125$ m^3/s.

The domain was modeled using 3 rows and 223 columns. The vertical grid spacing was 10 m and the radial grid spacing started at 0.05 m adjacent to the well and increased by a factor of 1.2 until the grid spacing became 5 m. The total radial distance was 1000 m. At this boundary, a total head of 10 m was imposed. The time step started at 3.6×10^{-4} s and was allowed to increase to 7200 s. The discretization was centered in space and time. Graphs of the model-predicted concentration distributions at four times are shown in Figure 2. Good agreement is obtained between model results and the approximate analytical solution of Gelhar and Collins (1971) as modified by Voss(1984). The agreement is not exact because the analytical solution is only approximate. The model results are in excellent agreement with those obtained by SUTRA (Voss, 1984).

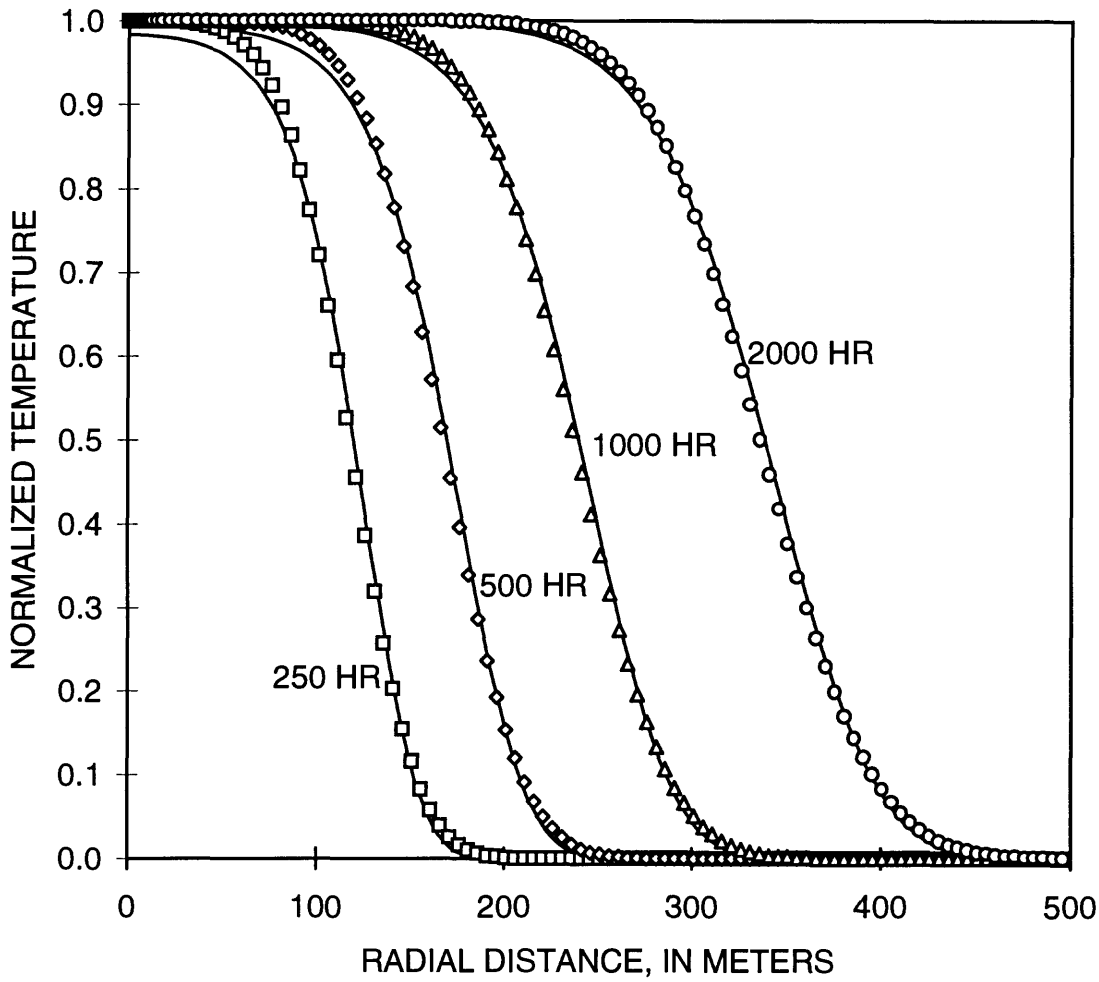

Figure 2. Results of test problem 2: normalized temperatures as calculated by VS2DH (symbols) and the approximate analytical solution of Gelhar and Collins (1971).

One-Dimensional Ponded Infiltration with Time-Varying (Diurnal) Temperature

This test problem simulates one-dimensional flow of water in the unsaturated zone in response to a ponded surface that experiences diurnal temperature fluctuations. The problem is constructed to replicate the field conditions reported by Jaynes (1990). In brief, Jaynes monitored depth of ponding, inflows required to maintain ponding, temperature of ponded water, and temperature of moist sediments at three depths below the ground surface. From the ponding depths and inflows, he determined infiltration rates. In an effort to qualitatively determine if daily temperature changes in the ponded water could explain the variation in infiltration, he used a simplified finite-difference approximation of the governing equations to simulate the problem. His calibration procedure consisted of varying the hydraulic conductivity of the

sediments. Properties of the sediments were not measured.

Jaynes (1990) found that he needed to simulate a lower hydraulic conductivity surface crust to adequately simulate the infiltration rates. He set the hydraulic conductivity of the surface crust to1/20 of that of the underlying sediments. Lacking complete description of the soil unsaturated characteristic curves, we assigned soil properties of the Columbia Sandy Loam (Laliberte and others, 1966, table C-5). We found that we needed to set K for the surface crust to 1/200 of that of the underlying sediments (probably because we did not use the same characteristic curves as Jaynes, 1990). Model parameters are:

$K = 4.0 \times 10^{-8}$ m/s for the surface crust;

$K = 8.0 \times 10^{-6}$ m/s for the underlying sediments;

$\phi = 0.496$;

$\alpha_L = \alpha_T = 0.01$ m;

$C_s = 2.18 \times 10^6$ J/m^3°C;

$K_T(\theta_r) = 1.5$ W/m°C;

$K_T(\phi) = 1.8$ W/m°C; and

$C_w = 4.18 \times 10^6$ J/m^3°C.

The domain was modeled in one dimension using 3 columns and 129 rows. The vertical grid spacing varied from 0.001 m at the surface to 0.5 m at depth. The total domain depth was 49.6 m from the ground surface to the water table. The total simulation time was 168 hours, consisting of 168 one-hour recharge periods. The timestep started at 360 s and was allowed to increase to 3600 s. The discretization was centered in space and in time.

For the entire simulation, the flow equation boundary conditions were a specified total head of 0.04 m at the ground surface (the average depth of ponded water) and a specified pressure head of zero at the water table. The energy equation boundary conditions consisted of specified temperatures at the ground surface and at the water table. The temperature at the water table was held constant at 21.3°C while the specified surface temperatures were changed every hour. The first 60 hours of the simulation were a start-up period, using a repeated cyclic temperature pattern at the surface. For the subsequent 108 hours of the simulation, Jaynes (1990) measured pond temperatures were used as the surface boundary condition.

Figure 3 shows the temperatures at depths of 0.1, 0.2 and 0.6 m below the ponded surface over a 120 hour period. VS2DH predictions are in very good agreement with field measurements. The slight disagreement at a depth of 0.6 m is likely due to a seasonal warming trend which was occurring during the field experiment but which was not simulated in the model. Figure 4 shows the infiltration rates that were measured and the predictions of both VS2DH and Jaynes' simplified finite difference model. Both simulations capture the diurnal variation, although neither captures the full amplitude of the variations. Interestingly, peak infiltration rates simulated in both models occur 2 to 4 hours before measured ones, although minimum simulated rates match well in time to those measured. Measured infiltration rates could be more closely matched by the simulation results if additional property values (besides just hydraulic conductivity) were varied in the calibration process.

Appendix 2 contains input and output files for the first recharge period of this example problem. Note that the specified total head at the upper boundary is entered as 0.0405 m although the average depth of

ponded water is only 0.04 m. The extra 0.0005 m was added to account for the 0.001 m thickness of the uppermost grid block. The head of 0.0405 m at the center of row 2 corresponds to a head of 0.04 m at the top of the second row, which is the actual border of the model domain. Precision such as this is usually unwarranted, but this approach is presented here as an example of how to accommodate specified head boundary conditions in this block-centered finite-difference formulation.

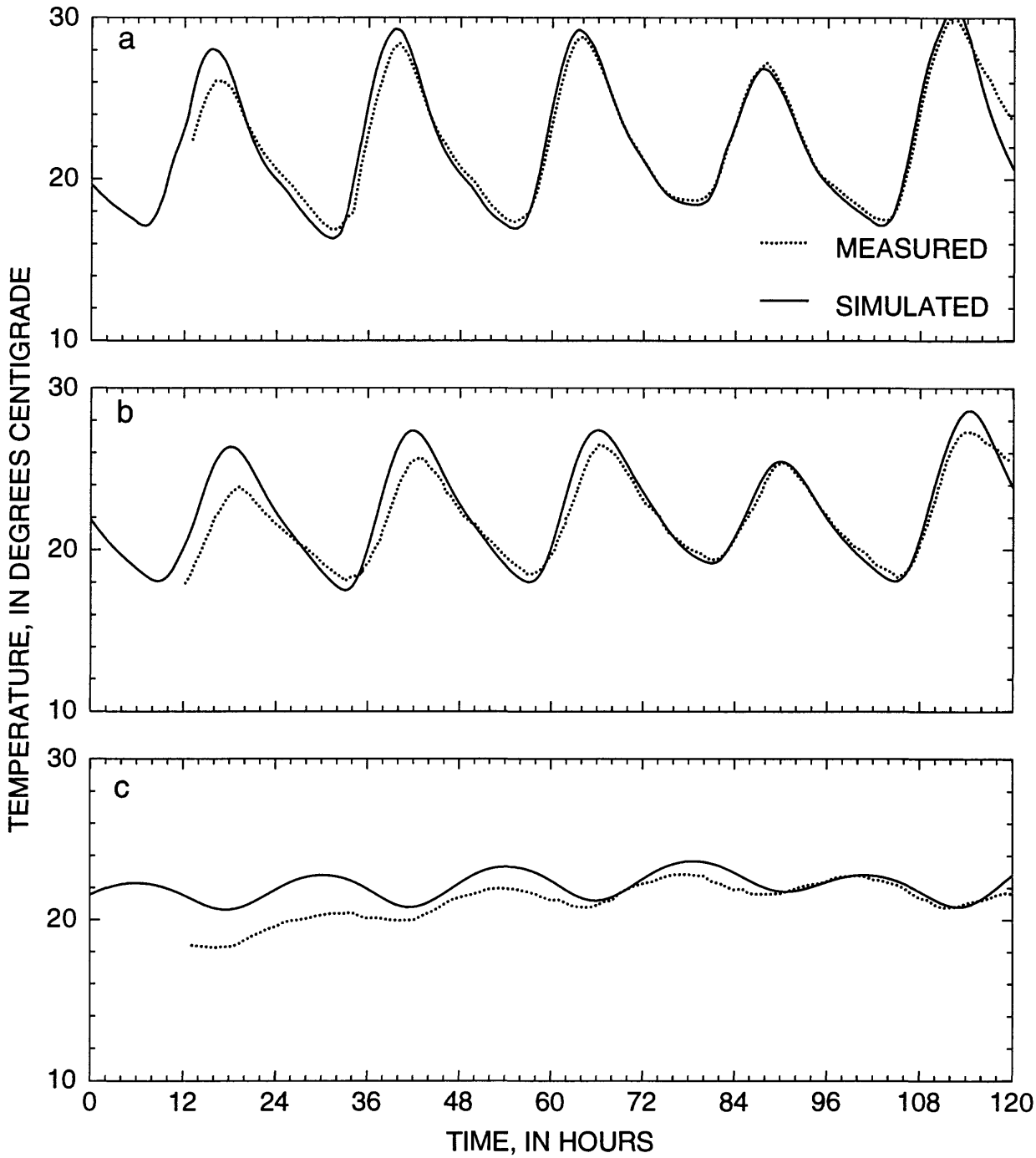

Figure 3. Soil temperatures for test problem 3 as a function of time as simulated by VS2DH and measured by Jaynes (1990) for depths of a) 0.1 m; b) 0.2 m; and c) 0.6 m.

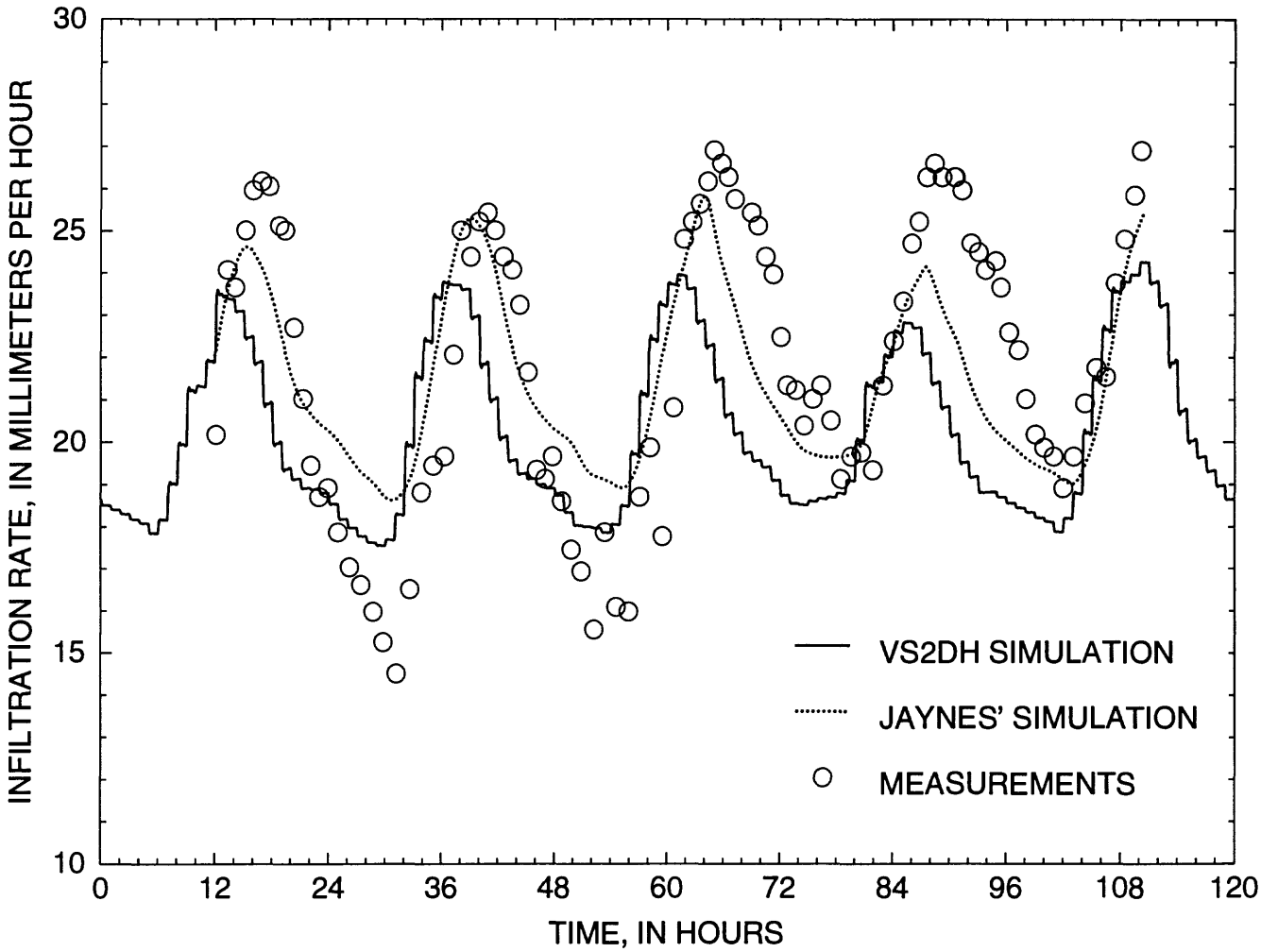

Figure 4. Infiltration rates for test problem 3 as a function of time as simulated by VS2DH and Jaynes (1990) and the measurements from Jaynes (1990).

SUMMARY

This report documents computer program VS2DH for solving problems of energy transport in variably saturated porous media. The program is a modification to the U.S. Geological Survey's computer program VS2DT, which simulates water and solute movement through variably saturated porous media. The advection-dispersion equation is used to describe energy transport and is solved using the finite difference method. Because temperature appears in both the flow equation (through the viscosity term) and the transport equation, the two equations are solved iteratively at each time step. The iteration is stopped when the maximum change in velocity between iterations at any node is less than a user supplied closure criterion. Regions can be simulated in one or two dimensions. Cartesian or radial coordinates can be used. Three test problems are used to demonstrate the ability of the computer program to match analytical and field results.

Analysis of results indicate that VS2DH is useful in modeling the near-surface transport of water and heat in porous sediments for cases in which transport in the vapor phase and density variations are negligible. Examples of field cases in which simulation with VS2DH is appropriate include modeling of nonisothermal infiltration during ponded irrigation, groundwater recharge, or streamflow loss, modeling of fluxes near buried heat sources/sinks in the shallow saturated zone, and modeling of nonisothermal ground water injection of water in shallow aquifers.

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APPENDIX 1

Data Input Formats

Line	Variable	Description
	[Line group A read by VSEXEC]	
A-1	TITL	80-character problem description (formatted read, 20A4).
A-2	TMAX	Maximum simulation time, sec.
	STIM	Initial time (usually set to 0), sec.
	ANG	Angle by which grid is to be tilted (Must be between -90 and +90 degrees, ANG = 0 for no tilting, see Healy (1990) for further discussion), degrees.
A-3	ZUNIT	Units used for length (A4), "m" for meters.
	TUNIT	Units used for time (A4), "sec" for seconds
	CUNX	Units used for heat (A4), "J" for Joules.
Note: Line A-3 is read in 3A4 format, so the unit designations must occur in columns 1-4, 5-8, 9-12, respectively		
A-4	NXR	Number of cells in horizontal or radial direction. NXR and NLY must both be less or equal to 600. NXR*NLY must be less than 1600.
	NLY	Number of cells in vertical direction.
A-5	NRECH	Number of recharge periods.
	NUMT	Maximum number of time steps.
A-6	RAD	Logical variable = T if radial coordinates are used; otherwise = F.
	ITSTOP	Logical variable = T if simulation is to terminate after ITMAX iterations in one time step; otherwise = F.
	TRANS	Logical variable = T if energy transport is to be simulated.
Line A-6A is present only if TRANS = T.		
A-6A	CIS	Logical variable = T if centered-in-space differencing is to be used; = F if backward-in-space differencing is to be used for transport equation.
	CIT	Logical variable = T if centered-in-time differencing is to be used; = F if backward-in-time or fully implicit differencing is to be used.
A-7	F11P	Logical variable = T if temperature, head,

Line	Variable	Description
		moisture content, and saturation at selected observation points are to be written to file 11 at end of each time step; otherwise = F.
A-7 (Continued)	F7P	Logical variable = T if head changes for each iteration in every time step are to be written in file 7; otherwise = F.
	F8P	Logical variable = T if output of pressure heads (and temperatures if TRANS = T) to file 8 is desired at selected observation times; otherwise = F.
	F9P	Logical variable = T if one-line mass balance summary for each time step is to be written to file 9; otherwise = F.
	F6P	Logical variable = T if mass balance is to be written to file 6 for each time step; = F if mass balance is to be written to file 6 only at observation times and ends of recharge periods.
A-8	THPT	Logical variable = T if volumetric moisture contents are to be written to file 6; otherwise = F.
	SPNT	Logical variable = T if saturations are to be written to file 6; otherwise = F.
	PPNT	Logical variable = T if pressure heads are to be written to file 6; otherwise F.
	HPNT	Logical variable = T if total heads are to be written to file 6; otherwise = F.
	VPNT	Logical variable = T if velocities are to be written to file 6; otherwise =F.
A-9	IFAC	= 0 if grid spacing in horizontal (or radial) direction is to be read in for each column and multiplied by FACX. = 1 if all horizontal grid spacing is to be constant and equal to FACX. = 2 if horizontal grid spacing is variable, with spacing for the first two columns equal to FACX and the spacing for each subsequent column equal to XMULT times the spacing of the previous column, until the spacing equals XMAX, whereupon spacing becomes constant at XMAX.

Line	Variable	Description
A-9	FACX	Constant grid spacing in horizontal (or radial) direction (if IFAC=1); constant multiplier for all spacing (if IFAC=0); or initial spacing (if IFAC=2), m.
Line set A-10 is present if IFAC = 0 or 2.		
If IFAC = 0,		
A-10	DXR	Grid spacing in horizontal or radial direction. Number of entries must equal NXR, m.
If IFAC = 2,		
A-10	XMULT	Multiplier by which the width of each cell is increased from that of the previous cell.
	XMAX	Maximum allowed horizontal or radial spacing, m.
A-11	JFAC	= 0 if grid spacing in vertical direction is to be read in for each row and multiplied by FACZ. = 1 if all vertical grid spacing is to be constant and equal to FACZ. = 2 if vertical grid spacing is variable, with spacing for the first two rows equal to FACZ and the spacing for each subsequent row equal to ZMULT times the spacing at the previous row, until spacing equals ZMAX, whereupon spacing becomes constant at ZMAX.
	FACZ	Constant grid spacing in vertical direction (if JFAC=1); constant multiplier for all spacing (if JFAC=0); or initial vertical spacing (if JFAC=2), m.
Line set A-12 is present only if JFAC = 0 or 2.		
If JFAC = 0,		
A-12	DELZ	Grid spacing in vertical direction; number of entries must equal NLY, m.
If JFAC = 2,		
A-12	ZMULT	Multiplier by which each cell is increased from that of previous cell.
	ZMAX	Maximum allowed vertical spacing, m.
Line sets A-13 to A-14 are present only if F8P = T,		
A-13	NPLT	Number of time steps to write pressure heads and temperatures to file 8 and heads, temperatures, saturations, moisture contents, and/or velocities to file 6.

Line	Variable	Description
		Must be less than 51.
A-14	PLTIM	Elapsed times at which pressure heads and temperatures are to be written to file 8, and heads, temperatures, saturations, velocities, and/or moisture contents to file 6, s.
Line sets A-15 to A-16 are present only if F11P = T,		
A-15	NOBS	Number of observation points for which heads, temperatures, moisture contents, and saturations are to be written to file 11. Must be less than 51.
A-16	J,N	Row and column of observation points. A double entry is required for each observation point, resulting in 2xNOBS values. No comments allowed.
Lines A-17 and A-18 are present only if F9P = T.		
A-17	NMB9	Total number of mass balance components written to file 9. Must be less than 73.
A-18	MB9	The index number of each mass balance component to be written to file 9. (See table 7, p. 66, in Healy (1990) and note that "solute" should be replaced by "energy".)
	[Line group B read by subroutine VSREAD]	
B-1	EPS	Head closure criterion for iterative solution of flow equation, m.
	HMAX	Relaxation parameter for iterative solution. See discussion in Lappala and others (1987) for more detail. Value is generally in the range of 0.4 to 1.2.
	WUS	Weighting option for intercell relative hydraulic conductivity: WUS = 1 for full upstream weighting. WUS = 0.5 for arithmetic mean. WUS = 0.0 for geometric mean.
	EPS1	Temperature closure criterion for iterative solution of transport equation, °C.
	EPS2	Velocity closure criterion for outer iteration loop at each time step, m/s.
B-3	MINIT	Minimum number of iterations per time step.
	ITMAX	Maximum number of iterations per time

Line	Variable	Description
		step. Must be less than 200.
B-4	PHRD	Logical variable = T if initial conditions are read in as pressure heads; = F if initial conditions are read in as moisture contents.
B-5	NTEX	Number of textural classes or lithologies having different values of hydraulic conductivity, specific storage, and/or constants in the functional relations among pressure head, relative conductivity, and moisture content, must be less than 11.
	NPROP	Number of flow properties to be read in for each textural class. When using Brooks and Corey or van Genuchten functions, set NPROP = 6; when using Haverkamp functions, set NPROP =8. When using tabulated data, set NPROP = 6 plus number of data points in table. [For example, if the number of pressure heads in the table is equal to N1, then set NPROP =3*(N1+1)+3]
	NPROP1	Number of transport properties to be read in for each textural class. For VS2DH set NPROP1 = 6.
Line sets B-6, B-7, and B-7A must be repeated NTEX times		
B-6	ITEX	Index to textural class.
B-7	ANIZ(ITEX)	Ratio of hydraulic conductivity in the z-coordinate direction to that in the x-coordinate direction for textural class ITEX.
	HK(ITEX,1)	Saturated hydraulic conductivity (K) at 20 °C in the x-coordinate direction for class ITEX, m/s.
	HK(ITEX,2)	Specific storage (S_s) for class ITEX, m^{-1}.
	HK(ITEX,3)	Porosity (ϕ)for class ITEX.

Definitions for the remaining sequential values on this line are dependent upon which functional relation is selected to represent the nonlinear coefficients. Four different functional relations are allowed: (1) Brooks and Corey, (2) van Genuchten, (3) Haverkamp, and (4) tabular data. The choice of which of these to use is made when the computer program is compiled, by including only the function subroutine which pertains to the desired relation (see discussion in Lappala and others (1987) for more detail). VS2DH uses the van Genuchten functional relations by default. In the following descriptions, definitions for the different functional relations are indexed by the above numbers. For tabular data, all pressure heads are input first (in decreasing order from the

Line	Variable	Description

largest to the smallest), all relative hydraulic conductivities are then input in the same order, followed by all moisture contents.

B-7 (Continued)

HK(ITEX,4)	(1)	h_b, m. (must be less than 0.0).
	(2)	α', m. (must be less than 0.0).
	(3)	A', m. (must be less than 0.0).
	(4)	Largest pressure head in table.
HK(ITEX,5)	(1)	Residual moisture content (θ_r).
	(2)	Residual moisture content (θ_r).
	(3)	Residual moisture content (θ_r).
	(4)	Second largest pressure head in table.
HK(ITEX,6)	(1)	pore-size distribution index (λ).
	(2)	β'.
	(3)	B'.
	(4)	Third largest pressure head in table.
HK(ITEX,7)	(1)	Not used.
	(2)	Not used.
	(3)	α, m. (must be less than 0.0).
	(4)	Fourth largest pressure head in table.
HK(ITEX,8)	(1)	Not used.
	(2)	Not used.
	(3)	β.
	(4)	Fifth largest pressure head in table.

For functional relations (1), (2), and (3) no further values are required on this line for this textural class. For tabular data (4), data input continues as follows:

HK(ITEX,9)	Next largest pressure head in table.
HK(ITEX,N1+3)	Minimum pressure head in table. Here N1 = Number of pressure heads in table; NPROP = 3*(N1+1)+3).
HK(ITEX,N1+4)	Always input a value of 99.
HK(ITEX,N1+5)	Relative hydraulic conductivity corresponding to first pressure head.
HK(ITEX,N1+6)	Relative hydraulic conductivity corresponding to second pressure head.
•	
•	
•	
HK(ITEX,2*N1+4)	Relative hydraulic conductivity corresponding to smallest pressure head.
HK(ITEX,2*N1+5)	Always input a value of 99.
HK(ITEX,2*N1+6)	Moisture content corresponding to first pressure head.
HK(ITEX,2*N1+7)	Moisture content corresponding to second pressure head.

Line	Variable	Description
B-7 (Continued)		
HK(ITEX,3*N1+5)	Moisture content corresponding to smallest pressure head.	
HK(ITEX,3*N1+6)	Always input a value of 99.	
Regardless of which functional relation is selected there must be NPROP+1 values on line B-7.		
Line B-7A is present only if TRANS = T.		
B-7A	HT(ITEX,1)	Longitudinal dispersivity (α_L), m.
	HT(ITEX,2)	Transverse dispersivity (α_T), m.
	HT(ITEX,5)	Heat capacity of dry solids (C_s), J/m^3 °C.
	HT(ITEX,9)	Thermal conductivity of water-sediment at residual moisture content, $K_T(\theta_r)$, W/m°C.
	HT(ITEX,10)	Thermal conductivity of water-sediment at full saturation, $K_T(\phi)$, W/m°C.
	HT(ITEX,11)	Heat capacity of water (C_w), which is the product of density times specific heat of water, J/m^3 °C.
B-8	IROW	If IROW = 0, textural classes are read for each row. This option is preferable if many rows differ from the others. If IROW = 1, textural classes are read in by blocks of rows, each block consisting of all the rows in sequence consisting of uniform properties or uniform properties separated by vertical interface.
Line set B-9 is present only if IROW = 0.		
B-9	JTEX	Indices (ITEX) for textural class for each node, read in row by row. There must be NLY*NXR entries.
Line set B-10 is present only if IROW = 1.		
As many groups of B-10 variables as are needed to completely cover the grid are required. The final group of variables for this set must have IR = NXR and JBT = NLY.		
B-10	IL	Left hand column for which texture class applies. Must equal 1 or IR (from previous line set)+1.
	IR	Right hand column for which texture class applies. Final IR for sequence of rows must

Line	Variable	Description
		equal NXR.
B-10 (Continued)	JBT	Bottom row of all rows for which the column designations apply. JBT must not be increased from its initial or previous value until IR = NXR.
	JRD	Texture class within block.
Note: As an example, for a column of uniform material: IL = 1, IR = NXR, JBT = NLY, and JRD = texture class designation for the column material. One line will represent the set for this example.		
B-11	IREAD	If IREAD = 0, all initial conditions in terms of pressure head or moisture content as determined by the value of PHRD are set equal to FACTOR. If IREAD = 1, all initial conditions are read from file IU in user-designated format and multiplied by FACTOR. If IREAD = 2 initial conditions are defined in terms of pressure head, and an equilibrium profile is specified above a free-water surface at a depth of DWTX until a pressure head of HMIN is reached. all pressure heads above this are set to HMIN.
	FACTOR	Multiplier or constant value, depending on value of IREAD, for initial conditions.
Line B-12 is present only if IREAD = 2,		
B-12	DWTX	Depth to free-water surface above which an equilibrium profile is computed, m.
	HMIN	Minimum pressure head to limit height of equilibrium profile, m. Must be negative.
Line B-13 is read only if IREAD =1,		
B-13	IU	Unit number from which initial head or moisture content values are to be read.
	IFMT	Format to be used in reading initial values from unit IU. Must be enclosed in quotation marks, for example '(10X,E10.3)'.
B-14	BCIT	Logical variable = T if evaporation is to be simulated at any time during the simulation; otherwise = F.
	ETSIM	Logical variable = T if evapotranspiration (plant-root extraction) is to be simulated at any time during the simulation.

Line	Variable	Description

Note: The reader is cautioned on the use of evaporation and evapotranspiration in VS2DH. These processes can influence and be influenced by soil temperature. As described in Lappala and others (1987) and implemented inVS2DH, these processes are simplistically assumed to be isothermal. Users should evaluate the ramifications of this assumption in their applications. If these processes are an integral component of an application, then use of another numerical model that treats evaporation and evapotranspiration in a more realistic fashion may be warranted.

Line B-15 is present only if BCIT = T or ETSIM = T.

B-15	NPV	Number of ET periods to be simulated. NPV values for each variable required for the evaporation and/or evapotranspiration options must be entered on the following lines. If ET variables are held constant throughout the simulation code, NPV = 1.
	ETCYC	Length of each ET period, s.

Line B-16 to B-18 are present only if BCIT = T.

B-16	PEVAL	Potential evaporation rate (PEV) at beginning of each ET period. Number of entries must equal NPV, m/s.

To conform with the sign convention used in most existing equations for potential evaporation, all entries must be greater than or equal to 0. The program multiplies all nonzero entries by -1 so that the evaporative flux is treated as a sink rather than a source.

B-17	RDC(1,J)	Surface resistance to evaporation (SRES) at beginning of ET period, m^{-1}. For a uniform soil, SRES is equal to the reciprocal of the distance from the top active node to land surface, or 2/DELZ(2). If a surface crust is present, SRES may be decreased to account for the added resistance to water movement through the crust. Number of entries must equal NPV.
B-18	RDC(2,J)	Pressure potential of the atmosphere (HA) at beginning of each ET period; may be estimated using equation 6 of Lappala and others (1987), m. Number of entries must equal NPV.

Lines B-19 to B-23 are present only if ETSIM = T.

B-19	PTVAL	Potential evapotranspiration rate (PET) at beginning of each ET period, m/s. Number of entries must equal NPV. As

Line	Variable	Description
		with PEV, all values must be greater than or equal to 0.
B-20	RDC(3,J)	Rooting depth at beginning of each ET period, m. Number of entries must equal NPV.
B-21	RDC(4,J)	Root activity at base of root zone at beginning of each ET period, m^{-2}. Number of entries must equal NPV.
B-22	RDC(5,J)	Root activity at top of root zone at beginning of each ET period, m^{-2}. Number of entries must equal NPV.

Note: Values for root activity generally are determined empirically, but typically range from 0 to $3x10^4$ m/m^3. As programmed, root activity varies linearly from land surface to the base of the root zone, and its distribution with depth at any time is represented by a trapezoid. In general, root activities will be greater at land surface than at the base of the root zone.

B-23	RDC(6,J)	Pressure head in roots (HROOT) at beginning of each ET period, m. Number of entries must equal NPV.
Lines B-24 and B-25 are present only if TRANS = T.		
B-24	IREAD	If IREAD = 0, all initial temperatures are set equal to FACTOR. If READ =1, all initial temperatures are read from file IU in user designated format and multiplied by FACTOR.
	FACTOR	Multiplier or constant value, depending on value of IREAD, for initial temperatures.
Line B-25 is present only if IREAD = 1.		
B-25	IU	Unit number from which initial temperatures are to be read.
	IFMT	Format to be used in reading initial temperature values from unit IU. Must be enclosed in quotation marks, for example '(10X, E10.3)'.

[Line group C read by subroutine VSTMER, NRECH sets of C lines are required]

C-1	TPER	Length of this recharge period, s.
	DELT	Length of initial time step for this period, s.
C-2	TMLT	Multiplier for time step length.
	DLTMX	Maximum allowed length of time step, s.
	DLTMIN	Minimum allowed length of time step, s.

Line	Variable	Description
	TRED	Factor by which time-step length is reduced if convergence is not obtained in ITMAX iterations. Values usually should be in the range 0.1 to 0.5. If no reduction of time-step length is desired, input a value of 0.0.
C-3	DSMAX	Maximum allowed change in head per time step for this period, m.
	STERR	Steady-state head criterion; when the maximum change in head between successive time steps is less than STERR, the program assumes that steady state has been reached for this period and advances to next recharge period, m.
C-4	POND	Maximum allowed height of ponded water for constant flux nodes. See Lappala and other (1987) for detailed discussion of POND, m.
C-5	PRNT	Logical variable = T if heads, temperature, moisture contents, and/or saturations are to be printed to file 6 after each time step; = F if they are to be written to file 6 only at observation times and ends of recharge periods.
C-6	BCIT	Logical variable = T if evaporation is to be simulated for this recharge period; otherwise = F.
	ETSIM	Logical variable = T if evapotranspiration (plant-root extraction) is to be simulated for this recharge period; otherwise = F.
	SEEP	Logical variable = T if seepage faces are to be simulated for this recharge period; otherwise = F.
C-7 to C-9 cards are present only if SEEP = T,		
C-7	NFCS	Number of possible seepage faces. Must be less than or equal to 8.
Line sets C-8 and C-9 must be repeated NFCS times.		
C-8	JJ	Number of nodes on the possible seepage face. Must be less than 26.
	JLAST	Number of the node which initially represents the highest node of the seep; value can range from 0 (bottom of the face) up to JJ (top of the face).

Line	Variable	Description
C-9	J,N	Row and column of each cell on possible seepage face, in order from the lowest to the highest elevation; JJ pairs of values are required.
C-10	IBC	Code for reading in boundary conditions by individual node (IBC=0) or by row or column (IBC=1). Only one code may be used for each recharge period, and all boundary conditions for period must be input in the sequence for that code.
Line set C-11 is read only if IBC = 0. One line is required for each node for which new boundary conditions are specified.		
C-11	JJ	Row number of node.
	NN	Column number of node.
	NTX	Node type identifier for boundary conditions. = 0 for no specified boundary (needed for resetting some nodes after initial recharge period); = 1 for specified pressure head; = 2 for specified flux per unit horizontal surface area in units of m/s; = 3 for possible seepage face; = 4 for specified total head; = 5 for evaporation; = 6 for specified volumetric flow in units of m^3/s.
	PFDUM	Specified head for NTX = 1 or 4 or specified flux for NTX = 2 or 6. If codes 0, 3, or 5 are specified, the line should contain a dummy value for PFDUM or should be terminated after NTX by a blank and a slash (/).
	NTC	Node type identifier for transport boundary conditions. = 0 for no specified boundary; = 1 for specified temperatures;
	CF	Specified temperature for NTC = 1 or NTX = 1, 2, 4, or 6. Present only if TRANS = T.
C-12 is present only if IBC = 1. One line should be present for each row or column for which new boundary conditions are specified,		
C-12	JJT	Top node of row or column of nodes sharing same boundary condition.

Line	Variable	Description
C-12 (Continued)	JJB	Bottom node of row or column of nodes having same boundary condition. Will equal JJT if a boundary row is being read.
	NNL	Left column in row or column of nodes having same boundary condition.
	NNR	Right column of row or column of nodes having same boundary condition. Will equal NNL if a boundary column is being read in.
	NTX	Same as line C-11.
	PFDUM	Same as line C-11.
	NTC	Same as line C-11.
	CF	Same as line C-11.
C-13	Designated end of recharge period. Must be included after line C-12 data for each recharge period. Two C-13 lines must be included after final recharge period. Line must always be entered as -999999 /.	

APPENDIX 2

Example Problem Input

```
1-D unsaturated flow with energy transport (Jaynes, 1990)
3600. 0. 0.                                        A2---TMAX,STIM,ANG
   M SEC    J                                      A3---ZUNIT,TUNIT,CUNX
3 129                                              A4---NXR,NLY
168 2400                                           A5---NRECH,NUMT
F T T                                              A6---RAD,ITSTOP,TRANS
T T F                                              A6A--CIS,CIT,SORP
T F T T F                                          A7---F11P,F7P,F8P,F9P,F6P
F F T F F                                          A8---THPT,SPNT,PPNT,HPNT,VPNT
1 1.0                                              A9---IFAC,FACX
0 1.0                                              A11--IFAC,FACZ
0.001  0.001  0.001  0.001  0.001  0.001  0.001  0.001  0.001  0.001
0.001  0.001  0.0015 0.0015 0.002  0.003  0.005  0.010  0.015  0.020
0.021  0.021  0.029  0.037  0.047  0.061  0.091  0.131  0.187  0.261
0.396  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500  0.500
1                                                  A13--NPLT
     3600.                                         A14--PLTIM
3                                                  A15--NOBS
22 2
25 2
29 2
1                                                  A17--NMB9
3                                                  A18--MB9
1.e-7 .90  0.00 1.0e-10 1.0e-7                     B1---EPS,HMAX,WUS,EPS1,EPS2
2   199                                            B3---MINIT,ITMAX
T                                                  B4---PHRD
2 6 6                                              B5---NTEX,NPROP,NPROP1
1                                                  B6---ITEX
1. 4.0e-08 .0 .496 -1.18 .15 4.8                   B7---ANIZ,HK
0.01 0.01 2.18e+6 1.5 1.8 4.18e+6                  B7A--HT
2                                                  B6---ITEX
1. 8.0e-06 .0 .496 -1.18 .15 4.8                   B7---ANIZ,HK
0.01 0.01 2.18e+6 1.5 1.8 4.18e+6                  B7A--HT
1                                                  B8---IROW
1 3   7 1                                          B10--IL,IR,JBT,JRD
1 3 129 2                                          B10--IL,IR,JBT,JRD
2 1.                                               B11--IREAD,FACTOR
100.  -0.7497                                      B12--DWTX,HMIN
F F                                                B14--BCIT, ETSIM
0 21.30                                            B24--IREAD,FACTOR
3600. 360.                                         C1---TPER,DELT
1.2 3600. 180. 0.5                                 C2---TMLT,DLTMX,DLTMIN,TRED
100. 0.                                            C3---DSMAX,STERR
0.0                                                C4---POND
F                                                  C5---PRNT
F F F                                              C6---BCIT,ETSIM,SEEP
0                                                  C10--IBC
2 2 1 0.0405 0 17.48                               C11--JJ,NN,NTX,PFDUM,NTC,CF
128 2 1 0.0 1 21.30                                C11--JJ,NN,NTX,PFDUM,NTC,CF
-999999 /                                          C13
-999999 /                                          C13
```

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+                                                             +
+                          VS2DH                              +
+     SIMULATION OF 2-DIMENSIONAL VARIABLY                    +
+     SATURATED FLOW AND ENERGY TRANSPORT                     +
+      THROUGH POROUS MEDIA.  VERSION DATED                   +
+                          8-1-96                             +
+                                                             +
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

```
*****************************************************************************************
    1-D unsaturated flow with energy transport (Jaynes, 1990)
*****************************************************************************************

         SPACE AND TIME CONSTANTS
         ------------------------
    MAXIMUM SIMULATION TIME =   0.360000E+04  SEC (  1.0000E+00 hr)
    STARTING TIME =     0.0000
    NUMBER OF RECHARGE PERIODS =       168
    MAXIMUM NUMBER OF TIME STEPS =       2400
    NUMBER OF ROWS =   129
    NUMBER OF COLUMNS =     3
    AXES TILTED BY ANGLE =     0.00
         SOLUTION OPTIONS
         ----------------
    WRITE ALL PRESSURE HEADS TO FILE 8 AT OBSERVATION TIMES? T
    STOP SOLUTION IF MAXIMUM NO. OF ITERATIONS EXCEEDED IN ANY TIME STEP?T
    WRITE MAXIMUM CHANGE IN HEAD FOR EACH ITERATION TO FILE 7? F
    WRITE RESULTS AT SELECTED OBSERVATION POINTS TO FILE 11? T
    WRITE MASS BALANCE RATES TO FILE 9?T
    WRITE MASS BALANCE RATES TO FILE 6? F
    WRITE MOISTURE CONTENTS TO FILE 6? F
    WRITE SATURATIONS TO FILE 6? F
    WRITE PRESSURE HEADS TO FILE 6? T
    WRITE TOTAL HEADS TO FILE 6? F
    WRITE VELOCITIES TO FILE 6? F
```

```
                                              GRID SPACING IN VERTICAL DIRECTION, IN  M
0.001     0.001     0.001     0.001     0.001     0.001     0.001     0.001     0.001     0.001
0.001     0.001     0.002     0.002     0.002     0.003     0.005     0.010     0.015     0.020
0.021     0.021     0.029     0.037     0.047     0.061     0.091     0.131     0.187     0.261
0.396     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500     0.500
                                              GRID SPACING IN HORIZONTAL OR RADIAL DIRECTION, IN  M
1.000     1.000     1.000
TIMES (IN  SEC) AT WHICH H WILL BE WRITTEN TO FILE 08
 0.36000E+04
ROW AND COLUMN OF OBSERVATION POINTS:
  22   2    25   2    29   2
MASS BALANCE COMPONENTS WRITTEN TO FILE 9
   3
COORDINATE SYSTEM IS RECTANGULAR
TRANSPORT TO BE SIMULATED
CENTRAL DIFFERENCING IN SPACE USED FOR TRANSPORT EQUATION
CENTRAL DIFFERENCING IN TIME USED FOR TRANSPORT EQUATION
MATRIX EQUATIONS TO BE SOLVED BY SIP
CONVERGENCE CRITERION FOR SIP FOR FLOW (EPS) =   1.000E-07  M
CONVERGENCE CRITERION FOR SIP FOR TRANSPORT (EPS1) =   1.000E-10
DAMPING FACTOR, HMAX =    9.000E-01
CONVERGENCE CRITERION FOR OUTER ITERATION (EPS2)  =    1.000E-07
GEOMETRIC MEAN USED FOR INTERCELL CONDUCTIVITY
NUMBER OF SOIL TEXTURAL CLASSES =         2
NUMBER OF SOIL PARAMETERS FOR EACH CLASS =         6
NUMBER OF TRANSPORT PARAMETERS FOR EACH CLASS =         6
MINIMUM PERMITTED NO. OF ITERATIONS/TIME STEP =        2
MAXIMUM PERMITTED NO. OF ITERATIONS/TIME STEP =      199
```

CONSTANTS FOR SOIL TEXTURAL CLASSES

	ANISOTROPY	KSAT	SPECIFIC STORAGE	POROSITY	HK(4)	HK(5)	HK(6)
	ALPHAL	ALPHAT	Cs	KT MIN	KT MAX	Cw	
CLASS # 1							
	1.000D+00	4.000D-08	0.000D+00	4.960D-01	-1.180D+00	1.500D-01	4.800D+00
	1.000D-02	1.000D-02	2.180D+06	1.500D+00	1.800D+00	4.180D+06	
CLASS # 2							
	1.000D+00	8.000D-06	0.000D+00	4.960D-01	-1.180D+00	1.500D-01	4.800D+00
	1.000D-02	1.000D-02	2.180D+06	1.500D+00	1.800D+00	4.180D+06	

TEXTURAL CLASS INDEX MAP

TEXTURAL CLASSES READ IN BY BLOCK

1	111
2	111
3	111
4	111
5	111
6	111
7	111
8	222
9	222
10	222
11	222
12	222
13	222
14	222
15	222
.	
.	
.	
115	222
116	222
117	222
118	222
119	222
120	222
121	222
122	222
123	222

```
  124  222
  125  222
  126  222
  127  222
  128  222
  129  222
 EQUILLIBRIUM PROFILE USED TO INITIALIZE PRESSURE HEADS ABOVE WATER TABLE AT    100.00  M   BELOW ORIGIN
 EQUILLIBRIUM PROFILE ONLY USED UNTIL PRESSURE HEADS EQUAL     -0.75  M
 PRESSURE HEADS BELOW    100.00  M   ARE HYDROSTATIC
 INITIAL TEMPERATURE SET TO A CONSTANT VALUE OF    2.130E+01 DEGREES C
 5SIP ITERATION PARAMETERS:  0.0000000D+00  0.8886089D+00  0.9875920D+00  0.9986179D+00  0.9998460D+00
  1-D unsaturated flow with energy transport (Jaynes, 1990)
 TOTAL ELAPSED TIME =  0.000000E+00  SEC (  0.0000E+00 hr)
 TIME STEP     0


                                                PRESSURE HEAD, IN M

Z, IN
 M                      X OR R DISTANCE, IN  M
            0.50
   0.00-7.50E-01
   0.00-7.50E-01
   0.00-7.50E-01
   0.00-7.50E-01
   0.00-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.01-7.50E-01
   0.02-7.50E-01
   0.02-7.50E-01
   0.02-7.50E-01
   0.03-7.50E-01
   0.04-7.50E-01
        .
        .
        .
  45.10-7.50E-01
```

45.60-7.50E-01
46.10-7.50E-01
46.60-7.50E-01
47.10-7.50E-01
47.60-7.50E-01
48.10-7.50E-01
48.60-7.50E-01
49.10-7.50E-01
49.60-7.50E-01

TEMPERATURE, IN DEGREES C

Z, IN
M X OR R DISTANCE, IN M

	0.50
0.00	21.300
0.00	21.300
0.00	21.300
0.00	21.300
0.00	21.300
0.01	21.300
0.01	21.300
0.01	21.300
0.01	21.300
0.01	21.300
0.01	21.300
.	
.	
.	
46.10	21.300
46.60	21.300
47.10	21.300
47.60	21.300
48.10	21.300
48.60	21.300
49.10	21.300
49.60	21.300

DATA FOR RECHARGE PERIOD 1

LENGTH OF THIS PERIOD = 3.60000E+03 SEC (1.0000E+00 hr)
LENGTH OF INITIAL TIME STEP FOR THIS PERIOD = 3.60000E+02 SEC
MULTIPLIER FOR TIME STEP = 1.200E+00
MAXIMUM TIME STEP SIZE = 3.60000E+03 SEC
MINIMUM TIME STEP SIZE = 1.80000E+02 SEC

```
      TIME STEP REDUCTION FACTOR =  5.000E-01
           MAXIMUM PRESSURE HEAD CHANGE ALLOWED IN ONE TIME STEP = 100.000  M
           STEADY-STATE CLOSURE CRITERION =    0.00000E+00  M
           MAXIMUM DEPTH OF PONDING =    0.00000E+00  M
           PRINT SOLUTION AFTER EVERY TIME STEP? F
           SIMULATE EVAPORATION? F
           SIMULATE EVAPOTRANSPIRATION? F
           SIMULATE SEEPAGE FACES? F

  NODE TYPE AND INITIAL BOUNDARY CONDITIONS FOR PERIOD    1
  LEGEND:
           0 = INTERIOR CELL
           1 = SPECIFIED PRESSURE HEAD CELL
           2 = SPECIFIED FLUX CELL
           3 = POTENTIAL SEEPAGE FACE NODE
           5 = NODE FOR WHICH EVAPORATION IS PERMITTED


    1     000
    2     010
    3     000
    4     000
    5     000
    6     000
    7     000
    8     000
    9     000
   10     000
   11     000
   12     000
   13     000
   14     000
   15     000
      .
      .
      .
  120     000
  121     000
  122     000
  123     000
  124     000
  125     000
```

```
  126     000
  127     000
  128     010
  129     000
TIME STEP     1  TIME =   0.432000E+03 SEC (  1.2000E-01 hr)  NIT =  26  NIT1 =  35  NIT3 =   3
TIME STEP     2  TIME =   0.950400E+03 SEC (  2.6400E-01 hr)  NIT =  22  NIT1 =  35  NIT3 =   3
TIME STEP     3  TIME =   0.157248E+04 SEC (  4.3680E-01 hr)  NIT =  16  NIT1 =  25  NIT3 =   2
TIME STEP     4  TIME =   0.231898E+04 SEC (  6.4416E-01 hr)  NIT =  15  NIT1 =  25  NIT3 =   2
TIME STEP     5  TIME =   0.321477E+04 SEC (  8.9299E-01 hr)  NIT =  16  NIT1 =  25  NIT3 =   2
TIME STEP     6  TIME =   0.360000E+04 SEC (  1.0000E+00 hr)  NIT =  13  NIT1 =  22  NIT3 =   2
     1-D unsaturated flow with energy transport (Jaynes, 1990)
    TOTAL ELAPSED TIME =  3.600000E+03  SEC (  1.0000E+00 hr)
    TIME STEP     6


                                                    PRESSURE HEAD, IN M
 Z, IN
  M                       X OR R DISTANCE, IN  M
             0.50
    0.00 4.05E-02
    0.00-9.46E-02
    0.00-2.30E-01
    0.00-3.67E-01
    0.00-5.10E-01
    0.01-6.71E-01
    0.01-7.66E-01
    0.01-7.66E-01
    0.01-7.66E-01
    0.01-7.66E-01
    0.01-7.66E-01
    0.01-7.67E-01
    0.01-7.67E-01
    0.02-7.67E-01
    0.02-7.67E-01
    0.02-7.67E-01
    0.03-7.67E-01
    0.04-7.68E-01
    0.06-7.68E-01
    0.08-7.68E-01
    0.10-7.68E-01
    0.13-7.67E-01
    0.16-7.66E-01
```

0.20-7.65E-01
0.25-7.63E-01
0.33-7.61E-01
0.44-7.59E-01
0.60-7.56E-01
0.82-7.53E-01
1.15-7.51E-01
1.60-7.50E-01
2.10-7.50E-01
2.60-7.50E-01
.
.
.
45.10-7.50E-01
45.60-7.50E-01
46.10-7.50E-01
46.60-7.50E-01
47.10-7.50E-01
47.60-7.49E-01
48.10-7.42E-01
48.60-6.68E-01
49.10-3.61E-01
49.60 0.00E+00

TEMPERATURE, IN DEGREES C

Z, IN
M X OR R DISTANCE, IN M

	0.50
0.00	17.480
0.00	17.480
0.00	17.492
0.00	17.513
0.00	17.540
0.01	17.572
0.01	17.606
0.01	17.642
0.01	17.679
0.01	17.717
0.01	17.755
0.01	17.801
0.01	17.856
0.02	17.918
0.02	18.004

0.02	18.135
0.03	18.377
0.04	18.806
0.06	19.411
0.08	20.024
0.10	20.506
0.13	20.906
0.16	21.162
0.20	21.268
0.25	21.296
0.33	21.300
0.44	21.300
0.60	21.300
0.82	21.300
.	
.	
.	
45.10	21.300
45.60	21.300
46.10	21.300
46.60	21.300
47.10	21.300
47.60	21.300
48.10	21.300
48.60	21.300
49.10	21.300
49.60	21.300

---------- MASS BALANCE SUMMARY FOR TIME STEP 6 ----------
PUMPING PERIOD NUMBER 1
TOTAL ELAPSED SIMULATION TIME = 3.600000E+03 SEC (1.0000E+00 hr)

VOLUMETRIC FLOW BALANCE	TOTAL M **3	TOTAL THIS TIME STEP M **3	RATE THIS TIME STEP M **3/ SEC
FLUX INTO DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	2.13977E-02	1.96995E-03	5.11370E-06
FLUX OUT OF DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	-2.88736E-03	-8.73949E-04	-2.26865E-06
FLUX INTO DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL FLUX INTO DOMAIN --	2.13977E-02	1.96995E-03	5.11370E-06
TOTAL FLUX OUT OF DOMAIN --	-2.88736E-03	-8.73949E-04	-2.26865E-06
EVAPORATION --	0.00000E+00	0.00000E+00	0.00000E+00
TRANSPIRATION --	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL EVAPOTRANSPIRATION --	0.00000E+00	0.00000E+00	0.00000E+00
CHANGE IN FLUID STORED IN DOMAIN --	3.26367E-02	1.09600E-03	2.84505E-06
FLUID VOLUME BALANCE --	-1.41264E-02	-1.59325E-10	-4.13585E-13

ENERGY MASS BALANCE	J	J	J / SEC
FLUX INTO DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	1.60997E+06	1.43937E+05	3.73640E+02
FLUX OUT OF DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES --	-2.57073E+05	-7.78112E+04	-2.01987E+02
FLUX INTO DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES --	0.00000E+00	0.00000E+00	0.00000E+00
DIFFUSIVE/DISPERSIVE FLUX INTO DOMAIN --	9.49780E-02	2.32151E-02	6.02632E-05
DIFFUSIVE/DISPERSIVE FLUX OUT OF DOMAIN --	-4.56388E+05	-2.12911E+04	-5.52686E+01
TOTAL FLUX INTO DOMAIN --	1.60997E+06	1.43937E+05	3.73640E+02
TOTAL FLUX OUT OF DOMAIN --	-7.13461E+05	-9.91022E+04	-2.57256E+02
TOTAL EVAPOTRANSPIRATION --	0.00000E+00	0.00000E+00	0.00000E+00
FIRST ORDER DECAY --	0.00000E+00	0.00000E+00	0.00000E+00
ADSORPTION/ION EXCHANGE --	0.00000E+00	0.00000E+00	0.00000E+00
CHANGE IN ENERGY STORED IN DOMAIN --	8.97832E+05	4.49999E+04	1.16813E+02
ENERGY MASS BALANCE --	-1.32277E+03	-1.65295E+02	-4.29082E-01

****
END OF SIMULATION
****

TOTAL NUMBER OF ITERATIONS FOR FLOW EQUATION = 191
TOTAL NUMBER OF ITERATIONS FOR TRANSPORT EQUATION = 294
TOTAL NUMBER OF ITERATIONS FOR OUTER LOOP = 14