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A MODEL OF VIRUS TRANSPORT IN UNSATURATED SOIL

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air, and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and control of toxic substances, pesticides, noise, and radiation, the agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the Laboratory are responsible for management of research programs to: a) determine the fate, transport, and transformation rates of pollutants in the soil, the unsaturated zone, and the saturated zones of the subsurface environment; b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; c) develop techniques for predicting the effect of pollutants on ground water, soil, and indigenous organisms; d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

The model described herein can be used to predict the fate and transport of disease-causing viruses in unsaturated soil. It can be used to help researchers design experiments so that important transport parameters are measured accurately. It can also be used in conjunction with a saturated flow model to help determine placement of waste sources relative to drinking water wells to minimize the potential for waterborne viral disease.

Clinton W. Hall
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ABSTRACT

As a result of the recently-proposed mandatory ground-water disinfection requirements to inactivate viruses in potable water supplies, there has been increasing interest in virus fate and transport in the subsurface. Several models have been developed to predict the fate of viruses in ground water, but few include transport in the unsaturated zone, and all require a constant virus inactivation rate. These are serious limitations in the models, as it has been well documented that considerable virus removal occurs in the unsaturated zone, and that the inactivation rate of viruses is dependent on environmental conditions. The purpose of this research was to develop a predictive model of virus fate and transport in unsaturated soils that allows the virus inactivation rate to vary based on changes in soil temperature. The model was developed based on the law of mass conservation of a contaminant in porous media and couples the flow of water, viruses, and heat through the soil. Model predictions were compared to measured data of virus transport in laboratory column studies, and were within the 95% confidence limits of the measured concentrations. The model should be a useful tool for anyone wishing to estimate the number of viruses entering ground water after traveling through the soil from a contamination source. In addition, model simulations were performed to identify variables that have a large effect on the results. This information can be used to help design experiments so that important variables are measured accurately.

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INTRODUCTION

The significance of viruses as agents of ground-waterborne disease in the United States has been well documented (Craun 1986, 1990). The increasing interest in preventing ground-water contamination by viruses and other disease-causing microorganisms has led to new U.S. Environmental Protection Agency regulations regarding ground-water disinfection (U.S.EPA, 1991), the development of wellhead protection zones, and stricter standards for the microbiological quality of municipal sludge (U.S.EPA, 1989) and treated effluent (California Department of Health Services, 1990) that is applied to land. For many of the new regulations, a predictive model of virus (or bacterial) transport would be helpful in the implementation process. For example, such a model could be used to determine where septic tanks could be placed or where land application of sludge or effluent could be practiced relative to drinking water wells to minimize negative impacts on the ground-water quality. Another application of microbial transport models is related to the ground-water disinfection rule (U.S.EPA, 1991). Water utilities wishing to avoid ground-water disinfection may use a pathogen transport model to demonstrate that adequate removal of viruses in the source water occurs during transport to the wellhead.

Several models of microbial transport have been developed during the past 15 to 20 years (Grosser, 1984; Harvey and Garabedian, 1991; Matthess et al., 1988; Park et al., 1990; Teutsch et al., 1991; Tim and Mostaghimi, 1991; Vilker and Burge, 1980; Yates and Yates, 1989). The models range from the very simple, requiring few input parameters, to the very complex, requiring numerous input parameters. For many of the more complex models, the data required for input are not available except for very limited environmental conditions. They may be useful for research purposes, but would be impractical for widespread use. The potential applications of these models also range considerably, from being useful only for screening purposes on a regional scale, to predicting virus behavior at one specific location.

One limitation of almost all of these models is that they have been developed to describe virus transport in saturated soils (i.e., ground water). However, it has been demonstrated many times that the potential for virus removal is greater in the unsaturated zone than in the ground water (Keswick and Gerba, 1980; Lance and Gerba, 1984; Powelson et al., 1990). Neglecting the unsaturated zone in any model of virus transport could lead to inaccurately high predictions of virus concentrations at the site of interest. This omission would be especially significant in areas with thick unsaturated zones, such as those in many western states. The one transport model (Tim and Mostaghimi, 1991) that has reportedly been developed for predicting virus transport in variably saturated media is not specific for viruses, but can be used for any contaminant. In addition, it has not been tested using data of virus transport in unsaturated soil.

Another, and more important, limitation of published models of virus transport is that none of them has been validated using actual data of virus transport in unsaturated soils. Most models are developed based on theory, and are fitted to data obtained from one or two experiments. Rarely are they tested by applying the model to data collected under a variety of conditions and then determining how well the model predicts what has been observed in the laboratory or field without any fitting or calibration of the model.

TRANSPORT PROCESSES

The transport of viruses through a porous medium such as soil is affected primarily by the following mechanisms and processes:

1. Advection. The advection of viruses or any other contaminants in water is due to the average velocity of water as it flows. It results in the entire mass of contaminant streaming from a zone of higher potential to one of lower potential.
2. Hydrodynamic dispersion. Hydrodynamic dispersion is the spreading of a contaminant caused by mechanical dispersion and molecular diffusion. Dispersion is the nonsteady irreversible mixing of two miscible fluids displacing one another. Diffusion is a random motion of molecules caused by thermal kinetics.
3. Adsorption (and desorption). The adsorption of viruses to soil particles is caused by a combination of electrostatic and van der Waals forces and hydrophobic interactions between the virus and soil particles. Adsorption reduces the concentration of viruses in the soil water. Desorption occurs due to changes in the ionic strength of the soil water.

4. Filtration. The physical filtration of viruses during the transport process occurs primarily by straining and sedimentation. Straining occurs when the particles in suspension in the porous matrix cannot pass through a smaller pore, and thus their transport is halted. For very small particles such as viruses, filtration is generally neglected (Corapcioglu and Haridas, 1986). However, if the viruses are adsorbed onto a solid particle entrained in the water or are present as aggregates, filtration can be an important removal process. Sedimentation of viruses in the soil pores occurs when the density of virus particles is higher than that of water.
5. Inactivation. Virus inactivation is the loss of infectivity toward host cells, and therefore ability to causes disease. The inactivation of viruses is caused by a variety of adverse chemical, biological, and physical processes.

FACTORS AFFECTING TRANSPORT PROCESSES

The transport of viruses through soil is controlled by climatic conditions such as the rate of rainfall (or water application) and evaporation and by soil properties such as soil water content, soil temperature, adsorption and desorption, filtration, soil pH, and salt concentration (Yates and Yates, 1988). The properties of the specific virus of interest are also important in determining its behavior in the subsurface. Some of the most important factors that affect the transport of viruses through soil research include soil water content, soil temperature, the rate of water application and evaporation, and soil heterogeneity.

Soil Water Content

The amount of water in the soil (soil water content) influences the movement of viruses through soil. Lance and Gerba (1984) found that saturated flow through loamy sand resulted in 7% recovery of poliovirus at a depth of 10 cm, but unsaturated flow resulted in only 0.5% recovery. Powelson et al. (1990) found that MS-2 virus was removed to a much greater extent under unsaturated flow conditions as compared to that during saturated flow conditions.

Soil Temperature

Soil temperature affects the length of time that viruses remain infective in the environment. At lower temperature, virus persistence is prolonged compared with that at higher temperature (Yates and Yates, 1988). Soil temperature also affects the transport of soil water, thereby indirectly affecting the transport of viruses through soils.

Water Application and Evaporation

Addition of water (e.g., by rainfall or irrigation) to the soil acts to move viruses through the soil profile. It can also act to desorb previously adsorbed viruses, thus allowing them to be transported deeper through the soil. The evaporation of water out of the soil surface causes the changes in the soil water content and soil temperature, thereby affecting the transport and fate of viruses.

Soil Heterogeneity

Soil is a heterogeneous system whose properties change with soil depth. At different soil layers, soil properties such as soil porosity, hydraulic conductivity, and thermal conductivity, are different. Therefore, the transport of viruses through soil, which is subjected to the soil properties, will change with soil depth.

OBJECTIVES

The purpose of this research was to develop a model that can be used to predict virus movement from a contamination source through unsaturated soil to the ground water. Several model simulations were performed to determine the effects of different input variables on model predictions. The model was tested by comparing model predictions to results of laboratory studies.

The specific objectives of this project were:

1. To develop a mathematical model to describe the transport of viruses in unsaturated soil that includes factors specific to viruses, and
2. To test model predictions with experimental data of virus transport in soil.

DEVELOPMENT OF TRANSPORT EQUATIONS

Transport equations were derived to describe the simultaneous transport of water, viruses, and heat for a soil profile shown schematically in Figure 1. The soil profile, which may contain soil with nonhomogeneous properties, is bound

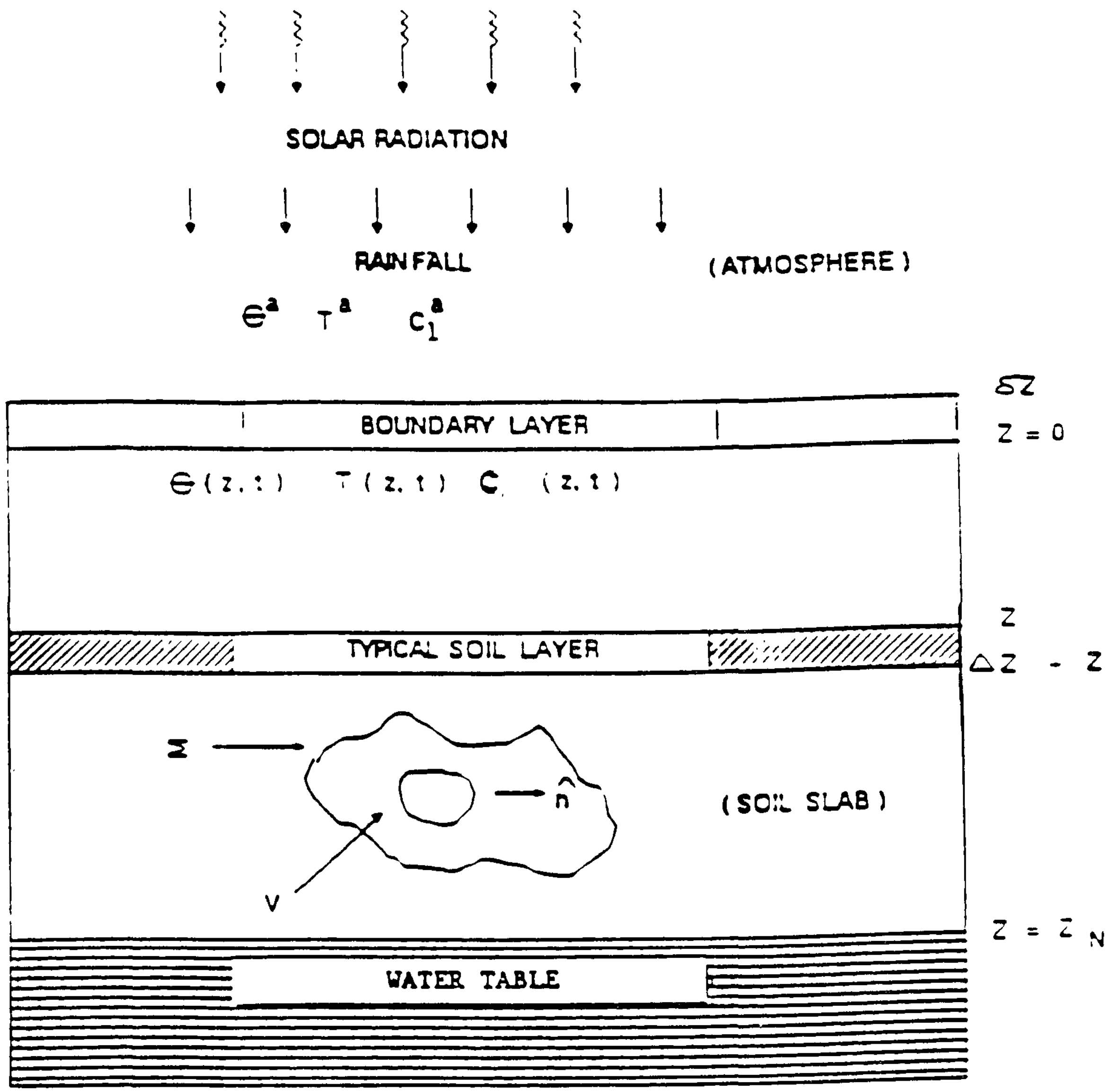

Figure 1. Schematic diagram of a soil profile for which the model is developed

below by a water table and above by the atmosphere.

The assumptions used in the development of transport equations pertaining to the atmosphere are:

1. Diurnal changes in air temperature and relative humidity can be characterized by a Fourier series;
2. Diurnal changes in solar intensity can be characterized by a Gaussian normal distribution function;
3. The initial distributions of water and temperature in the atmosphere are known;
4. The rate and duration of water application is prescribed.

The assumptions used in the development of transport equations pertaining to the soil profile are:

1. The soil can be characterized by known parameters such as: the soil porosity; the specific heats of solid, water, and air; the thermal conductivities of solid, water, and air; the latent heat of vaporization; the water potential function; the hydraulic conductivity function; and the densities of solid, water, air, and water vapor;
2. The atmosphere and soil surface are coupled for the water, virus, and heat fields by heat and mass transport rules operating in the boundary layer at the atmosphere-soil interface; and
3. The initial distributions of water content, temperature, and viruses in the soil profile are prescribed.

WATER AND HEAT TRANSPORT IN THE SOIL

Water and heat transport equations derived by Ouyang (1990) are given as:

$$\frac{\partial}{\partial t}\left[\, \rho_w \theta + \rho_{wv}^{sat}(T)\, h\, (e-\theta) \right] = -\nabla \cdot \left[\rho_w \theta\, \vec{V}_l + \rho_{wv}\, (e-\theta)\, \vec{V}_v \right] \tag{1}$$

for water transport, and:

$$\frac{\partial}{\partial t}\left[(1-\epsilon)\ c_{solid}\ \rho_{solid}\ T + (\epsilon-\theta)\ c_{air}\ \rho_{air}\ T + \theta\ c_w\ \rho_w T \right]$$

$$= -\nabla \bullet \left[(1-\epsilon)\ \vec{H}_{ss} + \theta\ \vec{H}_{sl} + (\epsilon-\theta)\ \vec{H}_{sv} \right] \tag{2}$$

for heat transport, where t is the time (hr), ρ_w is the density of water (g cm^{-3}), θ is the volumetric water content (cm^3 cm^{-3}), ρ_{wv}^{sat} (T) is the density of water vapor at saturation at temperature T (g vapor cm^{-3} air), h is the relative humidity (dimensionless), ϵ is the soil porosity (cm^3 soil voids cm^{-3} soil) $\vec{V}_l$ and $\vec{V}_v$ are the velocity vectors of water in the liquid and vapor phases (cm hr^{-1}), respectively, ρ_{wv} is the density of water vapor (g vapor cm^{-3} air), c_{solid} is the specific heat of soil particles (cal $soil^{-1}$ particle $°C^{-1}$), ρ_{solid} is the density of soil particles (g cm^{-3} solids), T is the temperature (°C), c_{air} and c_w are specific heats of air and water (cal g^{-1} $°C^{-1}$), respectively, ρ_{air} is the density of air (g cm^{-3}air), $\vec{H}_{ss}$ is the vector of heat conduction through the soil particles (cal cm^{-2} hr^{-1}), $\vec{H}_{sl}$ is the vector of heat conduction and convection in the liquid phase (cal cm^{-2} hr^{-1}), and $\vec{H}_{sv}$ is the vector of heat conduction in the vapor phase and the latent heat flux (cal cm^{-2} hr^{-1}).

The velocity vectors, $\vec{V}_l$ and $\vec{V}_v$, in equation (1) are defined as:

$$\vec{V}_l = -\vec{D}_{\theta_l} \bullet \nabla\theta - \vec{D}_{T_l} \bullet \nabla T + \vec{K} \bullet \left(\vec{z} - \frac{\partial\psi}{\partial z}\right), \tag{3}$$

and

$$\vec{V}_v = -\vec{D}_{\theta_v} \bullet \nabla\theta - \vec{D}_{T_v} \bullet \nabla T + \vec{D}_{\psi} \bullet \left(-\frac{\partial\psi}{\partial z}\right), \tag{4}$$

with

$$\vec{D}_{\theta_l} = \frac{\partial\psi}{\partial z}\vec{K}, \tag{5}$$

$$\vec{D}_{T_l} = \frac{\partial\psi}{\partial T}\vec{K}, \tag{6}$$

$$\vec{D}_{\theta_v} = D_{atm}\alpha_{tort}\left(\frac{g}{RT}\right)\left(\frac{\partial\psi}{\partial z}\right)\vec{E} , \tag{7}$$

$$\vec{D}_{T_v} = D_{atm}\alpha_{tort}\left[\left(\frac{1}{\rho_{wv}^{sat}}\right)\frac{d\rho_{wv}^{sat}}{dT} + \left(\frac{g}{RT}\right)\left(\frac{\partial\psi}{\partial z} - \frac{\psi}{T}\right)\right]\vec{E} , \tag{8}$$

$$\vec{D}_{\psi} = D_{atm}\alpha_{tort}\left(\frac{g}{RT}\right)\vec{E} , \tag{9}$$

where $\overleftrightarrow{D}_{\theta l}$ is the second rank tensor describing the diffusion coefficient of water in the liquid phase (cm2 hr^{-1}). $\overleftrightarrow{D}_{Tl}$ is the second tensor describing the thermal diffusivity in the liquid phase (cm^2hr^{-1}), $\overleftrightarrow{K}$ is the second rank tensor describing the water conductivity (cm hr^{-1}), $\vec{z}$ is the unit vector normal to plane z = 0 with positive orientation vertically downward, z is the soil depth (cm). ψ is the water potential (cm), $\overleftrightarrow{D}_{\theta v}$ is the second rank tensor describing the diffusion coefficient of water in the vapor phase (cm^2 hr^{-1}), $\overleftrightarrow{D}_{Tv}$ is the second rank tensor describing the thermal diffusivity in the vapor phase (cm^2 hr^{-1}), $\overleftrightarrow{D}_{\psi}$ is the second rank tensor describing the diffusion coefficient of water affected by the water potential (cm^2 hr^{-1}), D_{atm} is the water vapor molecular diffusion coefficient in air (cm^2 hr^{-1}), α_{tort} is the tortuosity factor of the soil, g is the gravitational constant (cm hr^{-1}), R is the gas constant (cm^{-2} hr^{-2} $°C^{-1}$), $\overleftrightarrow{E}$ is the second rank identity tensor (dimensionless), and ρ_{wv}^{sat} is the density of water vapor at saturation (g vapor cm^{-3} air).

The vectors $\vec{H}_{ss}$, $\vec{H}_{sl}$, and $\vec{H}_{sv}$ in equation (2) are defined as:

$$\vec{H}_{ss} = - \lambda_{solid} \nabla T , \tag{10}$$

$$\vec{H}_{sl} = - \lambda_{w} \nabla T + C_{w} \rho_{w}\vec{V}_{l} T , \tag{11}$$

and

$$\vec{H}_{sv} = -\xi D_{atm}\alpha_{tort}\nabla\rho_{wv} - \lambda_{air}\nabla T\,, \tag{12}$$

where λ_{solid} is the thermal conductivity of the solids (cal cm^{-1} hr^{-1} °C^{-1}), λ_w is the thermal conductivity of water (cal cm^{-1} hr^{-1} °C^{-1}), ξ is the latent heat of evaporation (cal g^{-1}), and λ_{air} is the thermal conductivity of the air (cal cm^{-1} hr^{-1} °C^{-1}).

The variables ρ_{wv}^{sat}, ρ_{wv}, h, and ξ in equations (1) and (12), which are functions of temperature, are given as (Weast, 1986):

$$\rho_{wv}^{sat} = 0.004928 + 0.0002581T + 0.0000183T^2 \tag{13}$$

for $0 < T \leq 22.5$°C, and

$$\rho_{wv}^{sat} = 0.00493 + 0.000258T + 0.0000396T^2 \tag{14}$$

for $T > 22.5$°C,

$$\rho_{wv} = \rho_{wv}^{sat}(T)\,h, \tag{15}$$

$$h = \exp\left(\frac{\psi g}{RT}\right)\,, \tag{16}$$

and

$$\xi = 598.88 - 0.547T\,. \tag{17}$$

VIRUS TRANSPORT IN SOIL

According to the law of conservation of mass, the virus transport equation in differential form can be expressed as:

$$\frac{\partial}{\partial t}[\rho_b C_s + \theta C_l] = \frac{\partial}{\partial z}[\theta D \frac{\partial C_l}{\partial z}]$$

$$- \frac{\partial V \theta C_l}{\partial z} - [\theta \mu_l C_l + \rho_b \mu_s C_s] - \theta f C_l , \tag{18}$$

where t is the time (hr). ρ_b is the bulk density of soil (g cm^{-3} soil), C_s is the concentration of viruses adsorbed onto the soil particles (mass g^{-1} solid), θ is the volumetric soil water content (cm^3 cm^{-3}), C_l is the concentration of viruses in soil water (mass cm^{-3} water), z is the soil depth (cm), D is the coefficient of hydrodynamic dispersion of viruses (cm^2 hr^{-1}), V is the flow velocity of water (cm hr^{-1}), μ_l and μ_s are the inactivation coefficients of viruses in liquid and solid phases (hr^{-1}), respectively, and f is the filtration coefficient of viruses (hr^{-1}).

The adsorption of viruses onto soil particles, C_s, in equation (18) can be expressed by using the Freundlich adsorption isotherm (Grosser, 1984; Corapcioglu and Haridas, 1986):

$$C_s = K_d C_l^n , \tag{19}$$

where C_s is the concentration of viruses adsorbed onto the soil particles (mass g^{-1} solid), K_d is the Freundlich constant (cm^3 water g^{-1} solid), n is the exponential constant (dimensionless), and C_l is the concentration of viruses in the soil water (mass cm^{-3} water). For many systems, the empirical constant n is not significantly different from unity and equation (19) reduces to a linear form (Vilker and Burge, 1980; Yates and Yates, 1988):

$$C_s = K_d C_l . \tag{20}$$

BOUNDARY CONDITIONS

Equations (1), (2), and (18) define the coupled transport of water, heat, and virus, respectively. Boundary conditions must be defined to be able to solve these equations.

Boundary Between the Atmosphere and the Soil Profile

Water

By using the "Gaussian Pill Box" concept (Figure 2), the conservation of mass law requires that:

$$\vec{q}_w \cdot (\vec{n} = \vec{z}) + \vec{q}_{rain} \cdot (\vec{n} = \vec{z}) + \vec{q}_{evap} \cdot (\vec{n} = -\vec{z}) = 0 \,, \tag{21}$$

where $\vec{q}_w$ is a vector describing the total water flux at the soil surface (g water cm^{-2} hr^{-1}), $\vec{n}$ is the unit vector outward going normal to the simple closed surface, $\vec{z}$ is the unit vector normal to plane $z = 0$ with positive orientation vertically downward, $\vec{q}_{rain}$ is a vector describing rainwater flux into the soil (g water cm^{-2} hr^{-1}), and $\vec{q}_{evap}$ is a vector describing evaporation flux or condensation flux of water out of, or into, the soil (g water cm^{-2} hr^{-1}).

The total water flux vector $\vec{q}_w$ at the soil surface ($z = 0$) can be defined as:

$$\vec{q}_w \big|_{z=0} = [\theta_o \rho_w \vec{V}_l + (\epsilon_o - \theta_o) \rho_{wv} \vec{V}_v] \big|_{z=0} \,, \tag{22}$$

the rainwater flux vector $\vec{q}_{rain}$ is written as:

$$\vec{q}_{rain} = \rho_w \vec{\Phi}_{rain} \,, \tag{23}$$

and the evaporation or condensation flux vector $\vec{q}_{evap}$ is given as:

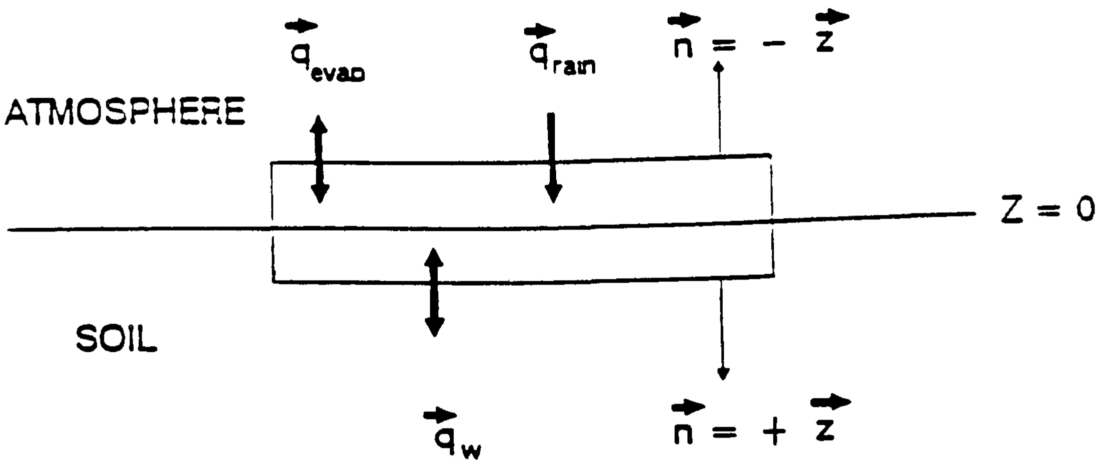

Figure 2. Gaussian Pill Box concept for water flow at the atmosphere-soil interface

$$\vec{Q}_{evap} = -D^{*}_{atm}[\frac{d\rho^{sat}_{wv}(T_a)}{dT_a}\theta_a(\frac{T_o-T_a}{\delta z})$$

$$+ \rho^{sat}_{wv}(T_a)(\frac{h-\theta_a}{\delta z})] \quad , \tag{24}$$

where θ_o is the water content at the atmosphere-soil interface (cm^3 cm^{-3}), ρ_w is the density of water (g cm^{-3}), $\vec{V}_l$ is the velocity vector of liquid water (cm hr^{-1}), ε_o is the soil porosity at the atmosphere-soil interface (cm^3 soil voids cm^{-3} soil), ρ_{wv} is the density of water vapor (g cm^{-3}), $\vec{V}_v$ is the velocity vector of water vapor (cm hr^{-1}), $\vec{\Phi}_{rain}$ is the vector describing the rainfall rate (cm hr^{-1}), $D^{\star}_{atm}$ is the the boundary layer wind-speed-dependent coefficient of dispersion of water vapor (cm^2 hr^{-1}), $\rho^{sat}_{wv}(T_a)$ is the density of water vapor at saturation at temperature T_a (g vapor cm^{-3}), T_a is the temperature in the atmosphere (°C), θ_a is the relative humidity in the atmosphere (dimensionless), T_o is the temperature at the atmosphere-soil interface (°C), δz is the thickness of the boundary layer at the atmosphere-soil interface (cm), and h is the relative humidity at the atmosphere-soil interface (dimensionless).

Substituting equations (22), (23) and (24) into equation (21) yields:

$$[\theta_o\rho_w\vec{V}_l + (\epsilon_o - \theta_o)\rho_{wv}\vec{V}_v]\ |_{z=0} \bullet \vec{n}$$

$$= \rho_w\Phi_{rain} - D^{*}_{atm}[\frac{d\rho^{sat}_{wv}(T_a)}{dT_a}\theta_a(\frac{T_o-T_a}{\delta z})$$

$$+ \rho^{sat}_{wv}(T_a)(\frac{h-\theta_a}{\delta z})] \quad , \tag{25}$$

Recall that equations (3) and (4) are written as:

$$\vec{V}_l = -\tilde{D}_{\theta_l}\bullet\nabla\theta - \tilde{D}_{T_l}\bullet\nabla T + \tilde{K}\bullet(\bar{z} - \frac{\partial\psi}{\partial z})$$

$$\vec{V}_v = -\tilde{D}_{\theta_v}\bullet\nabla\theta - \tilde{D}_{T_v}\bullet\nabla T + \tilde{D}_{\psi}\bullet(-\frac{\partial\psi}{\partial z})$$

and $\vec{n} = \vec{z}$, substituting $\vec{V}_l$ and $\vec{V}_v$ into equation (25) leads to:

$$(\theta_o \rho_w D_{\theta_l} + (\epsilon_o - \theta_o)\rho_{wv} D_{\theta v})(-\frac{\partial \theta}{\partial z})\Big|_{z=0}$$

$$+ (\theta_o \rho_w K(1 - \frac{\partial \psi}{\partial z})\Big|_{z=0} + (\epsilon_o - \theta_o)\rho_{wv} D_{\psi})(-\frac{\partial \psi}{\partial z})\Big|_{z=0}$$

$$+ (\theta_o \rho_w D_{T_l} + (\epsilon_o - \theta_o)\rho_{wv} D_{T_v})(-\frac{\partial T}{\partial z})\Big|_{z=0}$$

$$= \rho_w \phi_{rain} - D^{\circ}_{atm}[\frac{d\rho^{sat}_{wv}(T_a)}{dT_a}\theta_a(\frac{T_o - T_a}{\delta z})$$

$$\rho^{sat}_{wv}(T_a)(\frac{h - \theta_a}{\delta z}] \,, \tag{26}$$

which is the coupling upper boundary condition for water transport.

Heat

Analogous to the movement of water, again using the Gaussian Pill Box concept (Figure 3), conservation of heat requires that:

$$\vec{q}_{heatin} \bullet (\vec{n} = \vec{z}) + \vec{q}_{htevp} \bullet (\vec{n} = -\vec{z}) + \vec{q}_{htswr} \bullet (\vec{n} = \vec{z})$$

$$+ \vec{q}_{htssl} \bullet (\vec{n} = \vec{z}) + \vec{q}_{htlwra} \bullet (\vec{n} = \vec{z}) + \vec{q}_{htlwrs} \bullet (\vec{n} = -\vec{z})$$

$$+ \vec{q}_h \bullet (\vec{n} = \vec{z}) = 0 \,, \tag{27}$$

where $\vec{q}_{heatin}$ is a vector describing heat flux into the soil surface via rainwater (cal cm^{-2} hr^{-1}), $\vec{q}_{htevp}$ is a vector describing heat flux out of the soil surface due to evaporation or heat flux into the soil surface due to condensation (cal cm^{-2} hr^{-1}), $\vec{q}_{htswr}$ is a vector describing heat flux into the soil surface by short wave radiation (cal cm^{-1} hr^{-1}), $\vec{q}_{htssl}$ is a vector describing

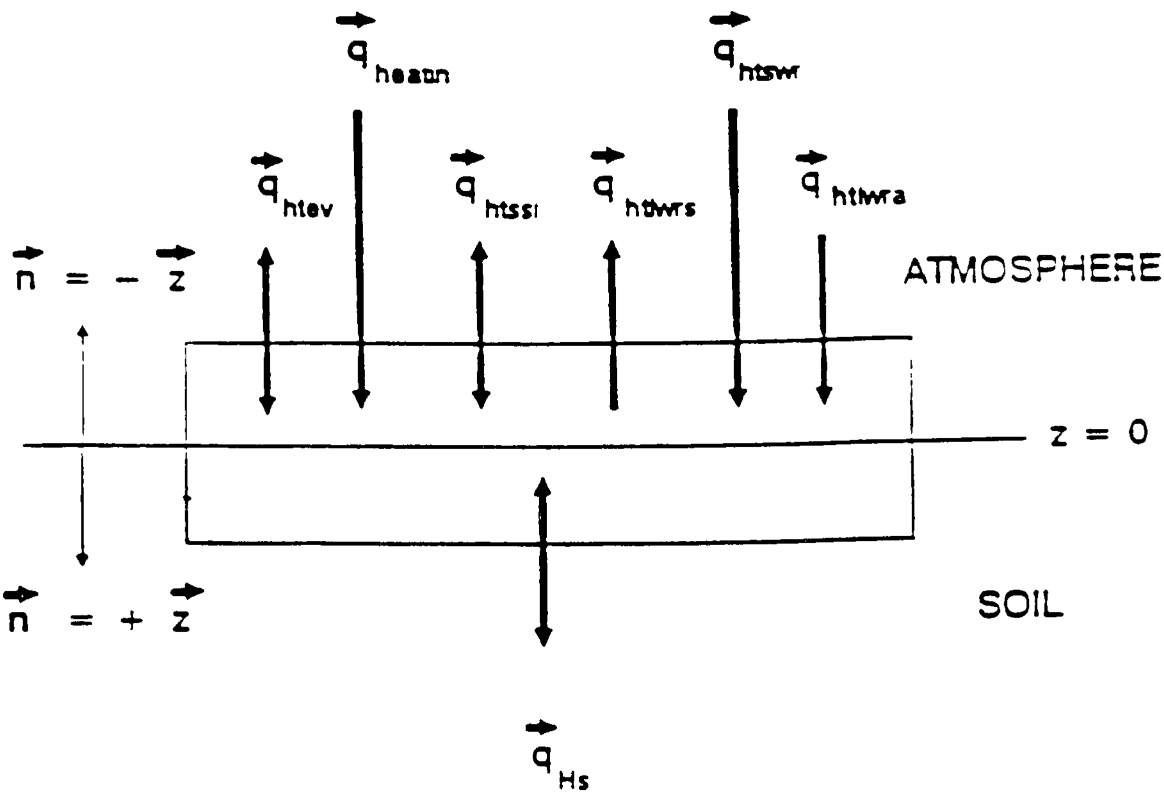

Figure 3. Gaussian Pill Box concept for heat flow at the atmosphere–soil interface

heat flux through the soil surface via sensible heat (cal cm^{-2} hr^{-1}), $\vec{q}_{htlwra}$ is a vector describing heat flux into the soil surface via long wave radiation (cal cm^{-2} hr^{-1}), $\vec{q}_{htlwrs}$ is a vector describing heat flux out of the soil surface via long wave radiation (cal cm^{-2} hr^{-1}), and $\vec{q}_h$ is a vector describing total heat flux into, or out of, the soil surface (cal cm^{-2} hr^{-1}).

The vectors in equation (27) are defined by (Lindstrom and Piver, 1985):

$$\vec{q}_{heatin} = \rho_w C_w T_{rw}\,\Phi_{rain}\,, \tag{28}$$

$$\vec{q}_{evap} = D^*_{atm}\Big[\frac{d\rho^{sat}_{wv}(T_a)}{dT_a}\theta_a\Big(\frac{T_o - T_a}{\delta z}\Big) + \rho^{sat}_{wv}(T_a)\Big(\frac{h - \theta_a}{\delta z}\Big)\Big]\xi\,, \tag{29}$$

$$\vec{q}_{htlswr} = [(1-\epsilon_o)(1-\alpha_{soil}) + \theta_o(1-\alpha_{water}) + (\epsilon_o-\theta_o)(1-\alpha_{air})]\,q_{swr} \tag{30}$$

$$\vec{q}_{htssl} = \lambda^*_{air}\Big(\frac{T_o - T_a}{\delta z}\Big)\,, \tag{31}$$

$$\vec{q}_{htlwra} = \epsilon_{air}\sigma T_a^4[0.605 + 0.048\sqrt{e_v^{air}}]\,, \tag{32}$$

$$\vec{q}_{htlwrs} = \sigma T_o^4[\epsilon_{soil}(1 - \epsilon_o) + \epsilon_{water}\theta_o + \epsilon_{air}(\epsilon_o - \theta_o)]\,, \tag{33}$$

$$\vec{q}_h = (1 - \epsilon_o)\vec{H}_{ss} + \theta_o\vec{H}_{sl} + (\epsilon_o - \theta_o)\vec{H}_{sv}\,, \tag{34}$$

with

$$D^*_{atm} = \frac{D_{atm}D_{wvmax}}{D_{atm} + (D_{wvmax} - D_{atm})\exp(-\beta_{evp}WS)}\,, \tag{35}$$

$$\lambda_{air}^{*} = \frac{\lambda_{air}\lambda_{amax}}{\lambda_{air} + (\lambda_{amax} - \lambda_{air})\exp(-\beta_{ht}WS)} \quad . \tag{36}$$

Definitions of variables in equations (28) through (36) are in Appendix II.

Substituting equations (28) through (36) into equation (27) with subsequent combination of variables leads to:

$$(\theta_o c_w \rho_w D_{\theta_l} T_o + (\epsilon_o - \theta_o)\xi \rho_{wv} D_{\theta v})(-\frac{\partial \theta}{\partial z})\Big|_{z=0}$$

$$+ \theta_o c_w \rho_w K(1 - \frac{\partial \psi}{\partial z})\Big|_{z=0} T_o + (\epsilon_o - \theta_o)\xi \rho_{wv} D_{\psi_l})(-\frac{\partial \psi}{\partial z})\Big|_{z=0}$$

$$+ [(1 - \epsilon_o)\lambda_{solid} + \theta_o(\lambda_w + c_w \rho_w D_{T_l} T_o)$$

$$+ (\epsilon_o - \theta_o)(\lambda_{air} + \xi \rho_{wv} D_{T_v})](-\frac{\partial T}{\partial z})\Big|_{z=0}$$

$$= \rho_w c_w T_{rw} \phi_{rain} - \xi D_{atm}^{*}[\frac{d\rho_{wv}^{sat}(T_a)}{dT_a}\theta_a(\frac{T_o - T_a}{\delta z})$$

$$+ \rho_{wv}^{sat}(T_a)(\frac{h - \theta_a}{\delta z})] - \lambda_{air}^{*}\frac{T_o - T_a}{\delta z}$$

$$+ [(1 - \epsilon_o)(1 - \alpha_{soil}) + \theta_o(1 - \alpha_{water})$$

$$+ (\epsilon_o - \theta_o)(1 - \alpha_{air})] q_{swr}$$

$$+ \sigma T_o^4 [\epsilon_{soil}(1 - \epsilon_o) + \epsilon_{water}\theta_o + \epsilon_{air}(\epsilon_o - \theta_o)]$$

$$\epsilon_{air}\sigma T_o^4 [0.605 + 0.048\sqrt{e_v^{air}}] \quad . \tag{37}$$

which is the coupling upper boundary conditions for heat transport.

Viruses

Analogous to the transport of water and heat, and again using the Gaussian Pill Box concept (Figure 4), the conservation of virus mass requires that:

$$\vec{q}_v \bullet (\vec{n} = \vec{z}) + \vec{q}_{rain} \bullet (\vec{n} = -\vec{z}) = 0 , \tag{38}$$

where $\vec{q}_v$ is a vector describing virus flux into the soil surface (mass cm^{-2} hr^{-1}) and $\vec{q}_{rain}$ is a vector describing virus flux through the soil surface by infiltration (mass cm^{-2} hr^{-1}).

The vectors in equation (38) are defined as:

$$\vec{q}_v = - D\theta (\frac{\partial C_1}{\partial z}) + \vec{V}\theta C_1 \tag{39}$$

and

$$\vec{q}_{rain} = C_{win} \vec{\Phi}_{rain} , \tag{40}$$

where C_{win} is the concentration of virus in water entering the soil (mass cm^{-1} water).

Substitution of equations (39) and (40) into equation (38) yields:

$$[(\theta D)^{n+1}_o + (\theta V)^{n+1}_o \Delta z_1] C^{n+1}_{1_o} - [\theta D]^{n+1}_o C^{n+1}_{1_1} = C^{n+1}_{win} \Phi^{n+1}_{rain} \Delta z_1 , \tag{41}$$

which is the coupling upper boundary condition for virus transport.

Boundary Between the Soil Profile and the Water Table

The boundary conditions at the interface between the soil profile and the fixed elevation water table for water and heat transport are assumed to be constant. These are:

$$\theta(z_w, t) = \theta_s , \tag{42}$$

and

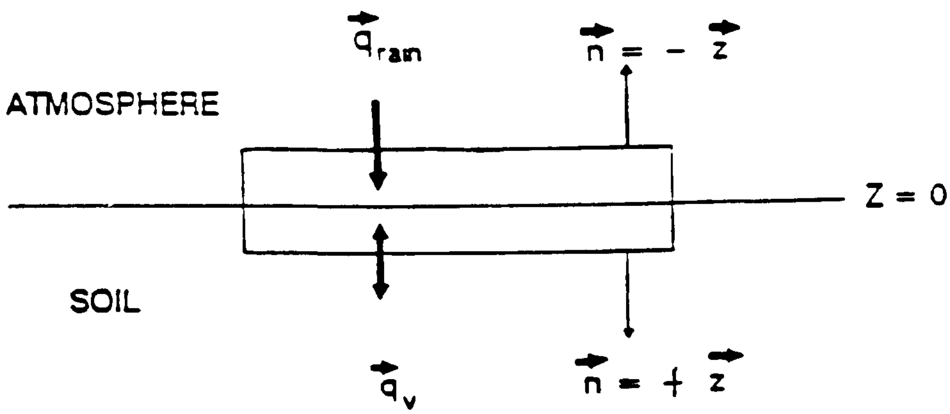

Figure 4. Gaussian Pill Box concept for virus flow at the atmosphere-soil interface

$$T(z_w,\ t) = T_g\ ,\qquad (43)$$

where z_w is the soil depth at the interface between the soil slab and the water table (cm), θ_s is the saturated soil water content ($cm^3\ cm^{-3}$), and T_g is the temperature at water table (°C).

The boundary condition for the virus field at the interface between the soil slab and the water table is not fixed. This boundary condition does not occur except for short periods of time, insufficient for the viruses to be transported from the top or from a buried source position to the water table. The more realistic boundary condition is obtained by applying the Gaussian Pill Box concept to virus transport at the interface between the soil and the water table and is given as (Lindstrom et al., 1990):

$$C_l(z_w,\ t) = \left(\frac{C_g}{\Delta z_*} + \frac{C_l(z_w - \Delta z_{Nz},\ t)}{\Delta z_{Nz}}\right) / \left(\frac{1}{\Delta z_{Nz}} + \frac{1}{\Delta z_*}\right)\ ,\qquad (44)$$

where $C_l(z_w,\ t)$ is the concentration of virus at the interface between the soil profile and the water table at time t (mass cm^{-3} water), C_g is the concentration of virus in the ground water (mass cm^{-3} water), z_w is the soil depth at the interface between the soil and the water table (cm), and Δz_{Nz} and Δz_* are the depth intervals above and below the interface between the soil profile and the water table, respectively (cm).

The water, heat, and virus transport equations and their boundary conditions, discussed above, are summarized in Tables 1 and 2.

SOLUTION OF TRANSPORT EQUATIONS

Since the solution of the virus transport equation (18) requires a point-wise knowledge of water and heat distributions in space and time, the water and heat transport equations (1) and (2) must be solved prior to solving the virus transport equation. The three transport equations were solved using the finite difference method. Solution of the water and heat transport equations were discussed and given in Ouyang (1990). Solution of the virus transport equation is discussed below.

Table 1. Equations for water, heat, and virus transport through the soil.

Water

$$\frac{\partial}{\partial t}[\rho_w \theta + \rho_{wv}^{sat}(T)\, h\, (e-\theta)] = -\nabla \bullet [\rho_w \theta \vec{V}_l + \rho_{wv} (e-\theta)\, \vec{V}_v]$$

Heat

$$\frac{\partial}{\partial t}[\, (1-e)\, c_{solid}\, \rho_{solid}\, T + (e-\theta)\, c_{air}\, \rho_{air}\, T + \theta\, c_w\, \rho_w T\,]$$

$$= -\nabla \bullet [\, (1-e)\, \vec{H}_{ss} + \theta\, \vec{H}_{sl} + (e-\theta)\, \vec{H}_{sv}\,]$$

Virus

$$\frac{\partial}{\partial t}[\rho_b\, C_s + \theta C_l\,] = \frac{\partial}{\partial z}[\, \theta D \frac{\partial C_l}{\partial z}\,]$$

$$- \frac{\partial v \theta C_l}{\partial z} - [\, \theta \mu_l\, C_l + \rho_b\, \mu_s C_s\,] - \theta f C_l$$

Table 2. Boundary conditions at: (1) the interface between the atmosphere and the soil surface; and (2) the water table.

Interface Between the Atmosphere and the Soil Surface

Water

$$(\theta_o \rho_w D_{\theta_l} + (\epsilon_o - \theta_o)\rho_{wv} D_{\theta v})(-\frac{\partial\theta}{\partial z})\Big|_{z=0}$$

$$+ (\theta_o \rho_w K(1 - \frac{\partial\psi}{\partial z})\Big|_{z=0} + (\epsilon_o - \theta_o)\rho_{wv} D_\psi)(-\frac{\partial\psi}{\partial z})\Big|_{z=0}$$

$$+ (\theta_o \rho_w D_{T_l} + (\epsilon_o - \theta_o)\rho_{wv} D_{T_v})(-\frac{\partial T}{\partial z})\Big|_{z=0}$$

$$= \rho_w \phi_{rain} - D^*_{atm}[\frac{d\rho^{sat}_{wv}(T_a)}{dT_a}\theta_a(\frac{T_o - T_a}{\delta z})$$

$$\rho^{sat}_{wv}(T_a)(\frac{h - \theta_a}{\delta z}]$$

Heat

$$(\theta_o c_w \rho_w D_{\theta_l} T_o + (\epsilon_o - \theta_o)\xi\rho_{wv} D_{\theta v})(-\frac{\partial\theta}{\partial z})\Big|_{z=0}$$

$$+ \theta_o c_w \rho_w K(1 - \frac{\partial\psi}{\partial z})\Big|_{z=0} T_o + (\epsilon_o - \theta_o)\xi\rho_{wv} D_{\psi_l})(-\frac{\partial\psi}{\partial z})\Big|_{z=0}$$

$$+ [(1 - \epsilon_o)\lambda_{solid} + \theta_o(\lambda_w + c_w \rho_w D_{T_l} T_o)$$

$$+ (\epsilon_o - \theta_o)(\lambda_{air} + \xi\rho_{wv} D_{T_v})](-\frac{\partial T}{\partial z})\Big|_{z=0}$$

$$= \rho_w c_w T_{rw}\phi_{rain} - \xi D^*_{atm}[\frac{d\rho^{sat}_{wv}(T_a)}{dT_a}\theta_a(\frac{T_o - T_a}{\delta z})$$

$$+ \rho^{sat}_{wv}(T_a)(\frac{h - \theta_a}{\delta z})] - \lambda^*_{air}\frac{T_o - T_a}{\delta z}$$

$$+ [(1 - \epsilon_o)(1 - \alpha_{soil}) + \theta_o(1 - \alpha_{water})$$

Table 2. Boundary conditions at: (1) the interface between the atmosphere and the soil surface; and (2) the water table (continued).

$$+ (\epsilon_o - \theta_o)(1 - \alpha_{air})] q_{swr}$$

$$+ \sigma T_o^4 [\epsilon_{soil}(1 - \epsilon_o) + \epsilon_{water}\theta_o + \epsilon_{air}(\epsilon_o - \theta_o)]$$

$$\epsilon_{air}\sigma T_o^4 [0.605 + 0.048\sqrt{e_v^{air}}]$$

Virus

$$[(\theta D)_o^{n+1} + (\theta V)_o^{n+1}\Delta z_1] C_{l_o}^{n+1} - [\theta D]_o^{n+1} C_{l_1}^{n+1} = C_{vin}^{n+1} \Phi_{rain}^{n+1} \Delta z_1$$

Interface Between the Soil Profile and the Water Table

Water

$$\theta(z_w, t) = \theta_s$$

Heat

$$T(z_w, t) = T_g$$

Virus

$$C_l(z_w, t) = (\frac{C_g}{\Delta z_e} + \frac{C_l(z_w - \Delta z_{Nz}, t)}{\Delta z_{Nz}}) / (\frac{1}{\Delta z_{Nz}} + \frac{1}{\Delta z_e})$$

Before approximating equation (18), define:

$$q = D\theta \frac{\partial C_l}{\partial z} - V\theta C_l \ , \qquad (45)$$

and

$$\Lambda = \theta \mu_l C_l + \rho_b \mu_s C_s + \theta f C_l \ . \qquad (46)$$

Putting equations (45) and (46) into equation (18) yields:

$$\frac{\partial}{\partial t}[\rho_b C_s + \theta C_l] = \frac{\partial}{\partial z}[q] - \Lambda \ , \qquad (47)$$

Following Varga's (1962) method of approximation, integration of both sides of equation (47) over the rectangular subregion of space and time [$(z_{i-1/2}, z_{i+1/2}) \times (t_n, t_{n+1})$] yields:

$$\int_{z_{i-1/2}}^{z_{i+1/2}} [\rho_b C_s + \theta C_l]_{t_{n+1}} dz - \int_{z_{i-1/2}}^{z_{i+1/2}} [\rho_b C_s + \theta C_l]_{t_n} dz$$

$$= \int_{t_n}^{t_{n+1}} [q]_{z_{i+1/2}} dt - \int_{t_n}^{t_{n+1}} [q]_{z_{i-1/2}} dt$$

$$- \int_{t_n}^{t_{n+1}} \int_{z_{i-1/2}}^{z_{i+1/2}} [\Lambda]\, dz dt. \qquad (48)$$

Applying the finite difference formulations in Appendix I, substituting equations (45) and (46) into equation (48), and defining $C_s = K_d C_l$, obtains:

$$[\frac{\Delta z_i + \Delta z_{i+1}}{2}]\{([\rho_b K_d + \theta) C_l]_i^{n+1} - [(\rho_b K_d + \theta) C_l]_i^n\}$$

$$= \Delta t\{[D\theta]_{i+1/2}^{n+1} \frac{C_{l_{i+1}}^{n+1} - C_{l_i}^{n+1}}{\Delta z_{i+1}} - [V\theta]_{i+1/2}^{n+1} \frac{C_{l_{i+1}}^{n+1} + C_{l_i}^{n+1}}{2}\}$$

$$- \Delta t\{[D\theta]_{i-1/2}^{n+1} \frac{C_{l_i}^{n+1} - C_{l_{i-1}}^{n+1}}{\Delta z_i} - [V\theta]_{i-1/2}^{n+1} \frac{C_{l_i}^{n+1} + C_{l_{i-1}}^{n+1}}{2}\}$$

$$- \Delta t \left[\frac{\Delta z_i + \Delta z_{i+1}}{2} \right] \{ (\theta \mu_l + \rho_b K_d \mu_s + \theta f)_i^{n+1} C_{l_i}^{n+1} \} \ . \qquad (49)$$

Multiplying both sides of equation (49) by $2/(\Delta z_i + \Delta z_{i+1/2})$ and rearranging terms into common coefficients yields:

$$- \frac{2\Delta t}{\Delta z_i + \Delta z_{i+1}} \left\{ \frac{[D\theta]_{i-1/2}^{n+1}}{\Delta z_i} + \frac{[V\theta]_{i-1/2}^{n+1}}{2} \right\} C_{l_{i-1}}^{n+1}$$

$$+ \left[\frac{2\Delta t}{\Delta z_i + \Delta z_{i+1}} \left\{ \frac{[D\theta]_{i+1/2}^{n+1}}{\Delta z_{i+1}} + \frac{[V\theta]_{i+1/2}^{n+1}}{2} + \frac{[D\theta]_{i-1/2}^{n+1}}{\Delta z_i} - \frac{[V\theta]_{i-1/2}^{n+1}}{2} \right\} \right.$$

$$\left. + \Delta t \{ (\theta \mu_l + \rho_b K_d \mu_s + \theta f)_i^{n+1} + \{ \rho_b K_d + \theta \}_i^{n+1} \right] C_{l_i}^{n+1}$$

$$- \frac{2\Delta t}{\Delta z_i + \Delta z_{i+1}} \left\{ \frac{[D\theta]_{i+1/2}^{n+1}}{\Delta z_{i+1}} - \frac{[V\theta]_{i+1/2}^{n+1}}{2} \right\} C_{l_{i+1}}^{n+1}$$

$$= [\rho_b K_d + \theta]_i^n C_{l_i}^n \ , \qquad (50)$$

which is a useful form for setting up the computer program.

VIRTUS: A MODEL OF VIRUS TRANSPORT IN UNSATURATED SOIL

The mathematical model developed herein was entitled VIRTUS (VIRus Transport in Unsaturated Soil). and programmed in FORTRAN for use on IBM and IBM-compatible PC's. A document describing the use of the program is contained in Appendix III. Sample input and output data that can be used to test the model are listed in Appendix IV. In this section, the mathematical model and corresponding computer program, VIRTUS, will be demonstrated in a variety of situations. The potential applications of this model and its limitations will also be discussed.

MODEL APPLICATIONS AND LIMITATIONS

Some of the features of this model include its ability to simulate:

1. unsteady flow in variably-saturated media
2. transport in layered soils
3. variable virus inactivation rate (e.g., function of temperature)
4. different virus inactivation rates for adsorbed versus freely suspended virus particles.
5. the flow of heat through soil (which affects water flow, virus inactivation rate, etc.)

As the model was programmed, the viruses are applied to the soil surface. This occurs when treated sewage effluent is used for irrigation purposes, where ground water is recharged with effluent, and when sewage effluent is discharged to dry stream beds (such as occurs in the southwest). If viruses are applied to the soil from a buried source, such as a septic tank, the model may still be applied; however, the boundary conditions in the program must be adjusted. VIRTUS also assumes that there is a water table at the bottom of the soil profile, if there is not, the appropriate boundary conditions must be introduced.

VERIFICATION OF VIRTUS

The numerical solution of the virus transport equations was verified using an analytical solution to the equations. The virus transport equation and initial and boundary conditions used were:

$$\frac{\partial}{\partial t}[\rho_b C_s + \theta C_l] = \frac{\partial}{\partial z}[\theta D \frac{\partial C_l}{\partial z}] - \frac{\partial v\theta C_l}{\partial z} - [\theta \mu_l C_l + \rho_b \mu_s C_s] - \theta f C_l , \tag{51}$$

$$C_1(z,\ 0) = 0\ , \tag{52}$$

$$C_1(0,\ t) = C_o\ , \tag{53}$$

and

$$C_1(\infty,\ t) = o\ . \tag{54}$$

The analytical solution of equations (51), (52), (53), and (54) is:

$$C_1(z,\ t) = \frac{C_o}{2}[\exp\frac{(\theta Vz - z\sqrt{(\theta V^2 + 4D\Lambda)\theta}}{2D\theta}$$

$$erfc(\frac{z\sqrt{\theta}(\rho_b K_d+\theta) - t\theta\sqrt{(\theta V^2 + 4D\Lambda)}}{2\theta\sqrt{Dt(\rho_b K_d+\theta)}})$$

$$+ \exp(\frac{\theta Vz + z\sqrt{(\theta V^2 - 4D\Lambda)\theta}}{2D\theta}$$

$$erfc(\frac{z\sqrt{\theta}(\rho_b K_d+\theta) + t\theta\sqrt{(\theta V^2 + 4D\Lambda)}}{2\theta\sqrt{Dt(\rho_b K_d+\theta)}})\ . \tag{55}$$

Equations (51), (52), and (53) were also solved using VIRTUS by a numerical method (with $C_1(z_1,t) = 0$ at the lower boundary $z = z_1$).

<u>Input Parameters</u>

Input parameters for the simulation were as follows:

1. Hydrodynamic dispersion coefficient: $D_1 = 4\ cm^2\ hr^{-1}$;
2. Saturated soil water content: $\theta_s = 0.3\ cm^3\ cm^{-3}$;
3. Freundlich constant: $K_d = -0.02$ ml g^{-1} soil;
4. Inactivation coefficient: $\mu_1 = 0.001\ hr^{-1}$;
5. Average linear flow velocity of water: $v_1 = 0.1\ cm\ hr^{-1}$;
6. Initial virus concentration: $C_o = 10^5$ PFU ml^{-1};

7. Bulk density: $\rho_b = 1.65$ g cm^{-3}; and

8. Soil depth: z = 100 cm.

Results

Comparisons of predictions made using the analytical solution versus the numerical solution of the virus transport equation are in Figures 5 and 6. These figures show the relative virus concentration as a function of soil depth at times of 5 and 10 hours. Good agreement was obtained between the analytical and numerical solutions as shown in the Figures.

MODEL SIMULATIONS

The capabilities of VIRTUS to simulate the simultaneous transport of water, viruses, and heat are demonstrated using data for two different soil types. Several simulations were performed to show the effects different variables on model predictions.

Simulation 1. Virus Transport Through Loam Soil With Temperature-Dependent Inactivation Rate.

This simulation calculated virus concentration profiles during transport through an unsaturated loam soil. The rate of virus inactivation changed as a function of soil temperature throughout the course of the transport process. Viruses adsorbed to soil particles were assumed to have an inactivation rate of zero.

Input Parameters

The specific values of the variables related to virus fate and transport are shown in Table 3. The values were chosen from published data of virus transport obtained from experiments conducted under conditions similar to those used in the simulation.

General input values for the simulation are shown in Table 4. The physical properties of the Indio loam soil are listed in Table 5. Parameters that varied as a function of time included air temperature, relative humidity of the air above the soil surface, and solar radiation. These variables were represented by the functions described below. These functions are only approximations of the daily changes measured in nature.

The daily course of air temperature can be characterized by a Fourier series (Ouyang, 1990):

$$T_{air}(t) = \bar{T} + \sum_{n=1}^{N} [A_{temp}(n)\cos(\omega_{1n}t) + B_{temp}(n)\sin(\omega_{1n}t)] \ , \qquad (56)$$

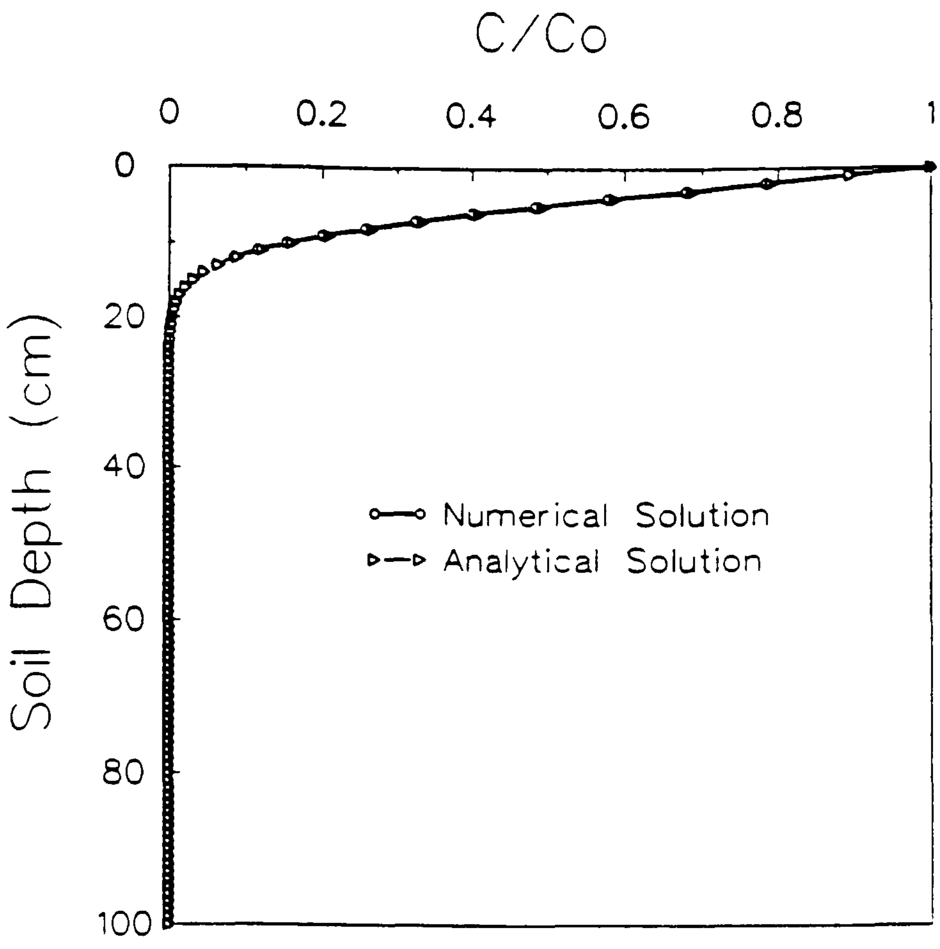

Figure 5. Comparison of analytical and numerical solutions of virus transport equation at 5 hours

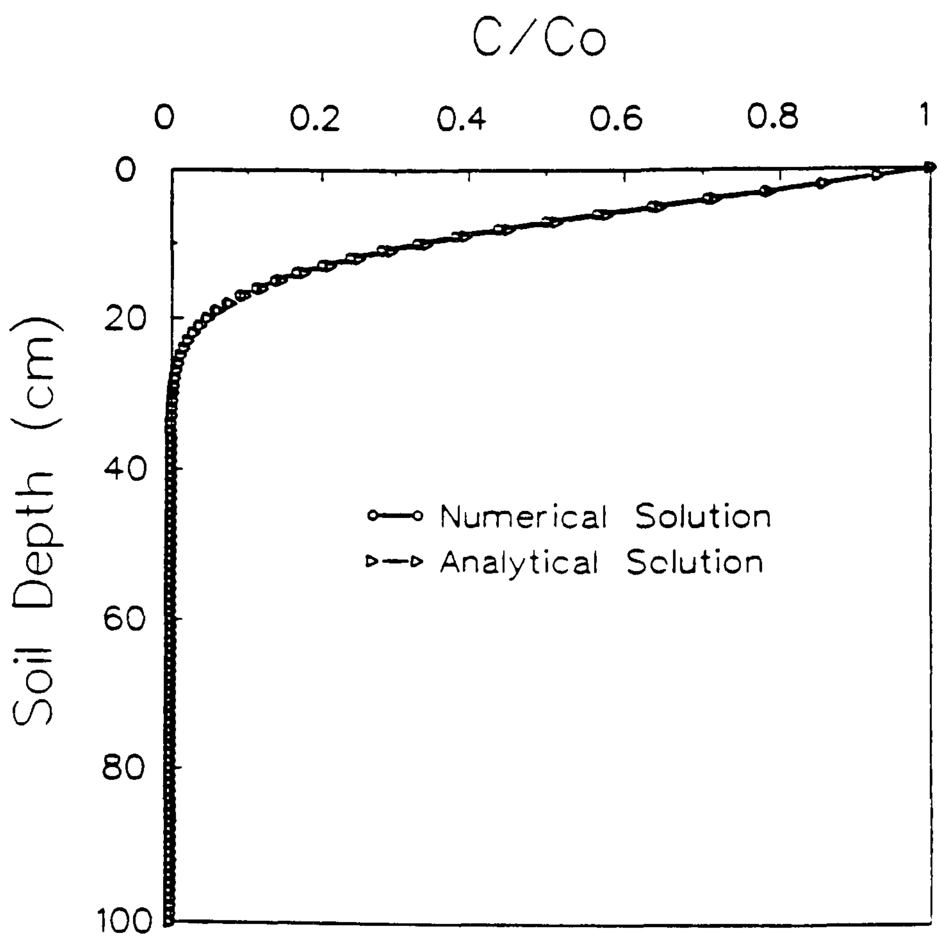

Figure 6. Comparison of analytical and numerical solutions of virus transport equation at 10 hours

Table 3. Parameters for the virus properties in simulation 1.

Parameters	Values/Units	References
Dispersion coefficient	$D_l = \alpha_{tort} D_{l0} + \alpha_{disp} \lvert V \rvert = 0.66 \times 0.000324 + 10 \lvert V \rvert$ $cm^2\ hr^{-1}$	Grosser, 1984, Bales et al., 1989 Lindstrom et al., 1990
Distribution coefficient	$K_d = 0.27$ ml g^{-1} soil	Powelson et al., 1990
Filtration coefficient	$f = 0.0$ cm^{-1}	
Inactivation* coefficient in liquid phase	$\mu_l = [(-0.181 + 0.0214\ T)$ $\mathrm{Ln}10]/24$ hr^{-1}	Yates and Yates, 1988
Inactivation coefficient in solid phase	$\mu_s = 0$	

* T is soil temperature (°C).

Table 4. General input parameters for simulations 1, 2, and 3.

Parameters	Values	Units
Simulation time	120	hrs
Simulation time step	0.025	hr
Simulation soil depth	100	cm
Simulation depth step	1.0	cm
Surface infiltration rate	0.1	cm hr^{-1}
Surface infiltration duration*	6	hrs
Initial soil water content	0.25	cm^3 cm^{-3}
Initial soil temperature	8.7	°C
Initial soil virus concentration	0.0	PFU ml^{-1}
Virus concentration in the surface infiltration water	10^5	PFU ml^{-1}
Initial virus concentration in ground water	0.0	PFU ml^{-1}
Virus type	MS-2 bacteriophage	
Soil type	Indio loam soil	

*Surface infiltration started at 0^{th} hour and ended at 6^{th} hour in the morning of the first day.

Table 5. Values of the soil parameters used for the Indio loam soil that remain constant throughout the simulations 1, 2, and 3.

Symbol	Meaning	Value/Units	Reference
α_{air}	Albedo of air	0.05	Weast, 1986
α_{soil}	Albedo of soil	0.09	Ghildyal and Tripathi, 1987
α_{tort}	Tortuosity factor	0.66	Hillel, 1982
α_{water}	Albedo of water	0.07	Weast, 1986
α_{θ}	Coefficient in equation (59)	1241.39 cm	Ouyang, 1990
β_{θ}	Coefficient in equation (59)	0.7079	Ouyang, 1990
c_{air}	Specific heat of air	0.24 cal g^{-1} $°C^{-1}$	Weast, 1986
c_{clay}	Specific heat of clay	0.175 cal g^{-1} $°C^{-1}$	Ghildyal and Tripathi, 1987
c_{sand}	Specific heat of sand	0.175 cal g^{-1} $°C^{-1}$	Ghildyal and Tripathi, 1987
c_{silt}	Specific heat of silt	0.175 cal g^{-1} $°C^{-1}$	Ghildyal and Tripathi, 1987
c_{water}	Specific heat of water	1.0 cal g^{-1} $°C^{-1}$	Weast, 1986
ϵ	Total porosity	0.55	McCoy, et al., 1984
ϵ_{air}	Emissivity of air above the soil	0.9	Weast, 1986
ϵ_{soil}	Emissivity of soil surface	0.5	Ghildyal and Tripathi, 1987
ϵ_{water}	Emissivity of water	0.95	Weast, 1986
K_s	Saturated conductivity in equation (60)	0.61 cm hr^{-1}	Ouyang, 1990
ρ_{air}	Density of air	0.0011 g cm^{-3}	Weast, 1986

Table 5. Values of the soil parameters used for the Indio loam soil that remain constant throughout the simulations 1, 2, and 3.

Symbol	Meaning	Value/Units	Reference
ρ_b	Bulk Density of soil	1.2 g cm^{-3}	McCoy, et al., 1984
ρ_{clay}	Density of clay	2.64 g cm^{-3}	Ghildyal and Tripathi, 1987
ρ_{sand}	Density of sand	2.66 g cm^{-3}	Ghildyal and Tripathi, 1987
ρ_{silt}	Density of silt	2.65 g cm^{-3}	Ghildyal and Tripathi, 1987
ρ_{water}	Density of water	1.00 g cm^{-3}	Weast, 1986
γ^c	Coefficient in equation (60)	6.5	Ouyang, 1990
λ_{solid}	Thermal conductivity of solids	18.9 cal cm^{-1} hr^{-1}	Ghildyal and Tripathi, 1987
λ_{water}	Thermal conductivity of water	5.14 cal cm^{-1} hr^{-1}	Ghildyal and Tripathi, 1987
λ_{air}	Thermal conductivity of air	0.2214 cal cm^{-1} hr^{-1}	Ghildyal and Tripathi, 1987
θ_r	Residual soil water content	0.029 cm^3 cm^{-3}	Ouyang, 1990
θ_s	Saturated soil water content	0.55 cm^3 cm^{-3}	Ouyang, 1990

where $T_{air}(t)$ is the air temperature (°C) at time t, $\bar{T}$ is the mean air temperature (°C), N is the number of the Fourier frequency, $A_{temp}(n)$ and $B_{temp}(n)$ are the temperature coefficients, ω_{1n} is the n^{th} temperature Fourier frequency, and t is time (hr).

The relative humidity in the atmosphere can be characterized by a Fourier series (Ouyang, 1990):

$$RH_{air}(t) = \overline{RH} + \sum_{n=1}^{N} [A_{rh}(n)\cos(\omega_{2n}t) + B_{rh}(n)\sin(\omega_{2n}t)] \ , \tag{57}$$

where RH_{air} (t) is the relative humidity (dimensionless) at time t, $\overline{RH}$ is the mean relative humidity (dimensionless), N is the number of the Fourier frequency, $A_{rh}(n)$ and $B_{rh}(n)$ are the relative humidity coefficients, ω_{2n} is the n^{th} relative humidity Fourier frequency, and t is time (hr).

The Gaussian normal distribution function of the form (Ouyang, 1990):

$$QSR(t) = E_1 \exp[-0.5 \frac{(t - E_2)^2}{E_3^2}] \ , \tag{58}$$

was used to describe rate of solar radiation as a function of time of day, where QSR(t) is the intensity of solar radiation (cal cm^{-2} hr^{-1}) at time t; E_1, E_2, and E_3 are coefficients of the equation, and t is time.

The power law function proposed by van Genuchten (1980) was used to describe the soil water potential as a function of water content:

$$\psi = -\alpha_\theta [(\frac{\theta_s - \theta_r}{\theta - \theta_r})^{\beta_\theta} - 1.0] \ , \tag{59}$$

where ψ is the water potential (cm), α_θ is a coefficient characterizing a specific soil (cm), β_θ is a coefficient characterizing a specific soil (dimensionless), θ_s is the saturated volumetric soil water content (cm^3 cm^{-3}), and θ_r is the residual volumetric soil water content (cm^3 cm^{-3}). Values of constant coefficients in equation (59) for the Indio loam soil are in Table 5.

The Kozeny function

$$K = K_s \left[\frac{\theta - \theta_r}{\theta_s - \theta_r} \right]^{\gamma_c} \tag{60}$$

proposed by Mualem (1976) was used to describe hydraulic conductivity as a function of soil water content. K is the hydraulic conductivity (cm hr^{-1}), K_s is the hydraulic conductivity at saturation (cm hr^{-1}), θ is the volumetric soil water content (cm^3 cm^{-3}), θ_r is the residual volumetric soil water content at air dry conditions (cm^3 cm^{-3}), θ_s is the saturated volumetric soil water content (cm^3 cm^{-3}), and γ_c is a coefficient characteristic for a specific soil. Values of constant coefficients in equation (60) for the Indio loam soil are in Table 5.

Results

The virus concentration profiles predicted during the simulation are shown in Figures 7 and 8. The concentration of viruses in the top few cm of soil changed rapidly from an initial value of zero to more than 5 x 10^4 PFU/ml during the 6 hours of infiltration (Figure 7). Figure 8 shows the change in virus concentration with time at two soil depths. It can be seen that as the concentration of viruses begins to decrease at the 5-cm depth after 48 h (as a result of advection, adsorption, and inactivation), the concentration at 10 cm begins to increase as a result of transport through the soil.

Changes in soil water content during 48 hours simulation are shown in Figure 9. This simulation started with a water application period from 0 to 6 hours at a rate of 0.1 cm hr^{-1}. The application rate was lower than the infiltration capacity of the soil, so that the infiltration profiles at 6 hours did not show the constant water content of a transmission zone followed by a rapid decrease in water content in the wetting zone or wetting front. Following the 6 hours of water application was a period of change in the water content of the soil profile, due to evaporation (Figure 10) at the soil surface and further penetration of the water into the soil due to a water potential gradient at the wetting front.

Daily cycles of soil temperature at several depths are shown in Figure 11. This figure shows that the temperature at the soil surface was close to the temperature of the applied water (4 °C). This water, which completely wetted the soil surface, decreased the temperature of the soil surface layer to the temperature of water at about 6 hours. As soon as water application stopped at

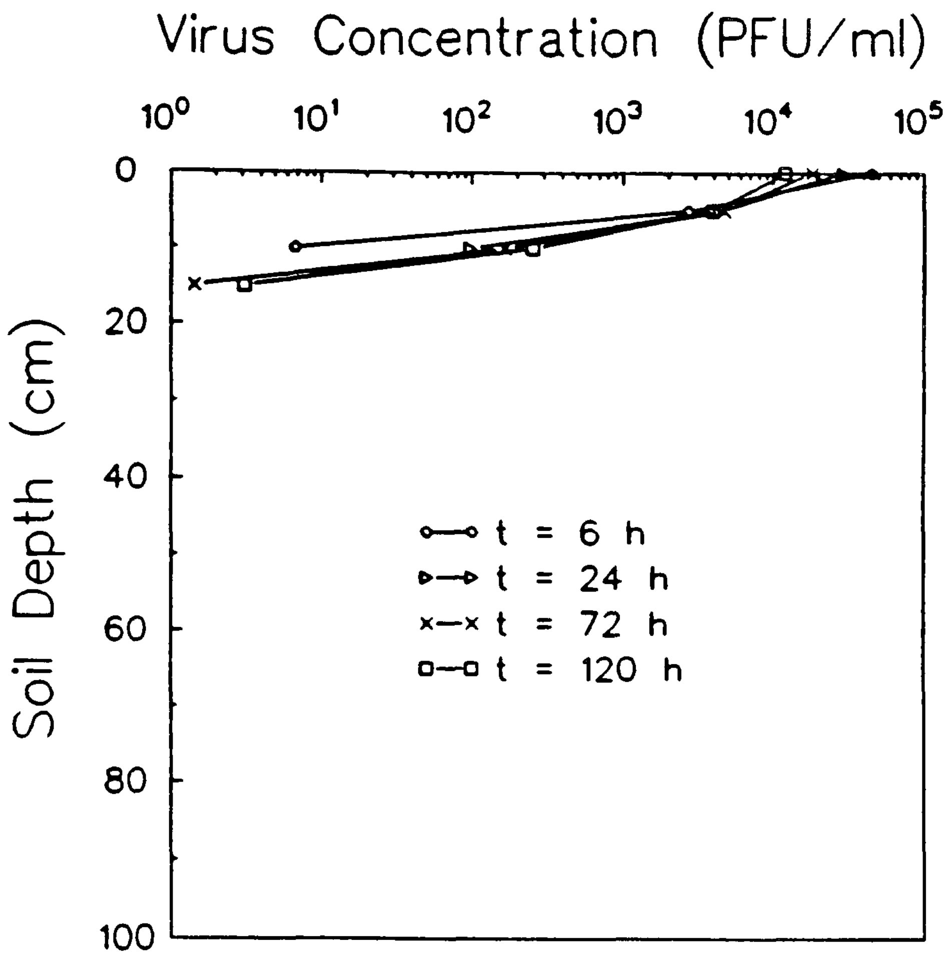

Figure 7. Virus concentration as a function of soil depth using a temperature-dependent inactivation rate in an Indio loam soil, simulation 1

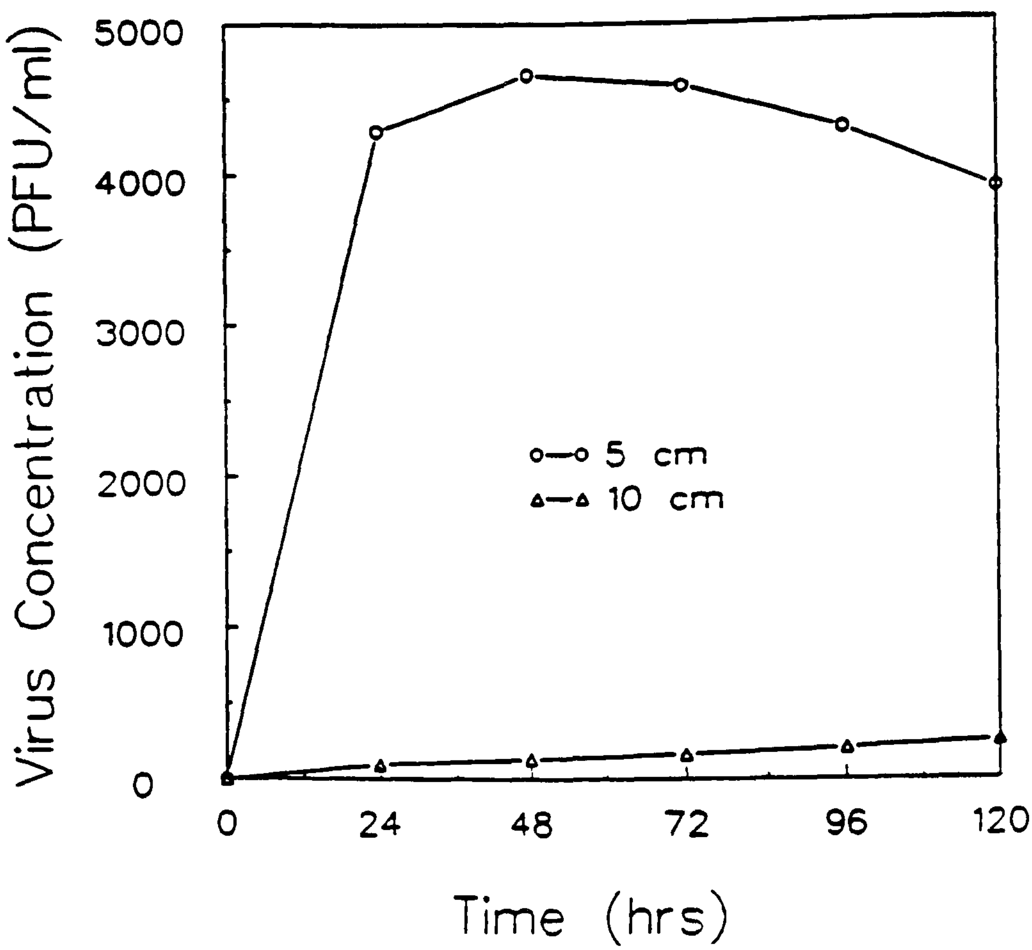

Figure 8. Virus concentration as a function of time using a temperature-dependent inactivation rate in an Indio loam soil, simulation 1

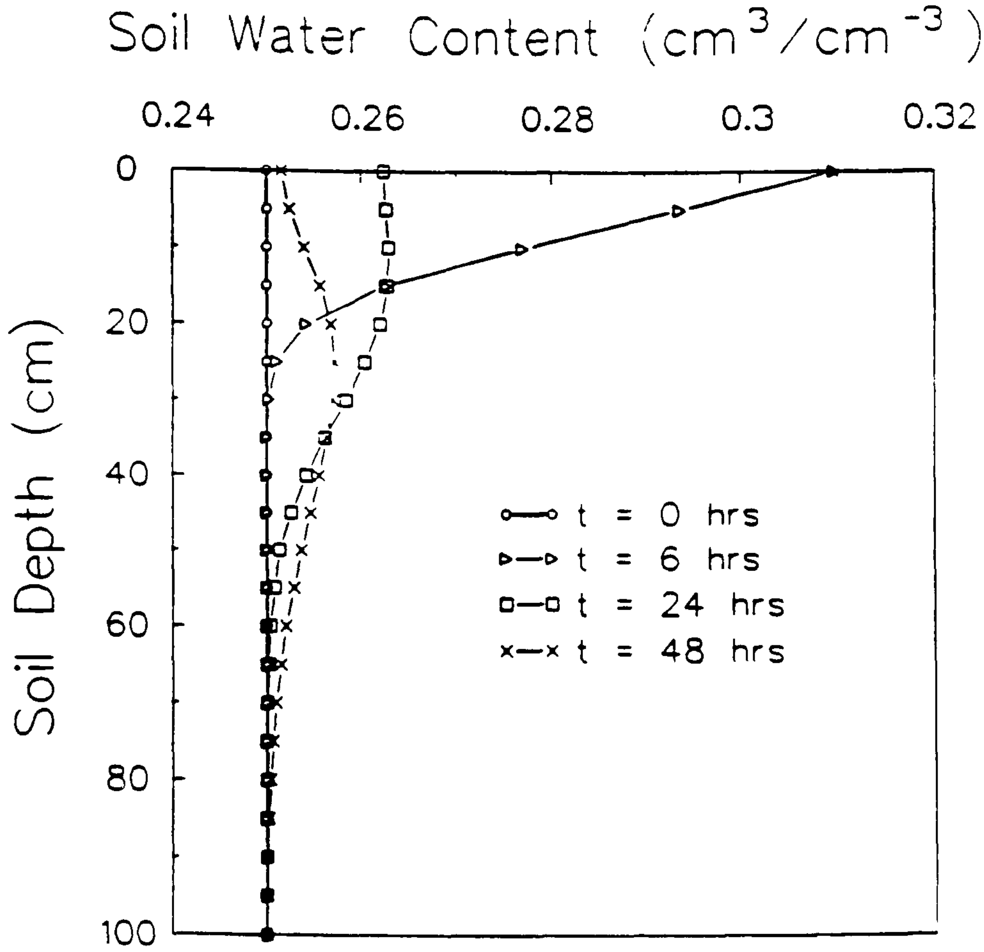

Figure 9. Soil-water content as a function of time in an Indio loam soil, simulation 1

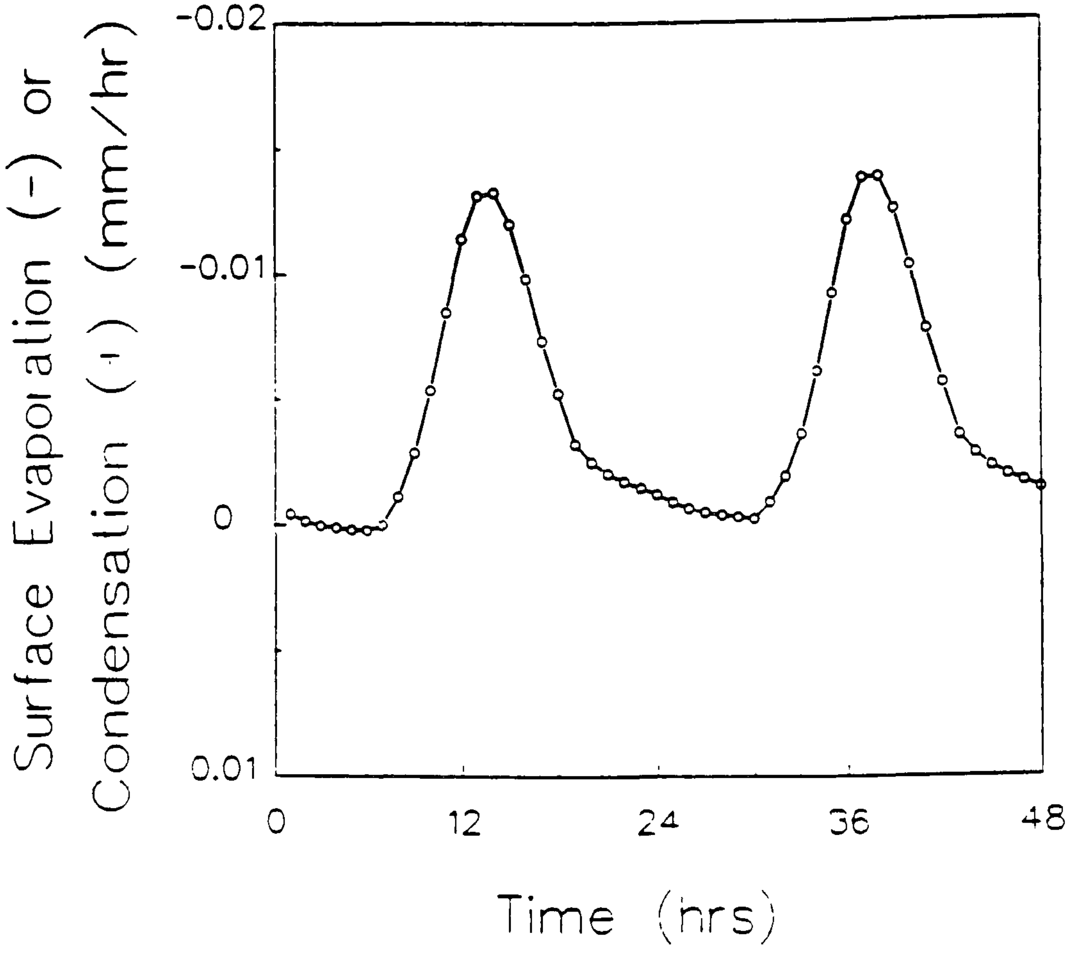

Figure 10. **Surface evaporation or condensation as a function of time in an Indio loam soil, simulation 1**

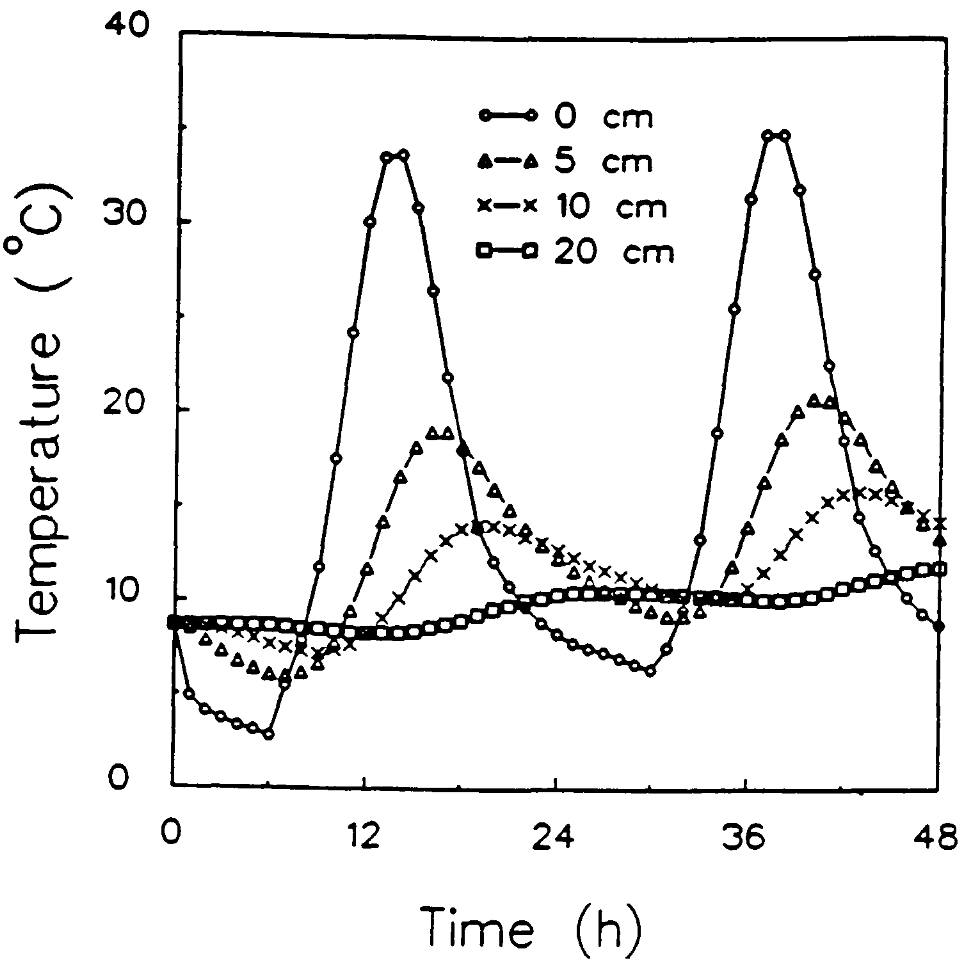

Figure 11. Soil temperature as a function of time in an Indio loam soil, simulation 1

6 hours, radiation started to warm the soil profile. The changes in soil temperature during the period from 6 to 48 hours showed the characteristic temperature cycle, with a decreasing temperature during the night followed by warming during the day.

Simulation 2. Virus Transport Through Loam Soil With Constant Inactivation Rate.

Most models of contaminant transport consider the movement of water and the transport of the contaminant in their development, and assume that the thermal conditions in the soil remain constant. In reality, under field conditions, this is not generally the case. Temperature fluctuations in soil can be considerable throughout the course of a 24-hour period, especially near the soil surface. Because the effects of temperature on virus inactivation rates in the environment can be quite significant, it seems logical to use a model of contaminant transport that also models heat flow.

This simulation demonstrates the effects of holding the inactivation rate of the viruses constant at a) 0.033 $\log_{10}$ per day, which would be expected at a soil temperature of 10 C; and b) 0.354 $\log_{10}$ per day, which would be expected at a soil temperature of 25 C.

Input Parameters

The input parameters used for this simulation were the same as for Simulation 1 and are shown in Tables 3, 4 and 5. The only exception is that the virus inactivation rate was 0.033 for Simulation 2a and 0.354 for Simulation 2b, rather than calculated as a function of temperature as shown in Table 3.

Results

The effects of allowing the virus inactivation rate to vary as a function of soil temperature as compared to holding it constant are graphically shown in Figures 12a and 12b. In the case where the virus inactivation rate was held constant at 0.033 $\log_{10}$ day^{-1} (10 C), the model predicted higher concentrations of viruses than would be predicted if the inactivation rate was allowed to vary as a function of temperature (Figure 12a). The opposite predictions were obtained in the case of a constant inactivation rate of 0.354 $\log_{10}$ day^{-1} (25 C) as shown in Figure 12b. Considering the inactivation rate to be a constant at 25 C resulted in an underprediction in the concentration of viruses as compared with the temperature-dependent inactivation rate.

The reasons for these predictions become apparent upon observation of the predicted change in soil temperature that occurs as applied water is infiltrated

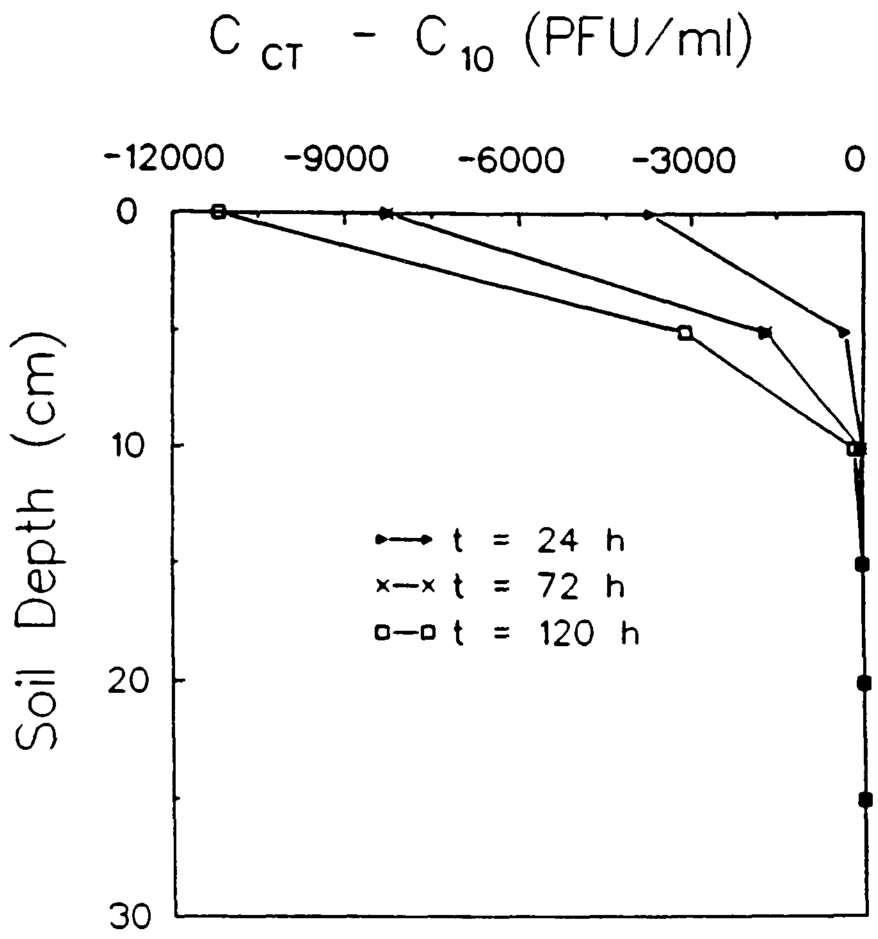

Figure 12a. Differences in predicted virus concentrations using a temperature-dependent (C_{ct}) vs. constant (C_{10}) inactivation rate in an Indio loam soil, simulation 2a

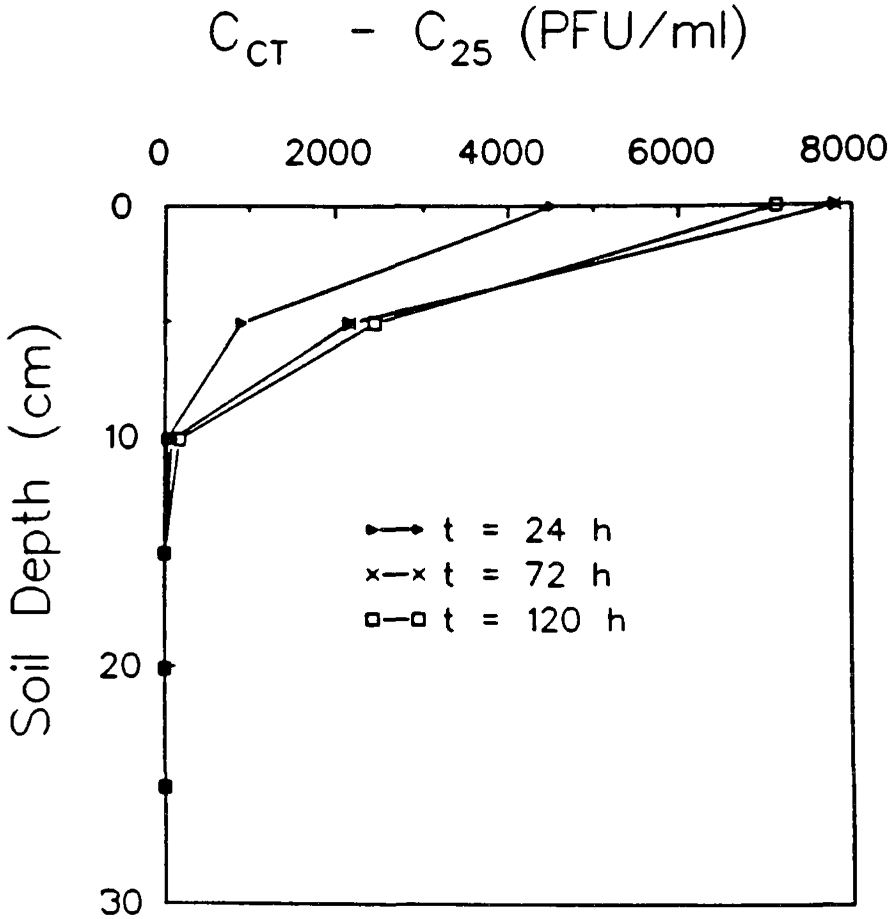

Figure 12b. Differences in predicted virus concentrations using a temperature-dependent (C_{ct}) vs. constant (C_{25}) inactivation rate in an Indio loam soil, simulation 2b

through the soil column (Figure 11). At the soil surface, over a 24-hour period, the soil temperature (which started at 8.7 C) decreased to 3 C at 6 h during the addition of cold water and increased to 35 C at 12 h due to the effects of solar radiation. Similar patterns would be expected at the 5- and 10-cm depths, although the magnitude of the variation would not be as large. In Simulation 2a, the virus inactivation rate was held constant at a value that would be expected for constant 10 C soil conditions. The fact that the soil temperature rose above 10 C for more than 12 hours in a 24-hour period resulted in a prediction of virus inactivation at relatively high rates (compared to the rate at a constant temperature of 10 C) for that period. Overall, maintaining the inactivation rate at a constant value had the effect of increasing the predicted concentration of viruses that were transported through the soil column by more than 4 orders of magnitude (Figure 12a).

In Simulation 2b, the soil temperature was considered to be constant at 25 C; consequently the virus inactivation was maintained at a relatively high rate throughout the transport process. In actuality, the soil temperature was at or above 25 C for a relatively short period of time (less than 6 hours), so viruses were inactivated at or above that high rate for only six hours in the simulation where the rate was temperature dependent. In this case (Figure 12b), assuming a constant inactivation rate would lead to a prediction that thousands of viruses fewer than the actual number (assuming that the variable inactivation rate simulation predicts the actual number) would be transported through the column.

The sensitivity of model predictions to changes in the temperature-dependent inactivation rate was determined by changing the inactivation rate while keeping all other variables constant. This sensitivity analysis showed that changing the value of the inactivation rate by 50% resulted in a 33% change in the predicted concentration of viruses being transported through the soil. A high sensitivity of model predictions to the virus inactivation rate has also been observed by Tim and Mostaghimi (1991) and Park, et al. (1990). These results demonstrate the need to accurately monitor virus inactivation and/or temperature during experiments of virus transport in the subsurface.

<u>Simulation 3. Virus Transport Through a Loam Soil With Inactivation Rate Dependent Upon Adsorption State.</u>

There have been reports in the literature of differences in measured rates of virus inactivation for viruses that are adsorbed to soil particles as compared to viruses that are freely suspended in the liquid medium (Hurst et al., 1980; Sobsey et al., 1980; Vaughn and Landry, 1983). Therefore, this model was developed to allow the user to input different values for inactivation rates for viruses in these two states. When a value for the inactivation rate of adsorbed viruses is specified, the model calculates the number of viruses adsorbed at a given time based on the adsorption coefficient specified by the user, and determines the number inactivated accordingly.

Input Parameters

It is difficult to obtain a quantitative value for the relative difference in inactivation rates for adsorbed as compared to freely suspended viruses. For the purposes of illustration, this simulation used an inactivation rate for adsorbed viruses equal to one-half that of free viruses. Inactivation rates for viruses in the adsorbed and free state were allowed to change as a function of the soil temperature. All other input values are as shown in Tables 3, 4, and 5.

Results

The model predictions made in Simulation 3 were compared to those of Simulation 1, in which the inactivation rate for adsorbed viruses was zero (Figure 13). As one would expect, the concentration of viruses transported through the soil column is larger when the solid-phase inactivation rate is zero than when it is one-half the liquid-phase rate. The difference increases with time, as shown in Figure 13. In a system in which the inactivation rate of adsorbed viruses is equal to that of free viruses, the differences would be even greater.

This example demonstrates the importance of knowing the inactivation rate for viruses in the adsorbed as well as in the liquid phase. If the inactivation rate for adsorbed viruses is actually lower than that of suspended viruses, it would be important to incorporate that information in a model so that accurate predictions can be made of virus concentration profiles. If the model assumes the same inactivation rate for all viruses, it would predict that fewer viruses are being transported than the actual number.

Simulation 4. Virus Transport Through an Unsaturated Sand

This simulation predicts virus concentration profiles during transport through an unsaturated Rehovot sand. This simulation was included to demonstrate the large differences in the transport properties of different soil types.

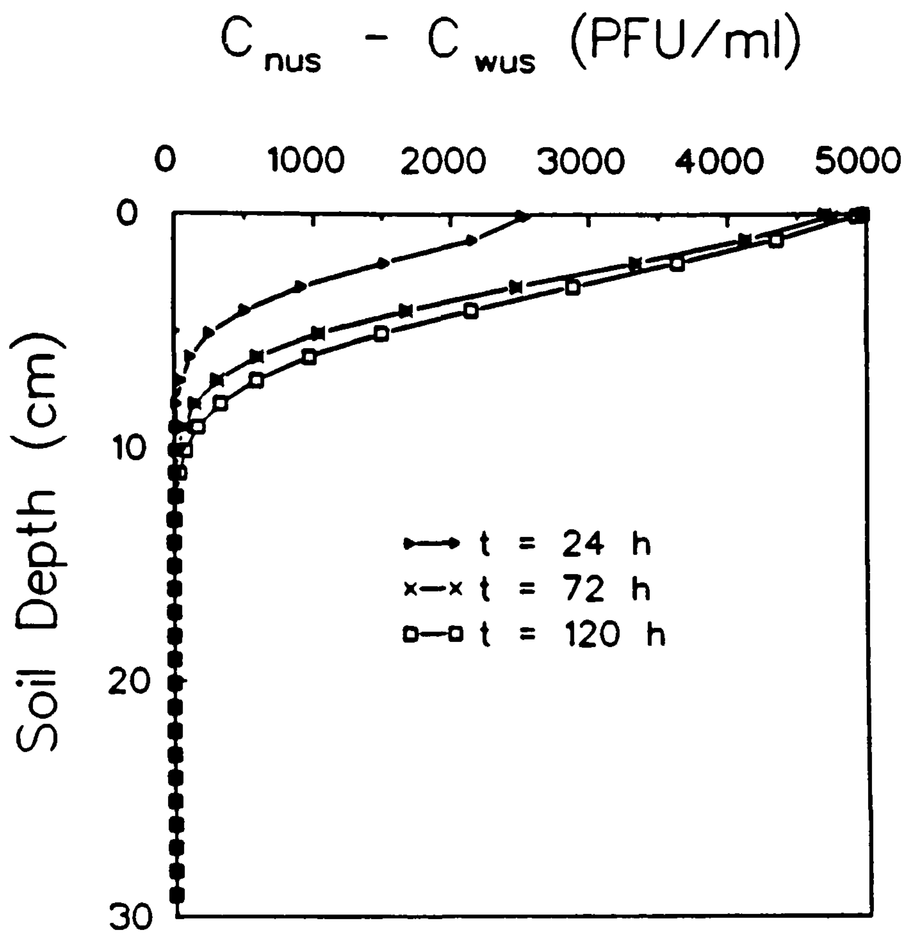

Figure 13. Effect of assuming no inactivation of adsorbed viruses (C_{nus}) vs. a non-zero inactivation rate of adsorbed viruses (C_{wus}) on model predictions for an Indio loam soil, simulation 3

Input Parameters

The general input values used for this simulation are shown in Table 3, with the exception of a value of 0.1 $cm^3\ cm^{-3}$ for the initial soil water content. The soil physical properties are shown in Table 6, and the virus fate and transport properties are listed in Table 7.

Results

This simulation illustrates the effects of soil properties on transport. The Rehovot sand has a much higher hydraulic conductivity (see Table 6) than the Indio loam (Table 5), thus water and contaminants can move through this soil more rapidly. As shown in Figures 14 and 15, the viruses were transported more rapidly and in higher concentrations in this soil as compared with the loam soil of the previous examples. After 6 hours, the viruses in the loam soil had been transported only 11 cm (Figure 7), as compared with more than 35 cm in the sandy soil (Figure 14). The differences between the two columns become more apparent at longer times: after 5 days approximately 30 viruses ml^{-1} had been transported 15 cm in the loam soil; whereas more than 10^2 viruses ml^{-1} were being recovered in the sand column effluent after the same amount of time.

Changes in soil water content during 120 hours of simulation are shown in Figure 16. This figure contrasts sharply with that for the loam soil (Figure 9).

Another reason for the relatively higher concentrations of viruses being transported through this soil, in addition to the higher hydraulic conductivity, is related to the adsorption coefficient. For this sand, based on reported values for virus adsorption to other sandy soils, an adsorption coefficient of zero was chosen. Thus, the rate at which the viruses were transported through the soil was not decreased as a result of adsorption to the soil particles, unlike the case for the loam soil.

MODEL TESTING

The model was tested for its ability to predict virus movement as measured in laboratory column studies. Two data sets that contained sufficient information about the soil properties for the model were obtained. In each case, the model was run using input values measured or reported by the respective investigator. No attempt was made to fit the model predictions to the measured results. Model predictions were then compared with the virus concentrations measured as a function of soil depth and time in the laboratory.

Table 6. Values of the soil parameters used for the Rehovot sand that remain constant throughout the simulation.

Symbol	Meaning	Value/Units	Reference
α_{air}	Albedo of air	0.05	Weast, 1986
α_{soil}	Albedo of soil	0.35	Ghildyal and Tripathi, 1987
α_{tort}	Tortuosity factor	0.66	Hillel, 1982
α_{water}	Albedo of water	0.07	Weast, 1986
α_{θ}	Coefficient in equation (59)	8.8654 cm	
β_{θ}	Coefficient in equation (59)	1.5024	
c_{air}	Specific heat of air	0.24 cal g^{-1} $°C^{-1}$	Weast, 1986
c_{clay}	Specific heat of clay	0.175 cal g^{-1} $°C^{-1}$	Ghildyal and Tripathi, 1987
c_{sand}	Specific heat of sand	0.175 cal g^{-1} $°C^{-1}$	Ghildyal and Tripathi, 1987
c_{silt}	Specific heat of silt	0.175 cal g^{-1} $°C^{-1}$	Ghildyal and Tripathi, 1987
c_{water}	Specific heat of water	1.0 cal g^{-1} $°C^{-1}$	Weast, 1986
ϵ	Total porosity	0.4	Ungs, et al., 1985
ϵ_{air}	Emissivity of air above the soil	0.9	Weast, 1986
ϵ_{soil}	Emissivity of soil surface	0.3	Ghildyal and Tripathi, 1987
ϵ_{water}	Emissivity of water	0.95	Weast, 1986
K_s	Saturated conductivity in equation (60)	52.8914 cm hr^{-1}	
ρ_{air}	Density of air	0.0011 g cm^{-3}	Weast, 1986

Table 6. Values of the soil parameters used for the Rehovot sand that remain constant throughout the simulation (continued).

Symbol	Meaning	Value/Units	Reference
ρ_b	Bulk Density of soil	1.595 g cm^{-3}	Ungs, et al., 1985
ρ_{clay}	Density of clay	2.64 g cm^{-3}	Ghildyal and Tripathi, 1987
ρ_{sand}	Density of sand	2.66 g cm^{-3}	Ghildyal and Tripathi, 1987
ρ_{silt}	Density of silt	2.65 g cm^{-3}	Ghildyal and Tripathi, 1987
ρ_{water}	Density of water	1.00 g cm^{-3}	Weast, 1986
γ^c	Coefficient in equation (60)	3.3421	
λ_{solid}	Thermal conductivity of solids	18.9 cal cm^{-1} hr^{-1}	Ghildyal and Tripathi, 1987
λ_{water}	Thermal conductivity of water	5.14 cal cm^{-1} hr^{-1}	Ghildyal and Tripathi, 1987
λ_{air}	Thermal conductivity of air	0.2214 cal cm^{-1} hr^{-1}	Ghildyal and Tripathi, 1987
θ_r	Residual soil water content	0.008 cm^3 cm^{-3}	Ungs, et al., 1985 (adapted)
θ_s	Saturated soil water content	0.4 cm^3 cm^{-3}	Ungs, et al., 1985

Table 7. Parameters for the virus transport properties in the simulation.

Parameters	Values/Units	References
Dispersion coefficient	$D_l = \alpha_{tort} D_{lo} + \alpha_{disp} \lvert V \rvert$ $= 0.66 \times 0.000324 + 10 \lvert V \rvert$ $cm^2\ hr^{-1}$	Grosser, 1984, Bales et al., 1989 Lindstrom et al., 1990
Distribution coefficient	$K_d = 0.0$ ml g^{-1} soil	Powelson et al., 1990
Filtration coefficient	$f = 0.0\ cm^{-1}$	
Inactivation* coefficient in liquid phase	$\mu_l = [(-0.181 + 0.0214\ T) \ln 10]/24\ hr^{-1}$	Yates and Yates, 1988
Inactivation coefficient in solid phase	$\mu_s = 0.0$	
Virus type	MS-2 bacteriophage	

* T is soil temperature (°C).

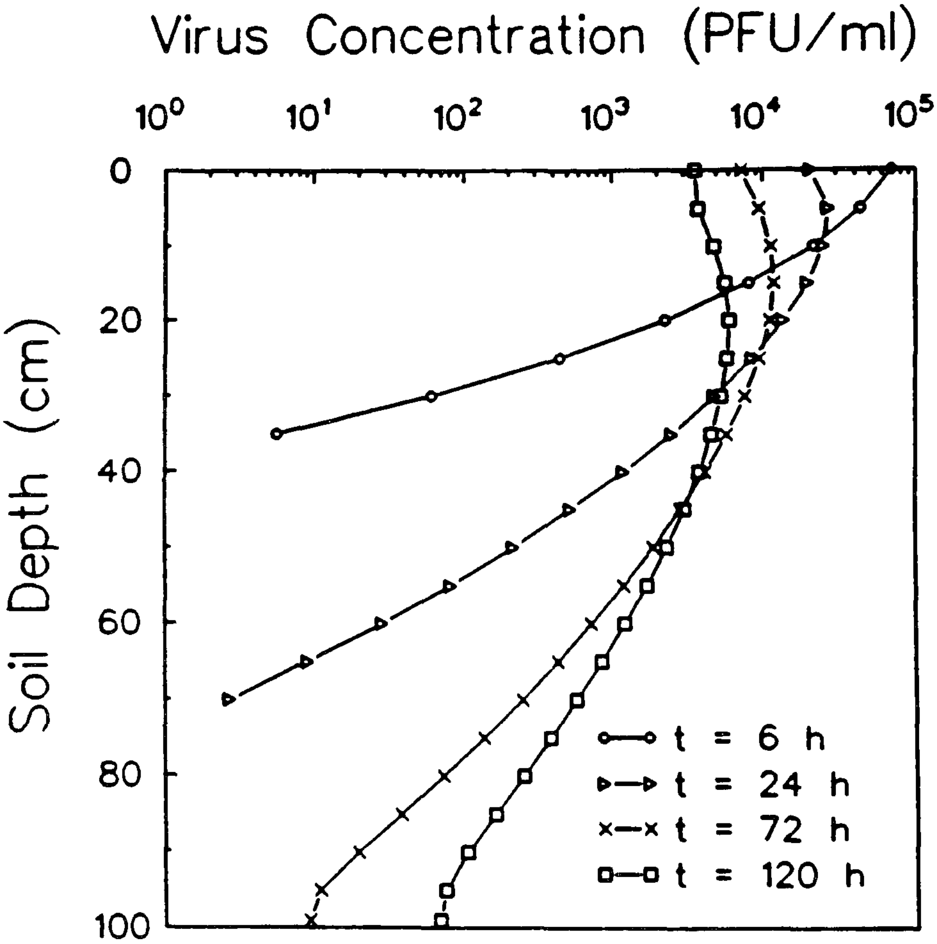

Figure 14. Virus concentration as a function of soil depth using a temperature-dependent inactivation rate in a Rehovot sand soil, simulation 4

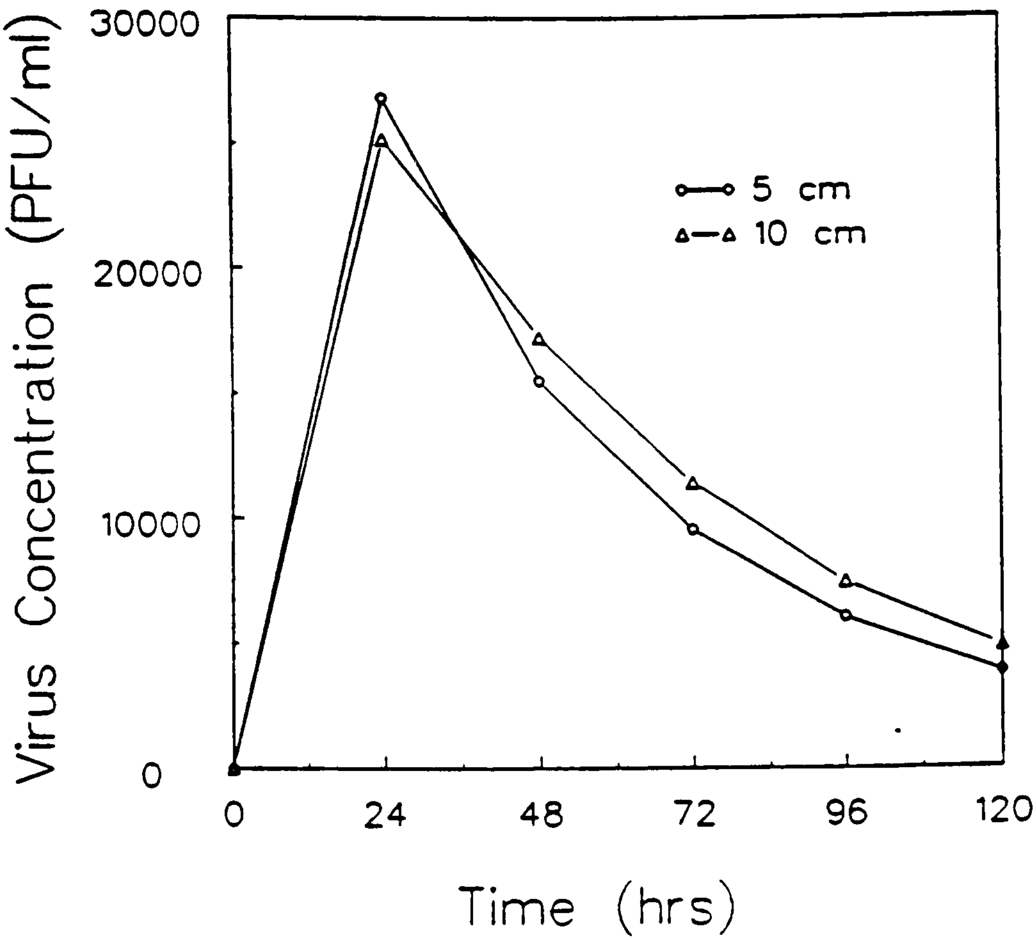

Figure 15. Virus concentration as a function of time using a temperature-dependent inactivation rate in a Rehovot sand soil, simulation 4

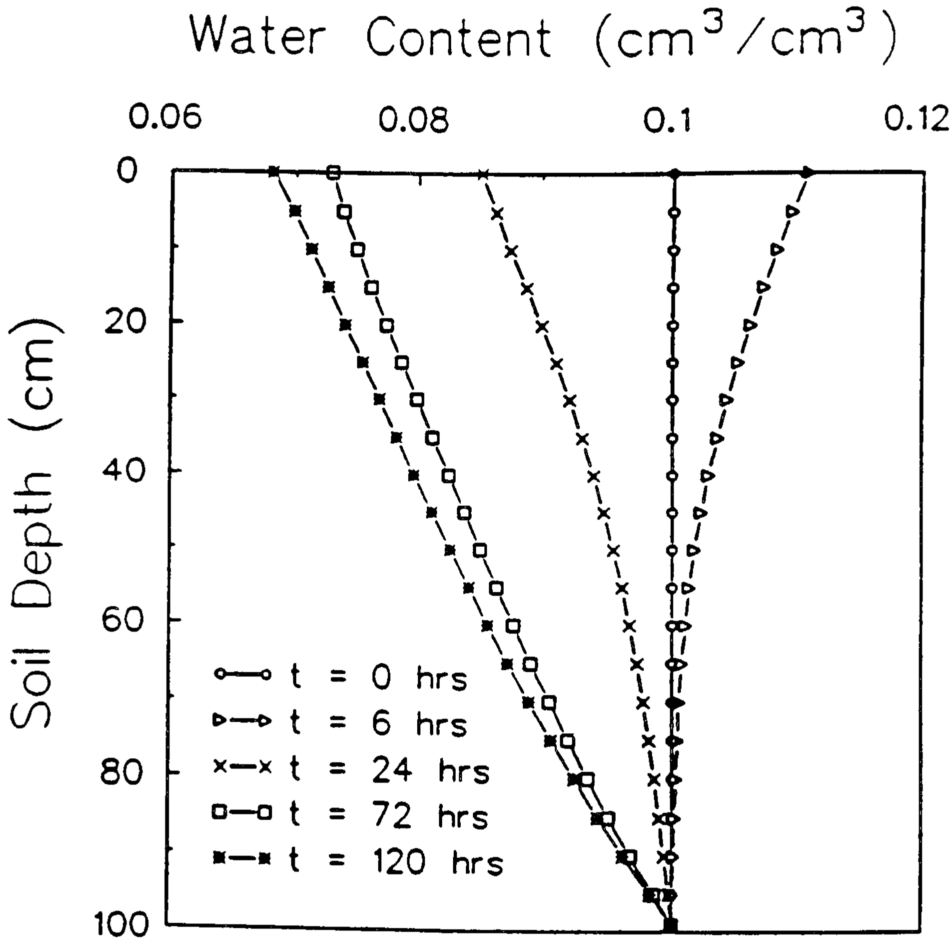

Figure 16. Soil-water content as a function of time in a Rehovot sand soil, simulation 4

Example 1. Virus Transport in a Saturated Gravelly Sand Column.

The data used for this example were obtained from virus transport experiments using saturated soil columns conducted by Grondin at the University of Arizona, Tucson (1987).

Input Parameters

The values used as input to VIRTUS are shown in Table 8. All of the values were determined experimentally by Grondin or calculated by him during fitting of his data to a model.

Results

When VIRTUS' predictions were compared to the results obtained by Grondin (1987) using a saturated soil column, the model predictions were within the 95% confidence limits of the measured virus concentrations (Figure 17).

Example 2. Virus Transport in an Unsaturated Loamy Sand.

Input Parameters

The data used as input for this example were obtained from virus transport experiments using unsaturated soil columns conducted by Powelson at the University of Arizona, Tucson and reported in Powelson et al. (1990). The input values are listed in Table 9. All values were either measured by the investigator or reported by him after model fitting.

Results

The virus concentration profiles predicted by VIRTUS are compared with the measured data of Powelson in Figure 18. The model predictions were very close to the measured virus concentration profiles, in all cases within the 95% confidence limits of the measured virus concentrations.

Table 8. Data used for model testing, example 1. (from Grondin, 1987)

Property	Input Value
Soil type	gravelly sand
Soil bulk density	1.65 g cm^{-3}
Hydrodynamic dispersion	78 cm^2 h^{-1}
Soil water content	0.26 cm^3 cm^{-3}
Average water velocity	48.3 cm h^{-1}
Soil column length	100 cm
Soil adsorption coefficient	-0.054 ml g^{-1} soil
Virus type	MS2 coliphage
Virus inactivation rate	0.082 log_{10} day^{-1}
Filtration coefficient	0 cm^{-1}
Input virus concentration	6.3 x 10^3 pfu ml^{-1}
Simulation time	48 min

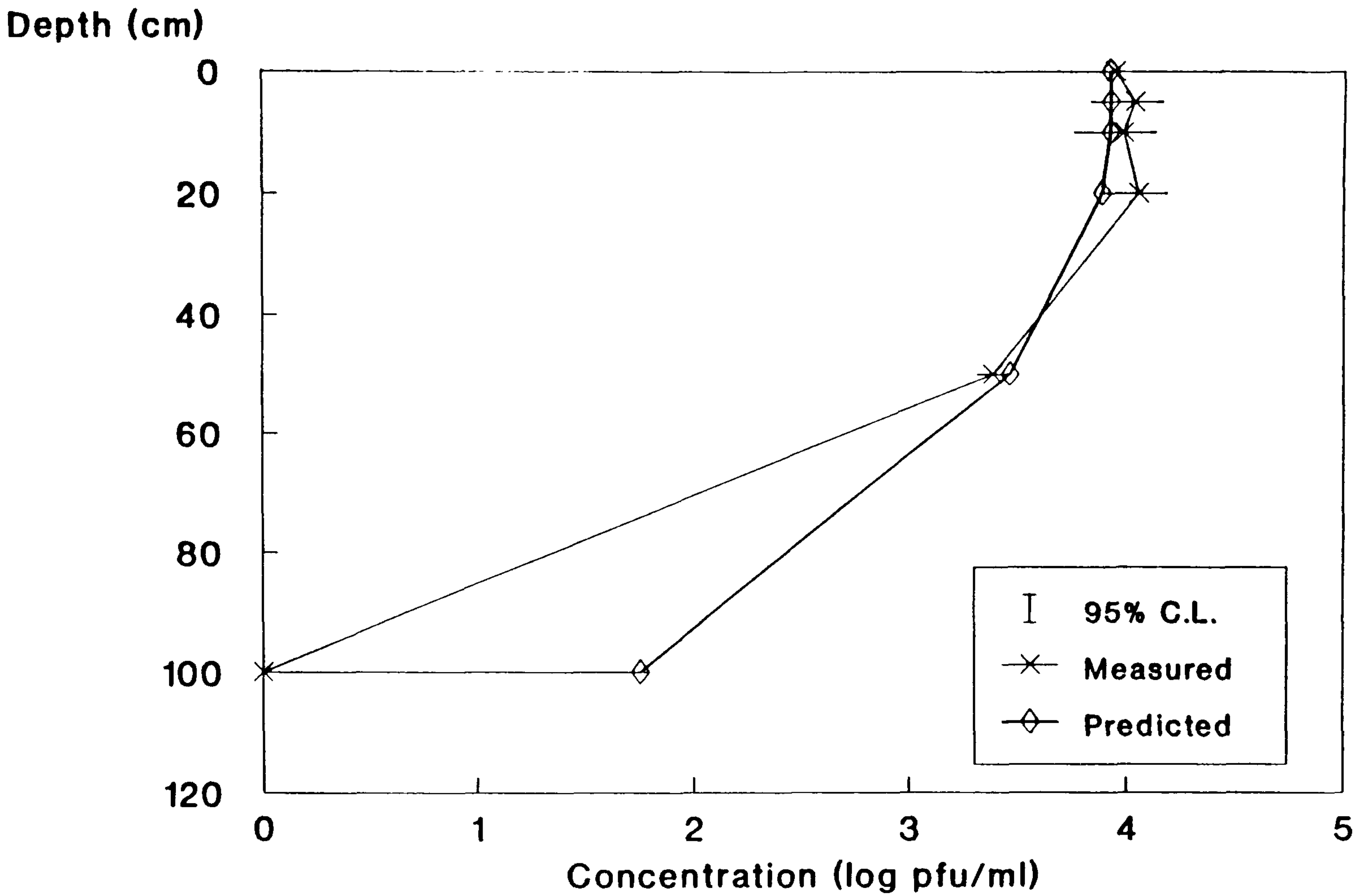

Figure 17. Comparison of model predictions to experimental data, Example 1

Table 9. Data used for model testing, example 2. (from Powelson et al. (1990))

Property	Input Value
Soil type	loamy fine sand
Soil bulk density	1.54 g cm^{-3}
Hydrodynamic dispersion	92.24 cm^2 h^{-1}
Soil water content	variable with depth
Average water velocity	1.54 cm h^{-1}
Soil column length	100 cm
Soil adsorption coefficient	0 ml g^{-1} soil
Virus type	MS2 coliphage
Virus inactivation rate	2.00 log_{10} day^{-1}
Filtration coefficient	0 cm^{-1}
Input virus concentration	10^5 pfu ml^{-1}
Simulation time	4 days

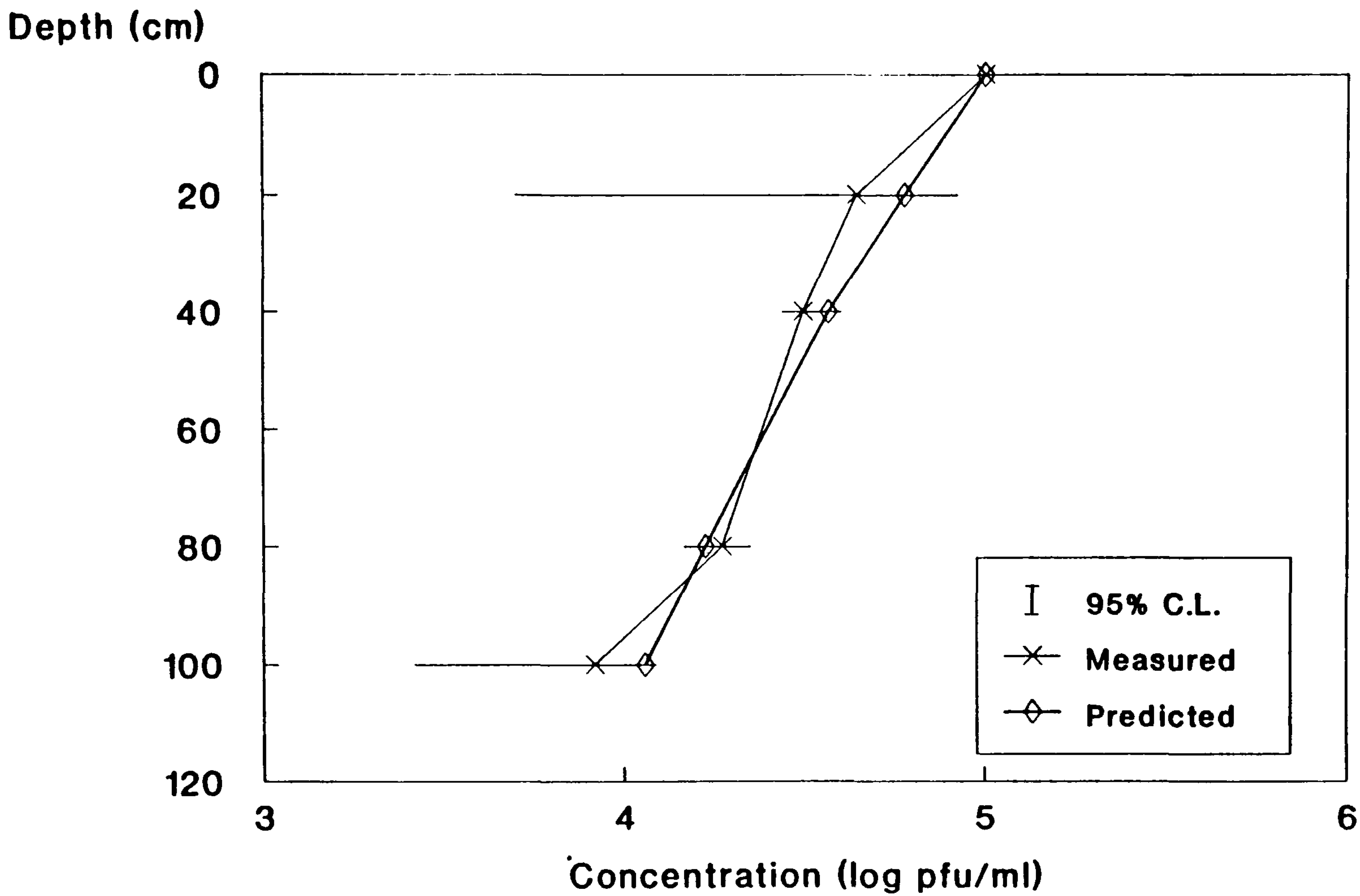

Figure 18. Comparison of model predictions to experimental data, Example 2

DISCUSSION

The ultimate measure of a model's usefulness as a predictive tool is its ability to accurately predict field observations of virus transport under a variety of environmental conditions. However, most models that have been developed to predict microbial transport have not been tested using field or laboratory data. There are a few exceptions to this (e.g., Teutsch et al., 1991; Harvey and Garabedian, 1991). However, both of these models were developed for use by the investigators in order to simulate their own data. In the case of the colloid filtration model of Harvey and Garabedian, extensive fitting of the required input parameters was performed by calibrating different solutions of the transport equation to the observed bacterial breakthrough curves. Thus, while these models may be able to simulate the investigator's data reasonably well, they may not be able to predict the results of other investigator's transport experiments. If a model is to be used for purposes other than research, such as for community planning or for making regulatory decisions, it must be able to predict microbial transport using data obtained by anyone under a wide range of environmental conditions.

In this research, a model to describe virus transport was developed based on the factors known to affect virus fate in the subsurface. A survey of the literature was conducted to locate data sets in which the investigators made measurements of not only virus properties, but also soil and hydraulic properties. Two data sets were located and used to test VIRTUS. No fitting or calibration of the model was performed; the data and measurements as reported by the respective investigators were used as model input. Model predictions compared favorably to measured experimental data. However, only one example of a comparison to one laboratory transport study in unsaturated soil using a single soil type and a single virus type was performed.

In addition, the temperature-dependent inactivation rate capabilities of the model could not be tested. This is due to the fact that the experiments were conducted under constant temperature conditions in the laboratory, thus the virus inactivation rate remained constant (theoretically) throughout the course of the experiment. In order to test the model's capacity to calculate new virus inactivation rates as a function of the changing soil temperature, data from a laboratory study in which the temperature is allowed to change (and is closely monitored) or from a field study in which the temperature is monitored will be required. This will allow an assessment of the model's capability to accurately calculate heat flow through the soil, which affects water flow (and thus virus transport) as well as the rate of virus inactivation during transport. More testing of the model is required before using it for any purposes other than research.

CONCLUSIONS

This research project has resulted in the development of a mathematical model that can be used to predict virus (or bacterial) transport in unsaturated soils. The model allows the user to specify the virus inactivation rate as a function of soil temperature. It will also allow the user to specify different inactivation rates for adsorbed versus freely suspended virus particles, if that information is available.

A sensitivity analysis of the model indicated that the inactivation rate of the virus has a large effect on model predictions. The adsorption coefficient and dispersivity also affect model predictions, although to a smaller extent.

Model predictions compared favorably to two data sets against which the model was tested. However, there is a lack of data available for extensive model testing. No complete data sets from field transport experiments were found that could be used to test VIRTUS. Before the model can be used for any purposes other than research, it should be extensively tested using actual field data.

In its present condition, the model requires the user to input several pieces of information related to climatic conditions. It also requires a large amount of information characterizing the physical properties of the soil, as do most models of contaminant transport. Before VIRTUS could be used for purposes other than research, a user interface, extensive help facilities, and a library of soil and virus properties would have to be added to the model.

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APPENDIX I: SOLVING THE VIRUS TRANSPORT EQUATIONS

The finite difference formulations used for solving the virus transport equation were:

$$\frac{\partial C_1}{\partial z}\Big|_{z_{i-1/2}} \doteq \frac{C_{1_i} - C_{1_{i-1}}}{\Delta z_i} \tag{1}$$

$$\frac{\partial C_1}{\partial z}\Big|_{z_{i+1/2}} \doteq \frac{C_{1_{i+1}} - C_{1_i}}{\Delta z_{i+1}} \tag{2}$$

$$C_{1_{i+1/2}} \doteq \frac{C_{1_{i+1}} + C_{1_i}}{2} \tag{3}$$

$$C_{1_{i-1/2}} \doteq \frac{C_{1_i} - C_{1_{i-1}}}{2} \tag{4}$$

$$\int_{t_n}^{t_{n+1}} \int_{z_{i-1/2}}^{z_{i+1/2}} \Lambda(z,t)\,dz\,dt \doteq \Delta t \left[\frac{\Delta z_i + \Delta z_{i+1}}{2}\right] \Lambda(z, t_{n+1}) \tag{5}$$

$$\int_{t_n}^{t_{n+1}} q(t)\,dt \doteq \Delta t\, q(t_{n+1}) \tag{6}$$

$$\int_{z_{i-1/2}}^{z_{i+1/2}} P(z)\,dz \doteq \left(\frac{\Delta z_i + \Delta z_{i+1}}{2}\right) P(z_i) \tag{7}$$

APPENDIX II: Definitions of Mathematical Symbols and Units For Equations (28) Through (36)

Symbol	Meaning	Units
α_{air}	Albedo of air	dimensionless
α_{soil}	Albedo of soil surface	dimensionless
α_{water}	Albedo of water surface	dimensionless
α_{tort}	Tortuosity of the soil	dimensionless
β_{evp}	Vaporization of water due to wind speed	$hr\ cm^{-1}$
β_{ht}	Loss of heat from soil due to wind speed	$hr\ cm^{-1}$
c_w	Specific heat of water	$cal\ g^{-1}\ {}^{o}C^{-1}$
D_{atm}	Molecular diffusion coefficient of water vapor in air	$cm^2\ hr^{-1}$
D_{wvmax}	Maximum value of the dispersion coefficient of water vapor in the boundary layer of the atmosphere	$cm^2\ hr^{-1}$
D^*_{atm}	Logistic representation of the boundary layer wind speed dependent coefficient of dispersion of water vapor	$cm^2\ hr^{-1}$
e_w^{air}	Saturated vapor pressure of of the air	mm Hg
ε	Soil porosity	cm^3 soil voids cm^{-3} soil
ε_{air}	Emissivity of the air above the soil	dimensionless

Symbol	Meaning	Units
ε_o	Porosity of the soil at the atmosphere-soil interface soil	cm^3 soil voids cm^{-3}
ε_{soil}	Emissivity of the soil	dimensionless
ε_{water}	Emissivity of the water	dimensionless
σ	Stefan-Boltzman constant	cal hr^{-1} cm^{-2} $°C^{-4}$
ϕ_{rain}	Infiltration of rainwater	cm hr^{-1}
ξ	Latent heat of evaporation	cal g^{-1}
$\vec{H}_{ss}$	Transfer of heat by conduction through the soil particles	cal cm^{-2} hr^{-1}
$\vec{H}_{sl}$	Transfer of heat by conduction and convection in the liquid phase water	cal cm^{-2} hr^{-1}
$\vec{H}_{sv}$	Transfer of heat by conduction in the vapor phase water and by transport in the form of latent heat	cal cm^{-2} hr^{-1}
h	Relative humidity at the atmosphere-soil interface	dimensionless
λ_{air}	Thermal conductivity of the air	cal cm^{-1} hr^{-1} $°C^{-1}$
λ_{amax}	Maximum value of the effective thermal conductivity of the air	cal cm^{-1} hr^{-1} $°C^{-1}$
λ_{solid}	Thermal conductivity of the solid	cal cm^{-1} hr^{-1} $°C^{-1}$
λ_w	Thermal conductivity of the water	cal cm^{-1} hr^{-1} $°C^{-1}$
λ^*_{air}	The effective thermal conductivity of the air at the boundary of atmosphere-soil interface	cal cm^{-1} hr^{-1} $°C^{-1}$

Symbol	Meaning	Units
θ_a	Relative humidity at the atmosphere-soil interface	dimensionless
θ_o	Water content at the atmosphere-soil interface	$cm^3\ cm^{-3}$
ρ_w	Density of water	$g\ cm^{-3}$
$\rho_{wv}^{sat}(T_o)$	Density of water vapor at saturation at T_o	$g\ cm^{-3}$
$\vec{q}_{heatin}$	Heat flux into the soil surface by rainwater	$cal\ cm^{-2}\ hr^{-1}$
$\vec{q}_{htevp}$	Heat flux out of the soil surface due to evaporation or heat flux into the soil surface due to condensation	$cal\ cm^{-2}\ hr^{-1}$
$\vec{q}_{htlswr}$	Heat flux into the soil surface by short wave radiation	$cal\ cm^{-1}\ hr^{-1}$
$\vec{q}_{htssl}$	Heat flux through the soil surface via sensible heat	$cal\ cm^{-2}\ hr^{-1}$
$\vec{q}_{htlwra}$	Heat flux into the soil surface by long wave radiation	$cal\ cm^{-2}\ hr^{-1}$
$\vec{q}_{htlwrs}$	Heat flux out of the soil surface by long wave radiation	$cal\ cm^{-2}\ hr^{-1}$
$\vec{q}_h$	Total heat flux into, or out of, the soil surface	$cal\ cm^{-2}\ hr^{-1}$
q_{swr}	Short wave radiation flux density	$cal\ cm^{-2}\ hr^{-1}$
T_{rw}	Temperature of rain water	°C

Symbol	Meaning	Units
T_o	Temperature at the atmosphere -soil interface	°C
T_a	Temperature at the air	°C
WS	Wind speed	cm hr^{-1}
δz	Thickness of boundary layer at the atmosphere-soil interface	cm
z	Soil depth	cm

APPENDIX III. VIRTUS USER MANUAL

This appendix describes the computer program, VIRTUS, developed from the mathematical model described in the main body of the report. The model was written to be run on an IBM XT, IBM AT or equivalent computer, which has 640K memory and an 8087 math co-processor. This document begins with a description of the program. A listing of FORTRAN variables for input with mathematical symbols, meanings, and units is given next. This is followed by a section on the preparation of input data files. The user is then guided through a section on the running of the program and a discussion of the output files.

PROGRAM DESCRIPTION

Program Organization

The program is written in ANSI Standard FORTRAN 77. It implements the mathematical model described in the main body of this report. The "include" feature of Microsoft FORTRAN (version 5.0) is used for global Common Blacks. There is one "include" file name: "COMMON.NEW" in the program. There are 12 FORTRAN source files, all with the extension ".FOR".

Flow Chart of the Program

Figure 1 shows the flow chart illustrating the modules in the execution of the program. Each module contains many helpful comments and is compiled separately, then the resulting object codes are linked together to create an executable file called MIXMAIN.EXE. The functions of each of the modules is described below.

Module	Functions
MIXMAIN.FOR	MAIN Program MIXMAIN
MIXREAD.FOR	Reads in simulation input data
MIXUNCS.FOR	Computes "universal porous media constants"
MIXWRTO.FOR	Prints out input system parameters, calculated system parameters, and initial distributions of water, temperature, and viruses so that the user knows what the run parameters are
MIXLREV.FOR	Makes decisions about starting and ending water application and light cycles
MIXING.FOR	Makes approximate time integrations of the water, heat, and virus systems

MIXWATR.FOR	Approximates soil water content distributions
MIXHEAT.FOR	Approximates soil temperature distributions
MIXTHOM.FOR	Solves resulting tri-diagonal systems of water and heat transport equations (and later virus transport equation)
MIXBNDY.FOR	Calculates all water- and heat-related variables
MIXVIR.FOR	Approximates virus concentration distributions
MIXCUM.FOR	Stores and prints simulation results

PROGRAM VARIABLES

This section contains a list of the program variables that are used in input. The variables are listed in alphabetic order (Table A1). The mathematical symbol corresponding to each variable is shown, with a brief description of the meaning of the variable and its units.

DATA FILES

Format Instructions

To run the program, the data file must be created in proper format. The user can create and modify the data file using a text editor or word processor. A data file must be created in ASCII format using the following standard FORTRAN formatting instructions.

Record 1		FORMAT (all of data files use free format).
	TO	Initial time for the simulation (usually set to zero).
	TCUT	Ending time for the simulation.
	DTO	Time step for the simulation.
Record 2	PRTIN(I)	Nonevent print interval. The program can print out the simulation results at any time according to the data given here.
Record 3	NPRINT(I)	Index for print out. See example given below for more information.
Record 4	NNSTRZ(I)	Number of storage node indexes. These

		indexes are used to print out simulation results at a given time and soil depth for checking the program.
Record 5	NSLZM1	Number of internal vertical soil nodes.
Record 6	DELTAZ	Top boundary layer thickness.
Record 7	DZ(I)	Soil depth step. See example given below for more information.
Record 8	ALBAIR	Albedo of soil surface air which is used for heat flux at the top boundary.
	ALBWAT	Albedo of water which is used for heat flux at the top boundary.
	ALBSOI	Albedo of soil which is used for heat flux at the top boundary.
Record 9	EMSAIR	Emissivity of air which is used for heat flux at the top boundary.
	EMSWAT	Emissivity of water which is used for heat flux at the top boundary.
	EMSSOI	Emissivity of soil which is used for heat flux at the top boundary.
Record 10	LAMBHT	Coefficient due to wind speed affecting on thermal conductivity of air.
Record 11	LAMSLD	Thermal conductivity of solids.
Record 12	SHTSAN	Specific heat of sand.
	SHTSIL	Specific heat of silt.
	SHTCLA	Specific heat of clay.
	SHTWAT	Specific heat of water.
	SHTAIR	Specific heat of air.
Record 13	RHOSND	Density of sand.
	RHOCLA	Density of clay.
	RHOSIL	Density of silt.
Record 14	GAMTLI	Derivative of surface tension with respect to temperature.

	BETATV	Derivative of saturation water vapor density with respect to temperature.
Record 15	NWVAIR	Number of characterizing parameters for the effective water vapor diffusivity in the top boundary layer. See example given below for more information.
Record 16	DWVAR	Effective water vapor diffusivity parameters in the top boundary layer. See example given below for more information.
Record 17	RHOWAT	Density of water.
	RHOAIR	Density of air.
Record 18	WS	Wind peed at the atmosphere-soil surface.
Record 19	NCFTMP	Number of coefficients in the Fourier Series (equation 56) representing n^{th} term of air temperature.
	NCFFRH	Number of coefficients in the Fourier Series (equation 57) representing n^{th} term of relative humidity.
Record 20	ATEMP(I)	Temperature coefficients in equation (56). These values are generated by fitting the daily air temperature data to equation (56). See Table 1 to identify the correspond mathematical symbol in equation (56).
	BTEMP(I)	Temperature coefficients in equation (56). These values are generated by fitting the daily air temperature data to equation (56).
	OMEGTP(I)	Temperature coefficients in equation (56). These values are generated by fitting the daily air temperature data to equation (56).
Record 21	ARHIN(I)	Relative humidity coefficients in equation (57). These values are generated by fitting the daily relative humidity data to equation (57). See Table 1 to identify the correspond

		mathematical symbol in equation (57).
	BRHIN(I)	Relative humidity coefficients in equation (57). These values are generated by fitting the daily relative humidity data to equation (57).
	OMGRHI(I)	Relative humidity coefficients in equation (57). These values are generated by fitting the daily relative humidity data to equation (57).
Record 22	TPINMU	Mean air temperature in equation (56).
	RHINMU	Mean relative humidity in equation (57).
	TPWATI	Temperature in rainwater.
Record 23	CWIN	Concentration of virus in infiltration water.
	CVGRD	Concentration of virus in ground water.
	DLO	Diffusion coefficient of virus.
	DISPLZ	Dispersivity coefficient of virus.
	KD	Virus adsorption coefficient.
	FILTRA	Filtration coefficient of virus.
	THTAST(J)	Saturated soil water content at each node of soil. These values are generated by fitting the experimental data (water content vs. water potential) to equation (59).
Record 24	TORT(J)	Tortuosity factor of soil.
Record 25	EPS(J)	Soil porosity.
Record 26	PCTSAN(J)	Percentage of sand.
Record 27	PCTCLA(J)	Percentage of clay.
Record 28	PCTSIL(J)	Percentage of silt.
Record 29	ALPTH(J)	Parameter in equation (59). The values are generated by fitting the experimental data to equation (59).
Record 30	BETATH(J)	Parameter in equation (59). The values

		are generated by fitting the experimental data to equation (59).
Record 31	GAMCNS(J)	Parameter in equation (60). The values are generated by fitting the experimental data to equation (60).
Record 32	KTHSTS(J)	Saturated conductivity in equation (60). These values are generated by fitting the experimental data to equation (60).
Record 33	THTRES(J)	Residual soil water content.
Record 34	DALPTZ	Derivative of α_θ with respect to soil depth z. See example given below for more information.
Record 35	DBETAZ	Derivative of β_θ with respect to soil depth z. See example given below for more information.
Record 36	DTHTSZ	Derivative of saturated water content with respect to soil depth z.
Record 37	DTHREZ	Derivative of residual water content with respect to soil depth z.
Record 38	THTAA	Initial air relative humidity.
	TEMPA	Initial air temperature.
Record 39	THTAS(J)	Initial soil water content.
	TEMPS(J)	Initial soil temperature.
	CV(J)	Initial soil virus concentration.
Record 40	QRAIN(J)	Parameters for rainfall rate. See example given below for more information.
	QSR(J)	Parameters for solar intensity. See example given below for more information.
Record 41	NLIEV	Number of light events.
	NRAEV	Number of rain events.
Record 42	TLION(I)	Time at which the light is turned on.
	TLIOF(I)	Time at which the light is turned off.

Record 43	TRAON(I)	Time at which the rain is turned on.
	TRAOF(I)	Time at which the rain is turned off.

Examples of Data Sets

Examples for input data files are presented and described in this section. These data files, together with the executable program, are included on the distribution diskette. It is recommended that these files be used as input to the program to verify that the program is working properly. These files can be modified to describe an actual scenario for model simulation.

Example Input Data File: WTV1.DAT

This section discusses the run control, upper boundary, and thermal properties input data that are in the file: WTV1.DAT. These data are read in by the subroutine MIXREAD in module MIXREAD.FOR. The data used by the program are numerical, in either real or integer form. Real numbers are handled by the program as double precision. The data is read using FORTRAN's "list-directed" input format. This is a free form input: numbers may occupy any number of positions; they are separated by spaces. The following are the descriptions of the actions of MIXREAD for the input file WTV1.DAT. The input data and the corresponding FORTRAN codes are first listed, then discussed briefly.

As the program begins to execute, the following message

```
'Reading from data file WTV1.DAT'
```

is shown on the screen. It tells the user that the program is beginning to read in data in the file: WTV1.DAT. Then it reads in the run control information in the first line of WTV1.DAT as follows:

```
0.0   2.1    0.1
READ(2,*) TO,TCUT,DTO
```

It first reads in the time for beginning the simulation, then the time for ending the simulation, and finally the time step for running the simulation. The time step may vary for simulations. The user should try several time steps to decide which is required for the purpose of achieving the desired accuracy.

```
1.0  5.99 11.99 17.99 23.99 29.99 35.99 41.99 47.99 71.99 95.99
119.99 139.99 149.99 159.99 169.99 179.99
```

```
READ(2,*) (PRTIN(I), I=1,16)
```

The program reads in the number of times for printing the simulation results. The first number in the above data file is the time for printing the simulation results in output file: "test.out". The other numbers are times for printing the simulation results in output file: "plrnfl". In order to print the results at 6 hours, the number 5.99 is used. This is to avoid possible numerical roundoff which may cause the program to print the results before or after 6 hours.

```
0 0 0 0 0 0 0 0 1 0 1 0 1 0 0 0 0 0 1 0

READ(2,*) (NPRINT(I),I=1,20)
```

The program reads in the index for the print out. The user may not have to change these numbers.

```
1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22
23 24 25

READ(2,*)(NNSTRZ(I),I=1,25)
```

The program reads in the number of storage node indexes for the output file: TEST.OUT. In this example, the simulation results of the top 25 nodes for every hour are saved in the file of TEST.OUT.

```
99

READ(2,*) NSLZM1
NSLZZZ=NSLZM1+1
NSLZP1=NSLZZZ+1
```

First, the number of internal vertical soil nodes is read in. Then, the upper and bottom nodes are computed.

```
1.0
0.1
1.0
1.0
 .
 .
 .
1.0

READ(2,*) DELTAZ
DO 18, I=1,NSLZZZ
READ(2,*) DZ(I)
 18 CONTINUE
```

The program reads in the upper boundary layer thickness and distance between nodes. The depth step in this example is 1 cm although it is not necessary to have equal space for all depth steps. However, it is recommended that the first soil layer (DZ(1)) should be kept small (0.1) for the purpose of obtaining accurate results.

```
0.05        0.07        0.09
0.90        0.95        0.50
```

```
3.33000E-4
3.43
0.175     0.175     0.175     1.0      0.24

READ(2,*) ALBAIR,ALBWAT,ALBSOI
READ(2,*) EMSAIR,EMSWAT,EMSSOI
READ(2,*) LAMBET
READ(2,*) LAMSLD
READ(2,*) SHTSAN,SHTSIL,SHTCLA,SHTWAT,SHTAIR
```

The program reads in the albedos, emissivities, thermal conductivities, and specific heats of air, water, and soil. All these coefficients may be kept constant except the albedo coefficients of soil (ALBSOI), which may change for different types of soil.

```
2.66     2.64     2.65

READ(2,*) RHOSND,RHOCLA,RHOSIL
```

The program reads in soil particle densities, which are always constant.

```
-2.0900E-3 1.05600E-6
3
954.0     4770.0    3.33000E-4

READ(2,*) GAMTLI,BETATV
READ(2,*) NWVAIR
READ(2,*)(DWVAR(I),I=1,NWVAIR)
```

The program reads in liquid and vapor phase water parameters. These parameters may be kept constant for all the simulations.

```
1.0  0.0011

READ(2,*) RHOWAT,RHOAIR
```

The program reads in the densities of water and air, which are always constant.

```
0.0

READ(2,*) WS
```

The program reads in wind speed constant. It is assumed to be zero in this example.

```
2  5
-1.006722008  -2.356626769   0.261199
-0.371835795  1.000000000    0.523598
0.0371929656  0.0675873369   0.261199
-.0052916350  -.0274241549   0.523598
-.0094577865  0.0116668147   0.785397
0.0363752911  -.0043302556   1.047196
-.0061084983  0.0040792275   1.308995

   READ(2,*) NCFTMP,NCFFRH
   DO 13, I = 1,NCFTMP
      READ(2,*) ATEMP(I),BTEMP(I),OMEGTP(I)
13 CONTINUE
   DO 23, I = 1,NCFFRH
      READ(2,*) ARHIN(I),BRHIN(I),OMGRHI(I)
23 CONTINUE
```

The program reads in the number of air temperature coefficients (in equation 56) and relative humidity coefficients (in equation 57). These coefficients are generated by fitting the measurement data to equations (56) and (57).

```
8.7578        0.869          277.0

READ(2,*) TPINMU,RHINMU,TPWATI
```

The first two variables are the mean air temperature in equation (56) and mean relative humidity in equation (57), respectively. The third variable is the temperature in the applied water.

Example Input Data File: WTV2.DAT

This section discusses the virus transport properties input data in file: WTV2.DAT. It is read in by subroutine MIXREAD in module MIXREAD.FOR. The following are the descriptions of the actions of MIXREAD for the input file WTV2.DAT.

As the program begins to execute, the following message

```
'Reading from file WTV2.DAT'
```

is shown on the screen. It tells the user that the program is beginning to read data in the WTV2.DAT file. Then, it reads in the virus transport properties as follows:

```
1.0E+5  0.0  0.000324  200.0  0.27  0.0

READ(3,*)   CWIN, CVGRD, DLO, DISPLZ, KD, FILTRA
```

Table 1A lists the definitions and units of the above FORTRAN variables. The user may need to change the values of the variables according to a specific simulation.

Example Input Data File: WTV3.DAT

This section discusses the soil physical properties input data in file: WTV3.DAT. It is read in by subroutine MIXREAD in module MIXREAD.FOR. The following are the descriptions of the actions of MIXREAD for the input file WTV2.DAT.

As the program begins to execute, the following message

```
'Reading from file WTV3.DAT'
```

is shown on the screen. It tells the user that the program is beginning to read data in WTV3.DAT file. Then, it reads in the soil physical properties as follows:

```
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
```

```
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55
```

```
READ(4,*)(THTAST(J),J=1,NSLZP1)
```

The program reads in the saturated soil water content at each node of the soil profile. The saturated soil water content varies for different types of soil.

```
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600
```

```
READ(4,*)(TORT(J),J=1,NSLZP1)
```

The program reads in the tortuosity factor at each node of the soil profile. These values may be kept constant for most soils (Hillel, 1982).

```
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55    0.55    0.55    0.55
0.55    0.55    0.55    0.55
```

```
READ(4,*)(EPS(J),J=1,NSLZP1)
```

The program reads in the soil porosity at each node of the soil profile. These values vary for different types of soil.

```
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
```

```
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3     0.3     0.3     0.3
0.3     0.3     0.3     0.3
```

```
READ(4,*)(PCTSAN(J),J=1,NSLZP1)
```

The program reads in the percentage of sand at each node of the soil profile. These values are extracted from experimental measurements. If the values are not available for a specific soil, the user can estimate them easily through the soil textural triangle diagram, which is commonly shown in the soil science text book (Brady. 1984).

```
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000
```

```
READ(4,*)(PCTCLA(J),J=1,NSLZP1)
```

The program reads in the percentage of clay at each node of the soil profile. As with the percentage of sand, if the values are not available for a specific soil, the user can estimate them easily through the soil textural triangle diagram.

```
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6     0.6     0.6     0.6
0.6     0.6     0.6     0.6
```

```
READ(4,*)(PCTSIL(J),J=1,NSLZP1)
```

The program reads in the percentage of silt at each node of the soil profile.

Again, if the values are not available for a specific soil, the user can estimate them easily through the soil textural triangle diagram.

```
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39 1241.39 1241.39 1241.39 1241.39
1241.39 1241.39 1241.39
```

```
READ(4,*)(ALPTH(J),J=1,NSLZP1)
```

The program reads in the parameter in equation (59) at each node of the soil profile. These values are generated by fitting the experimental data to equation (59). The user can identify the FORTRAN variable to the corresponding mathematical symbol using Table 1A.

```
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079   .7079   .7079   .7079   .7079
.7079   .7079   .7079
```

```
READ(4,*)(BETATH(J),J=1,NSLZP1)
```

The program reads in the parameter in equation (59) at each node of the soil profile. These values are generated by fitting the experimental data to equation (59).

```
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
6.5   6.5   6.5   6.5   6.5   6.5   6.5
```

6.5	6.5	6.5	6.5

```
READ(4,*)(GAMCHS(J),J=1,NSLZP1)
```

The program reads in the parameter in equation (60) at each node of the soil profile. These values are generated by fitting the experimental data to equation (60).

0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61			

```
READ(4,*)(KTHSTS(J),J=1,NSLZP1)
```

The program reads in the saturated conductivity at each node of the soil profile. These values are generated by fitting the experimental data to equation (60).

0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029				

```
READ(4,*)(THTRES(J),J=1,NSLZP1)
```

The program reads in the residual soil water content at each node of the soil profile. These values are generated by fitting the experimental data to equation (59).

0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

```
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0

0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0

0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0

0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0     0.0     0.0     0.0
0.0     0.0     0.0     0.0
```

```
READ(4,*)(DALPTZ(J),J=1,NSLZP1)
READ(4,*)(DBETAZ(J),J=1,NSLZP1)
READ(4,*)(DTHTSZ(J),J=1,NSLZP1)
READ(4,*)(DTHREZ(J),J=1,NSLZP1)
```

The program reads in the derivatives of parameters in equations (59) and (60) with respect to soil depth. Since these parameters are assumed to be constant throughout the soil profile, the derivatives of parameters with respect to soil depth should be all zero. The user may not have to change them.

Example Input Data File: WTV4.DAT

This section discusses the initial distributions of water, temperature, and virus input data in file: WTV4.DAT. It is read in by subroutine MIXREAD in module MIXREAD.FOR. The following are the descriptions of the actions of MIXREAD for the input file WTV4.DAT.

As the program begins to execute, the following message

```
'Reading from file  WTV4.DAT'
```

is shown on the screen. It tells the user that the program is beginning to read data in WTV4.DAT file.

```
0.892     281.72

READ(5,*) THTAA,TEMPA
```

The program reads in the initial relative humidity and air temperature at the upper boundary layer. The user may change these values according to the location and beginning season.

```
0.25      281.72   0.0
0.25      281.72   0.0
 .          .       .
 .          .       .
 .          .       .
0.25      281.72   0.0
0.25      281.72   0.0

      DO 127, J=1,NSLZP1
         READ(5,*) THTAS(J),TEMPS(J),CV(J)
  127 CONTINUE
```

The program reads in the initial soil water contents, temperatures, and virus concentrations.

Example Input Data File: WTV5.DAT

This section discusses the rainfall rate, solar radiation, rain and light cycles input data in file: WTV5.DAT. It is read in by subroutine MIXREAD in module MIXREAD.FOR. The following are the descriptions of the actions of MIXREAD for the input file WTV5.DAT.

As the program begins to execute, the following message

```
'Reading from file  WTV5.DAT'
```

is shown on the screen. It tells the user that the program begins to read data in WTV5.DAT file.

```
0.0       0.0
0.1       35.607219
0.0       6.6392447
0.0       2.5100518
0.0       0.15

      DO 15, I=1,5
         READ(6,*) QRAIN(I),QSR(I)
   15 CONTINUE
```

The program reads in the parameters for the rainfall rate and the solar intensity. The value in the second row of column one above is the rainfall rate. The values in the second to fourth rows of column two are for the parameters in equation (58). The value in the fifth row of column two is the solar intensity factor during the rainy period, which is assumed to be 15% of the total solar intensity as compared to that of no rain. Other zero values are control indexes which the user may not have to change.

```
5        2

READ(6,*) NLIEV,NRAEV
```

The program reads in the numbers of sunrise and sunset cycles and rain events.

```
  6.0      18.0
 30.0      42.0
 54.0      66.0
 78.0      90.0
102.0     114.0

DO 16, I=1,NLIEV
   READ(6,*) TLION(I),TLIOF(I)
16 CONTINUE
```

The program reads in the times for sunrise and sunset.

```
  0.0       6.0
130.0     140.0

DO 17, I=1,NRAEV
   READ(6,*) TRAON(I),TRAOF(I)
17 CONTINUE
```

The program reads in the times for rain start and rain stop.

RUNNING THE PROGRAM AND OUTPUT FILES

Instructions for Running the Program

The program can be run on IBM PC, IBM AT computer, or their equivalents, which have 640K memory and an 8087 math co-processor. A hard disk is desirable, but not absolutely necessary. The program was developed under DOS 4.0, using Microsoft FORTRAN Version 5.0. The distribution diskette includes the executable form of the program (MIXMAIN.EXE), input data files, and output files.

There is one Batch file on the distribution diskette: MIX.INP, which is used to run the program. To start running the program, the user may just type:

```
C:\>MIXMAIN <MIX.INP
```

If the user wants to type the input files from the screen, s/he may just type:

```
C:\>MIXMAIN
```

at this point, the computer will ask for one output file (see next section about the output files), five input files, and two other output files consecutively by displaying on the screen.

When the program is run, it will display information on the screen. First, it will show the messages about the reading of input data, the writing of all input data, the convergence checking (those ". . . ." on the screen), and the times. If the program should stop due to a data error, or for some other unexpected reason, the last messages displayed will give an indication of the program that caused the error. If the program runs well, it will show how much computing time is used at the end of running.

Output Files

File TEST.OUT shows the information read from WTV1.DAT, WTV2.DAT, WTV2.DAT, WTV3.DAT, WTV4.DAT, AND WTV5.DAT, together with computed data. This information should be examined to be sure that the data were read in correctly. All the numbers are labeled to indicate what they represent. Next, it shows some simulation results at each hour, including simulation time, water content, temperature, virus concentration, water potential, conductivity, water flow velocity, and the upper boundary parameters. This information should also be examined to be sure the right simulation results were generated mathematically and scientifically.

File P1RNFL shows water content, temperature, and virus concentration at all of the node points in the soil profile at selected print times. They are used to draw graphs.

File P2RNFL shows soil temperature and surface evaporation rate at each hour at the selected soil depths. They are also used to draw graphs.

Table A1. Program Variables for Input Data

FORTRAN Variable	Math Symbol	Meaning	Unit
ALBAIR	α_{air}	Albedo of surface air	
ALBSOL	α_{soil}	Albedo of surface soil	
ALBWAT	α_{water}	Albedo of surface water	
ALPTH	α_{θ}	Parameter for equation (59)	cm
ARHIN	A_{rh}	Relative humidity coefficient in equation (57)	
ATEMP	A_{tem}	Temperature coefficient in equation (56)	
BATATH	β_{θ}	Parameter for equation (59)	
BETATV	$d\rho_{wv}^{sat}/dT$	Derivative of saturated water vapor density with respect to temperature	g/cm^3 °K
BRHIN	B_{rh}	Relative humidity coefficient in equation (57)	
BTEMP	B_{tem}	Temperature coefficient in equation (56)	
CV	C_1	Concentration of virus in soil water	mass cm^{-3} water
CVGRD	C_g	Concentration of virus in ground water	mass cm^{-3} water
CWIN	C_{win}	Concentration of virus in infiltration water	mass cm^{-3} water
DALPTZ	$d\alpha_{\nu}/dz$	Derivative of α_{θ} with respect to soil depth z	
DBETAZ	$d\beta_{\nu}/dz$	Derivative of β_{θ} with respect to soil depth z	
DELTAZ	δz	Upper boundary layer thickness	cm
DISPLZ	α_{disp}	Dispersivity coefficient of virus	cm
DLO	D_{1o}	Diffusion coefficient of virus	cm^2/hr
DTO	Δt	Time step for running the model	hr

Table A1. Program Variables for Input Data (continued)

FORTRAN Variable	Math Symbol	Meaning	Unit
DTHREZ	$d\theta_r/dz$	Derivative of θ_r with respect to soil depth z	
DTHTSZ	$d\theta_s/dz$	Derivative of θ_s with respect to soil depth z	
DWVAR		Effective water vapor diffusivity parameters in boundary layer	
DZ	Δz	Depth step of soil profile	cm
EMSAIR	ε_{air}	Emissivity of air above soil	
EMSSOI	ε_{soil}	Emissivity of soil surface	
EMSWAT	ε_{water}	Emissivity of water	
EPS	ε	Soil porosity	cm^3/cm^3
FILTRA	f	Filtration coefficient of virus	1/cm
GAMCNS	γ^t	Parameter for equation (60)	
GAMTLI	d(surf. tension)/dT	Derivative of surface tension with respect to temperature	1/°K
KD	K_d	Virus adsorption coefficient	ml/g soil
KTHSTS	K_s	Saturated conductivity of soil	cm/hr
LAMBHT	β_{ht}	Coefficient due to wind speed effects on thermal conductivity of air	
LAMSLD	λ_{solid}	Thermal conductivity of solids	cal/cm hr °K
NCFFRH		Number of coefficients in the Fourier series (equation 56) representing n^{th} term of air temperature	
NCFTMP		Number of coefficients in the Fourier series (equation 57) representing n^{th} term of relative humidity	

Table A1. Program Variables for Input Data (continued)

FORTRAN Variable	Math Symbol	Meaning	Unit
NLIEV		Number of light events	
NNSTRZ		Storage node indexes	
NPRINT		Indices for print out	
NRAEV		Number of rain events	
NSLZM1		Number of internal vertical soil nodes	
NWVAIR		Number of characterizing parameters for the effective water vapor diffusivity in the boundary layer	
OMEGTP	ω_{1n}	Parameter in equation (56)	
OMGRHI	ω_{2n}	Parameter in equation (56)	
PCTCLA		Percentage of clay	
PCTSAN		Percentage of sand	
PCTSIL		Percentage of silt	
QRAIN		Parameter for rainfall rate	cm/hr
QSR		Light flux charactering parameters	cal/cm^2 hr
RHINMU	$\overline{RH}$	Parameter in equation (57)	
RHAIR	ρ_{air}	Bulk density of air	g cm^{-3}
RHOCLA	ρ_{clay}	Bulk density of clay	g cm^{-3}
RHOSIL	ρ_{silt}	Bulk density of silt	g cm^{-3}
RHOSND	ρ_{sand}	Bulk density of sand	g cm^{-3}
RHOWAT	ρ_{water}	Bulk density of water	g cm^{-3}
SHTAIR	c_{air}	Specific heat of air	cal/g °K
SHTCLA	c_{clay}	Specific heat of clay	cal/g °K
SHTSAN	c_{sand}	Specific heat of sand	cal/g °K

Table A1. Program Variables for Input Data (continued)

FORTRAN Variable	Math Symbol	Meaning	Unit
SHTSIL	c_{silt}	Specific heat of silt	cal/g °K
SHTWAT	c_{water}	Specific heat of water	cal/g °K
TO		Start time for simulation	hr
TCUT		End time for simulation	hr
TEMPA	T_{air}	Initial air temperature	°K
TEMPS	T	Initial soil temperature	°K
THTAA	θ_{air}	Initial air relative humidity	
THTAS	θ	Initial soil water content	cm^3/cm^3
THTAST	θ_s	Saturated soil water content	cm^3/cm^3
THTRES	θ_r	Residual soil water content in equations (59) and (60)	cm^3/cm^3
TLIOF		Time at which the light is turned off	hr
TLION		Time at which the light is turned on	hr
TORT	α_{tort}	Tortuosity factor of soil	
TPINMU	$\bar{T}$	Parameter in equation (56)	°K
TPWATI		Temperature of rain water	°K
TRAOF		Time at which the rain is turned off	hr
TRAON		Time at which the rain is turned on	hr
WS		Wind speed at the atmosphere-soil surface	cm

APPENDIX IV: LISTING OF INPUT AND OUTPUT FILES

Input Data File: wtv1.dat

```
0.0   6.1    0.1
1.0  2.99 5.99 17.99 23.99 29.99 35.99 41.99 47.99 71.99 95.99
119.99 139.99 149.99 159.99 169.99 179.99
 0 0 0 0 0 0 0 0 1 0 1 0 1 0 0 0 0 0 1 0
  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22
23 24 25
99
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1.0
1.0
0.05       0.07       0.09
0.90       0.95       0.50
3.33000E-4
3.43
0.175      0.175      0.175      1.0        0.24
2.66       2.64       2.65
-2.0900E-3 1.05600E-6
 3
954.0      4770.0     3.33000E-4
1.0        0.0011
0.0
 2  5
-1.006722008  -2.356626769    0.261199
-0.371835795  1.000000000     0.523598
0.0371929656  0.0675873369    0.261199
-.0052916350  -.0274241549    0.523598
-.0094577865  0.0116668147    0.785397
0.0063752911  -.0043302556    1.047196
-.0061084983  0.0040792275    1.308995
8.7578        0.869           277.0
```

Input Data File: WTV2.dat

1.0E+5 0.0 0.000324 1.0 0.27 0.0

Input Data File: WTV3.dat

```
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600   .6600   .6600   .6600   .6600
.6600   .6600   .6600
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55   0.55   0.55   0.55
0.55   0.55   0.55   0.55
0.3   0.3   0.3   0.3   0.3   0.3   0.3
0.3   0.3   0.3   0.3   0.3   0.3   0.3
0.3   0.3   0.3   0.3   0.3   0.3   0.3
0.3   0.3   0.3   0.3   0.3   0.3   0.3
0.3   0.3   0.3   0.3   0.3   0.3   0.3
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0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3    0.3    0.3    0.3
0.3    0.3    0.3    0.3
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
.1000    .1000    .1000    .1000    .1000    .1000    .1000
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0.6    0.6    0.6    0.6    0.6    0.6    0.6
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0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6    0.6    0.6    0.6
0.6    0.6    0.6    0.6
      1241.39      1241.39      1241.39      1241.39      1241.39      1241.39
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      1241.39      1241.39      1241.39      1241.39      1241.39      1241.39
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    1241.39     1241.39     1241.39     1241.39     1241.39     1241.39
1241.39
    1241.39     1241.39     1241.39     1241.39     1241.39     1241.39
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    1241.39     1241.39     1241.39     1241.39     1241.39     1241.39
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    1241.39     1241.39     1241.39     1241.39     1241.39     1241.39
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    1241.39     1241.39     1241.39     1241.39     1241.39     1241.39
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    1241.39     1241.39     1241.39
    .7079     .7079     .7079     .7079     .7079     .7079     .7079
    .7079     .7079     .7079     .7079     .7079     .7079     .7079
    .7079     .7079     .7079     .7079     .7079     .7079     .7079
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    .7079     .7079     .7079     .7079     .7079     .7079     .7079
    .7079     .7079     .7079
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5     6.5     6.5     6.5
    6.5     6.5     6.5     6.5
    0.61     0.61     0.61     0.61     0.61     0.61     0.61
    0.61     0.61     0.61     0.61     0.61     0.61     0.61
    0.61     0.61     0.61     0.61     0.61     0.61     0.61
    0.61     0.61     0.61     0.61     0.61     0.61     0.61
    0.61     0.61     0.61     0.61     0.61     0.61     0.61
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0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
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0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61	0.61	0.61	0.61
0.61	0.61	0.61	0.61			
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029	0.029	0.029	0.029	0.029
0.029	0.029	0.029				
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0

0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0			

Input Data File: WTV4.dat

0.892	281.72	
0.25	281.72	0.0
0.25	281.72	0.0
0.25	281.72	0.0
0.25	281.72	0.0
0.25	281.72	0.0
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Input Data File: WTV5.dat

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6.0	18.0
30.0	42.0
54.0	66.0
78.0	90.0
102.0	114.0
0.0	6.0
130.0	140.0

Output Data File: P1RNFL

TIMEST= .3000E+01

LAYER	NODE POSITION (CM)	WATER (CM3/CM3 SOIL)	TEMP (K)	VIRUS (PFU/ML)	RCV
1	.0000E+00	.2931E+00	.2772E+03	.7458E+05	.7458E+00
2	.1000E+00	.2926E+00	.2773E+03	.6307E+05	.6307E+00
3	.1100E+01	.2889E+00	.2781E+03	.1059E+05	.1059E+00
4	.2100E+01	.2849E+00	.2787E+03	.1096E+04	.1096E-01
5	.3100E+01	.2809E+00	.2793E+03	.7991E+02	.7991E-03
6	.4100E+01	.2770E+00	.2798E+03	.4212E+01	.4212E-04
7	.5100E+01	.2731E+00	.2802E+03	.1636E+00	.1636E-05
8	.6100E+01	.2694E+00	.2806E+03	.4710E-02	.4710E-07
9	.7100E+01	.2660E+00	.2809E+03	.1003E-03	.1003E-08
10	.8100E+01	.2629E+00	.2811E+03	.1572E-05	.1572E-10
11	.9100E+01	.2601E+00	.2813E+03	.1799E-07	.1799E-12
12	.1010E+02	.2578E+00	.2814E+03	.1488E-09	.1488E-14
13	.1110E+02	.2558E+00	.2815E+03	.8829E-12	.8829E-17
14	.1210E+02	.2543E+00	.2816E+03	.3731E-14	.3731E-19
15	.1310E+02	.2531E+00	.2816E+03	.1119E-16	.1119E-21
16	.1410E+02	.2522E+00	.2817E+03	.2380E-19	.2380E-24
17	.1510E+02	.2515E+00	.2817E+03	.3610E-22	.3610E-27
18	.1610E+02	.2510E+00	.2817E+03	.3948E-25	.3948E-30
19	.1710E+02	.2507E+00	.2817E+03	.3167E-28	.3167E-33
20	.1810E+02	.2505E+00	.2817E+03	.1911E-31	.1911E-36
21	.1910E+02	.2503E+00	.2817E+03	.8955E-35	.8955E-40
22	.2010E+02	.2502E+00	.2817E+03	.3381E-38	.3381E-43
23	.2110E+02	.2501E+00	.2817E+03	.1070E-41	.1070E-46
24	.2210E+02	.2501E+00	.2817E+03	.2949E-45	.2949E-50
25	.2310E+02	.2501E+00	.2817E+03	.7331E-49	.7331E-54
26	.2410E+02	.2500E+00	.2817E+03	.1691E-52	.1691E-57
27	.2510E+02	.2500E+00	.2817E+03	.3702E-56	.3702E-61
28	.2610E+02	.2500E+00	.2817E+03	.7820E-60	.7820E-65
29	.2710E+02	.2500E+00	.2817E+03	.1612E-63	.1612E-68
30	.2810E+02	.2500E+00	.2817E+03	.3271E-67	.3271E-72
31	.2910E+02	.2500E+00	.2817E+03	.6564E-71	.6564E-76
32	.3010E+02	.2500E+00	.2817E+03	.1308E-74	.1308E-79
33	.3110E+02	.2500E+00	.2817E+03	.2593E-78	.2593E-83
34	.3210E+02	.2500E+00	.2817E+03	.5122E-82	.5122E-87
35	.3310E+02	.2500E+00	.2817E+03	.1009E-85	.1009E-90
36	.3410E+02	.2500E+00	.2817E+03	.1984E-89	.1984E-94
37	.3510E+02	.2500E+00	.2817E+03	.3893E-93	.3893E-98
38	.3610E+02	.2500E+00	.2817E+03	.7628E-97	.7628-102
39	.3710E+02	.2500E+00	.2817E+03	.1493-100	.1493-105
40	.3810E+02	.2500E+00	.2817E+03	.2917-104	.2917-109
41	.3910E+02	.2500E+00	.2817E+03	.5693-108	.5693-113
42	.4010E+02	.2500E+00	.2817E+03	.1110-111	.1110-116
43	.4110E+02	.2500E+00	.2817E+03	.2160-115	.2160-120
44	.4210E+02	.2500E+00	.2817E+03	.4201-119	.4201-124
45	.4310E+02	.2500E+00	.2817E+03	.8161-123	.8161-128
46	.4410E+02	.2500E+00	.2817E+03	.1583-126	.1583-131
47	.4510E+02	.2500E+00	.2817E+03	.3069-130	.3069-135

48	.4610E+02	.2500E+00	.2817E+03	.5940-134	.5940-139
49	.4710E+02	.2500E+00	.2817E+03	.1149-137	.1149-142
50	.4810E+02	.2500E+00	.2817E+03	.2219-141	.2219-146
51	.4910E+02	.2500E+00	.2817E+03	.4281-145	.4281-150
52	.5010E+02	.2500E+00	.2817E+03	.8252-149	.8252-154
53	.5110E+02	.2500E+00	.2817E+03	.1589-152	.1589-157
54	.5210E+02	.2500E+00	.2817E+03	.3056-156	.3056-161
55	.5310E+02	.2500E+00	.2817E+03	.5873-160	.5873-165
56	.5410E+02	.2500E+00	.2817E+03	.1127-163	.1127-168
57	.5510E+02	.2500E+00	.2817E+03	.2162-167	.2162-172
58	.5610E+02	.2500E+00	.2817E+03	.4141-171	.4141-176
59	.5710E+02	.2500E+00	.2817E+03	.7924-175	.7924-180
60	.5810E+02	.2500E+00	.2817E+03	.1515-178	.1515-183
61	.5910E+02	.2500E+00	.2817E+03	.2893-182	.2893-187
62	.6010E+02	.2500E+00	.2817E+03	.5521-186	.5521-191
63	.6110E+02	.2500E+00	.2817E+03	.1053-189	.1053-194
64	.6210E+02	.2500E+00	.2817E+03	.2005-193	.2005-198
65	.6310E+02	.2500E+00	.2817E+03	.3814-197	.3814-202
66	.6410E+02	.2500E+00	.2817E+03	.7250-201	.7250-206
67	.6510E+02	.2500E+00	.2817E+03	.1377-204	.1377-209
68	.6610E+02	.2500E+00	.2817E+03	.2613-208	.2613-213
69	.6710E+02	.2500E+00	.2817E+03	.4954-212	.4954-217
70	.6810E+02	.2500E+00	.2817E+03	.9383-216	.9383-221
71	.6910E+02	.2500E+00	.2817E+03	.1776-219	.1776-224
72	.7010E+02	.2500E+00	.2817E+03	.3357-223	.3357-228
73	.7110E+02	.2500E+00	.2817E+03	.6343-227	.6343-232
74	.7210E+02	.2500E+00	.2817E+03	.1197-230	.1197-235
75	.7310E+02	.2500E+00	.2817E+03	.2258-234	.2258-239
76	.7410E+02	.2500E+00	.2817E+03	.4255-238	.4255-243
77	.7510E+02	.2500E+00	.2817E+03	.8011-242	.8011-247
78	.7610E+02	.2500E+00	.2817E+03	.1507-245	.1507-250
79	.7710E+02	.2500E+00	.2817E+03	.2833-249	.2833-254
80	.7810E+02	.2500E+00	.2817E+03	.5321-253	.5321-258
81	.7910E+02	.2500E+00	.2817E+03	.9985-257	.9985-262
82	.8010E+02	.2500E+00	.2817E+03	.1872-260	.1872-265
83	.8110E+02	.2500E+00	.2817E+03	.3508-264	.3508-269
84	.8210E+02	.2500E+00	.2817E+03	.6569-268	.6569-273
85	.8310E+02	.2500E+00	.2817E+03	.1229-271	.1229-276
86	.8410E+02	.2500E+00	.2817E+03	.2297-275	.2297-280
87	.8510E+02	.2500E+00	.2817E+03	.4291-279	.4291-284
88	.8610E+02	.2500E+00	.2817E+03	.8010-283	.8010-288
89	.8710E+02	.2500E+00	.2817E+03	.1494-286	.1494-291
90	.8810E+02	.2500E+00	.2817E+03	.2785-290	.2785-295
91	.8910E+02	.2500E+00	.2817E+03	.5186-294	.5186-299
92	.9010E+02	.2500E+00	.2817E+03	.9653-298	.9653-303
93	.9110E+02	.2500E+00	.2817E+03	.1795-301	.1795-306
94	.9210E+02	.2500E+00	.2817E+03	.3336-305	.3336-310
95	.9310E+02	.2500E+00	.2817E+03	.6196-309	.6196-314
96	.9410E+02	.2500E+00	.2817E+03	.1150-312	.1150-317
97	.9510E+02	.2500E+00	.2817E+03	.2133-316	.2124-321
98	.9610E+02	.2500E+00	.2817E+03	.3957-320	.0000E+00
99	.9710E+02	.2500E+00	.2817E+03	.0000E+00	.0000E+00

100	.9810E+02	.2500E+00	.2817E+03	.0000E+00	.0000E+00
101	.9910E+02	.2500E+00	.2817E+03	.0000E+00	.0000E+00

TIMEST= .6000E+01

LAYER	NODE POSITION (CM)	WATER (CM3/CM3 SOIL)	TEMP (K)	VIRUS (PFU/ML)	RCV
1	.0000E+00	.3059E+00	.2763E+03	.1061E+06	.1061E+01
2	.1000E+00	.3056E+00	.2764E+03	.9794E+05	.9794E+00
3	.1100E+01	.3026E+00	.2770E+03	.3055E+05	.3055E+00
4	.2100E+01	.2995E+00	.2776E+03	.6254E+04	.6254E-01
5	.3100E+01	.2964E+00	.2781E+03	.9466E+03	.9466E-02
6	.4100E+01	.2932E+00	.2786E+03	.1097E+03	.1097E-02
7	.5100E+01	.2899E+00	.2791E+03	.1001E+02	.1001E-03
8	.6100E+01	.2867E+00	.2795E+03	.7306E+00	.7306E-05
9	.7100E+01	.2835E+00	.2798E+03	.4309E-01	.4309E-06
10	.8100E+01	.2802E+00	.2802E+03	.2063E-02	.2063E-07
11	.9100E+01	.2771E+00	.2804E+03	.8033E-04	.8033E-09
12	.1010E+02	.2740E+00	.2807E+03	.2540E-05	.2540E-10
13	.1110E+02	.2710E+00	.2809E+03	.6503E-07	.6503E-12
14	.1210E+02	.2682E+00	.2810E+03	.1342E-08	.1342E-13
15	.1310E+02	.2655E+00	.2812E+03	.2218E-10	.2218E-15
16	.1410E+02	.2631E+00	.2813E+03	.2918E-12	.2918E-17
17	.1510E+02	.2609E+00	.2814E+03	.3034E-14	.3034E-19
18	.1610E+02	.2589E+00	.2815E+03	.2478E-16	.2478E-21
19	.1710E+02	.2572E+00	.2815E+03	.1579E-18	.1579E-23
20	.1810E+02	.2558E+00	.2816E+03	.7813E-21	.7813E-26
21	.1910E+02	.2545E+00	.2816E+03	.2990E-23	.2990E-28
22	.2010E+02	.2535E+00	.2816E+03	.8835E-26	.8835E-31
23	.2110E+02	.2527E+00	.2817E+03	.2015E-28	.2015E-33
24	.2210E+02	.2521E+00	.2817E+03	.3559E-31	.3559E-36
25	.2310E+02	.2516E+00	.2817E+03	.4890E-34	.4890E-39
26	.2410E+02	.2512E+00	.2817E+03	.5274E-37	.5274E-42
27	.2510E+02	.2509E+00	.2817E+03	.4517E-40	.4517E-45
28	.2610E+02	.2507E+00	.2817E+03	.3119E-43	.3119E-48
29	.2710E+02	.2505E+00	.2817E+03	.1768E-46	.1768E-51
30	.2810E+02	.2503E+00	.2817E+03	.8399E-50	.8399E-55
31	.2910E+02	.2503E+00	.2817E+03	.3421E-53	.3421E-58
32	.3010E+02	.2502E+00	.2817E+03	.1222E-56	.1222E-61
33	.3110E+02	.2501E+00	.2817E+03	.3916E-60	.3916E-65
34	.3210E+02	.2501E+00	.2817E+03	.1149E-63	.1149E-68
35	.3310E+02	.2501E+00	.2817E+03	.3144E-67	.3144E-72
36	.3410E+02	.2500E+00	.2817E+03	.8153E-71	.8153E-76
37	.3510E+02	.2500E+00	.2817E+03	.2029E-74	.2029E-79
38	.3610E+02	.2500E+00	.2817E+03	.4893E-78	.4893E-83
39	.3710E+02	.2500E+00	.2817E+03	.1153E-81	.1153E-86
40	.3810E+02	.2500E+00	.2817E+03	.2672E-85	.2672E-90
41	.3910E+02	.2500E+00	.2817E+03	.6113E-89	.6113E-94
42	.4010E+02	.2500E+00	.2817E+03	.1386E-92	.1386E-97
43	.4110E+02	.2500E+00	.2817E+03	.3118E-96	.3118-101
44	.4210E+02	.2500E+00	.2817E+03	.6981-100	.6981-105
45	.4310E+02	.2500E+00	.2817E+03	.1557-103	.1557-108
46	.4410E+02	.2500E+00	.2817E+03	.3460-107	.3460-112
47	.4510E+02	.2500E+00	.2817E+03	.7669-111	.7669-116

48	.4610E+02	.2500E+00	.2817E+03	.1696-114	.1696-119
49	.4710E+02	.2500E+00	.2817E+03	.3745-118	.3745-123
50	.4810E+02	.2500E+00	.2817E+03	.8255-122	.8255-127
51	.4910E+02	.2500E+00	.2817E+03	.1817-125	.1817-130
52	.5010E+02	.2500E+00	.2817E+03	.3992-129	.3992-134
53	.5110E+02	.2500E+00	.2817E+03	.8760-133	.8760-138
54	.5210E+02	.2500E+00	.2817E+03	.1920-136	.1920-141
55	.5310E+02	.2500E+00	.2817E+03	.4202-140	.4202-145
56	.5410E+02	.2500E+00	.2817E+03	.9185-144	.9185-149
57	.5510E+02	.2500E+00	.2817E+03	.2005-147	.2005-152
58	.5610E+02	.2500E+00	.2817E+03	.4372-151	.4372-156
59	.5710E+02	.2500E+00	.2817E+03	.9520-155	.9520-160
60	.5810E+02	.2500E+00	.2817E+03	.2071-158	.2071-163
61	.5910E+02	.2500E+00	.2817E+03	.4498-162	.4498-167
62	.6010E+02	.2500E+00	.2817E+03	.9759-166	.9759-171
63	.6110E+02	.2500E+00	.2817E+03	.2115-169	.2115-174
64	.6210E+02	.2500E+00	.2817E+03	.4577-173	.4577-178
65	.6310E+02	.2500E+00	.2817E+03	.9895-177	.9895-182
66	.6410E+02	.2500E+00	.2817E+03	.2136-180	.2136-185
67	.6510E+02	.2500E+00	.2817E+03	.4608-184	.4608-189
68	.6610E+02	.2500E+00	.2817E+03	.9925-188	.9925-193
69	.6710E+02	.2500E+00	.2817E+03	.2136-191	.2136-196
70	.6810E+02	.2500E+00	.2817E+03	.4589-195	.4589-200
71	.6910E+02	.2500E+00	.2817E+03	.9851-199	.9851-204
72	.7010E+02	.2500E+00	.2817E+03	.2112-202	.2112-207
73	.7110E+02	.2500E+00	.2817E+03	.4524-206	.4524-211
74	.7210E+02	.2500E+00	.2817E+03	.9677-210	.9677-215
75	.7310E+02	.2500E+00	.2817E+03	.2068-213	.2068-218
76	.7410E+02	.2500E+00	.2817E+03	.4413-217	.4413-222
77	.7510E+02	.2500E+00	.2817E+03	.9408-221	.9408-226
78	.7610E+02	.2500E+00	.2817E+03	.2003-224	.2003-229
79	.7710E+02	.2500E+00	.2817E+03	.4261-228	.4261-233
80	.7810E+02	.2500E+00	.2817E+03	.9054-232	.9054-237
81	.7910E+02	.2500E+00	.2817E+03	.1922-235	.1922-240
82	.8010E+02	.2500E+00	.2817E+03	.4074-239	.4074-244
83	.8110E+02	.2500E+00	.2817E+03	.8628-243	.8628-248
84	.8210E+02	.2500E+00	.2817E+03	.1825-246	.1825-251
85	.8310E+02	.2500E+00	.2817E+03	.3857-250	.3857-255
86	.8410E+02	.2500E+00	.2817E+03	.8142-254	.8142-259
87	.8510E+02	.2500E+00	.2817E+03	.1717-257	.1717-262
88	.8610E+02	.2500E+00	.2817E+03	.3616-261	.3616-266
89	.8710E+02	.2500E+00	.2817E+03	.7609-265	.7609-270
90	.8810E+02	.2500E+00	.2817E+03	.1599-268	.1599-273
91	.8910E+02	.2500E+00	.2817E+03	.3358-272	.3358-277
92	.9010E+02	.2500E+00	.2817E+03	.7045-276	.7045-281
93	.9110E+02	.2500E+00	.2817E+03	.1476-279	.1476-284
94	.9210E+02	.2500E+00	.2817E+03	.3090-283	.3090-288
95	.9310E+02	.2500E+00	.2817E+03	.6461-287	.6461-292
96	.9410E+02	.2500E+00	.2817E+03	.1350-290	.1350-295
97	.9510E+02	.2500E+00	.2817E+03	.2817-294	.2817-299
98	.9610E+02	.2500E+00	.2817E+03	.5873-298	.5873-303
99	.9710E+02	.2500E+00	.2817E+03	.1223-301	.1223-306

100	.9810E+02	.2500E+00	.2817E+03	.2545-305	.2545-310
101	.9910E+02	.2500E+00	.2817E+03	.1435-305	.1435-310

Output Data File: P2RNFL

TIME	WATER EVAP.	TEMP1	TEMP5	TEMP10	TEMP20	TEMP50
.1000E+01	-.6399E-03	.2784E+03	.2814E+03	.2817E+03	.2817E+03	.2817E+03
.2000E+01	-.3555E-03	.2777E+03	.2808E+03	.2816E+03	.2817E+03	.2817E+03
.3000E+01	-.2015E-03	.2772E+03	.2802E+03	.2814E+03	.2817E+03	.2817E+03
.4000E+01	-.9010E-04	.2769E+03	.2798E+03	.2812E+03	.2817E+03	.2817E+03
.5000E+01	-.1567E-04	.2766E+03	.2794E+03	.2809E+03	.2817E+03	.2817E+03
.6000E+01	.3717E-04	.2763E+03	.2791E+03	.2807E+03	.2816E+03	.2817E+03

Output Data File: TEST.OUT

```
                 RUN CONTROL INFORMATION.
      TO=      .0000  TCUT=    6.1000  DTO=      .1000

      PRTIN(I)=     1.0000     2.9900     5.9900    17.9900    23.9900

   29.9900    35.9900    41.9900    47.9900    71.9900

   95.9900   119.9900   139.9900   149.9900   159.9900

  169.9900
NPRINT(I)=  0  0  0  0  0  0  0  0  1  0  1  0  1  0  0  0  0  0  1  0

NNSTRZ(I)=  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
24 25

      LAYER, THICKNESS(CM), NODAL POSITION(CM).

          1        .1000E+00      .0000E+00
          2        .1000E+01      .1000E+00
          3        .1000E+01      .1100E+01
          4        .1000E+01      .2100E+01
          5        .1000E+01      .3100E+01
          6        .1000E+01      .4100E+01
          7        .1000E+01      .5100E+01
          8        .1000E+01      .6100E+01
          9        .1000E+01      .7100E+01
         10        .1000E+01      .8100E+01
         11        .1000E+01      .9100E+01
         12        .1000E+01      .1010E+02
         13        .1000E+01      .1110E+02
         14        .1000E+01      .1210E+02
         15        .1000E+01      .1310E+02
         16        .1000E+01      .1410E+02
         17        .1000E+01      .1510E+02
         18        .1000E+01      .1610E+02
         19        .1000E+01      .1710E+02
         20        .1000E+01      .1810E+02
         21        .1000E+01      .1910E+02
         22        .1000E+01      .2010E+02
         23        .1000E+01      .2110E+02
         24        .1000E+01      .2210E+02
         25        .1000E+01      .2310E+02
         26        .1000E+01      .2410E+02
         27        .1000E+01      .2510E+02
         28        .1000E+01      .2610E+02
         29        .1000E+01      .2710E+02
         30        .1000E+01      .2810E+02
         31        .1000E+01      .2910E+02
         32        .1000E+01      .3010E+02
         33        .1000E+01      .3110E+02
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34	.1000E+01	.3210E+02
35	.1000E+01	.3310E+02
36	.1000E+01	.3410E+02
37	.1000E+01	.3510E+02
38	.1000E+01	.3610E÷02
39	.1000E+01	.3710E+02
40	.1000E+01	.3810E+02
41	.1000E+01	.3910E+02
42	.1000E+01	.4010E+02
43	.1000E+01	.4110E+02
44	.1000E+01	.4210E+02
45	.1000E+01	.4310E+02
46	.1000E+01	.4410E+02
47	.1000E+01	.4510E+02
48	.1000E+01	.4610E+02
49	.1000E+01	.4710E+02
50	.1000E+01	.4810E+02
51	.1000E+01	.4910E+02
52	.1000E+01	.5010E+02
53	.1000E+01	.5110E+02
54	.1000E+01	.5210E+02
55	.1000E+01	.5310E+02
56	.1000E+01	.5410E+02
57	.1000E+01	.5510E+02
58	.1000E+01	.5610E+02
59	.1000E+01	.5710E+02
60	.1000E+01	.5810E+02
61	.1000E+01	.5910E+02
62	.1000E+01	.6010E+02
63	.1000E+01	.6110E+02
64	.1000E+01	.6210E+02
65	.1000E+01	.6310E+02
66	.1000E+01	.6410E+02
67	.1000E+01	.6510E+02
68	.1000E+01	.6610E+02
69	.1000E+01	.6710E+02
70	.1000E+01	.6810E+02
71	.1000E+01	.6910E+02
72	.1000E+01	.7010E+02
73	.1000E+01	.7110E+02
74	.1000E+01	.7210E+02
75	.1000E+01	.7310E+02
76	.1000E+01	.7410E+02
77	.1000E+01	.7510E+02
78	.1000E+01	.7610E+02
79	.1000E+01	.7710E+02
80	.1000E+01	.7810E+02
81	.1000E+01	.7910E+02
82	.1000E+01	.8010E+02
83	.1000E+01	.8110E+02
84	.1000E+01	.8210E+02
85	.1000E+01	.8310E+02

86	.1000E+01	.8410E+02
87	.1000E+01	.8510E+02
88	.1000E+01	.8610E+02
89	.1000E+01	.8710E+02
90	.1000E+01	.8810E+02
91	.1000E+01	.8910E+02
92	.1000E+01	.9010E+02
93	.1000E+01	.9110E+02
94	.1000E+01	.9210E+02
95	.1000E+01	.9310E+02
96	.1000E+01	.9410E+02
97	.1000E+01	.9510E+02
98	.1000E+01	.9610E+02
99	.1000E+01	.9710E+02
100	.1000E+01	.9810E+02

NUMBER OF INTERNAL SOIL NODES= 99 SOIL THICKNESS (CM)= 99.1000

BOUNDARY LAYER THICKNESS= 1.0000

RHOSND= .2660E+01 RHOCLA= .2640E+01 RHOSIL= .2650E+01

ALBAIR= .5000E-01 ALBWAT= .7000E-01 ALBSOI= .9000E-01

EMSAIR= .9000E+00 EMSWAT= .9500E+00 EMSSOI= .5000E+00

LAMBHT= .3330E-03

LAMSLD = .3430E+01

SHTSAN= .1750E+00 SHTSIL= .1750E+00 SHTCLA= .1750E+00 SHTWAT=
.1000E+01 SHTAIR= .2400E+00

GAMTLI= -.2090E-02 BETATV= .1056E-05

DWVAR(I)= .9540E+03 .4770E+04 .3330E-03

RHOWAT= .1000E+01 RHOAIR= .1100E-02 WS = .0000E+00

DRIVING FUNCTION PARAMETERS.

FOURIER COEFFICIENTS

NCFTMP = 2 NCFFRH = 5

INDEX	ATEMP	BTEMP
1	-1.006722	-2.356627

2	-.371836	1.000000

INDEX	ARHIN	BRHIN
1	.037193	.067587
2	-.005292	-.027424
3	-.009458	.011667
4	.006375	-.004330
5	-.006108	.004079

TPINMU = 8.757800 RHINMU = .869000 TPWATI = 277.000000

INDEX	OMEGTP
1	.261199
2	.523598

INDEX	OMGRHI
1	.261199
2	.523598
3	.785397
4	1.047196
5	1.308995

INDEX	QRAIN	QSR
1	.0000E+00	.0000E+00
2	.1000E+00	.3561E+02
3	.0000E+00	.6639E+01
4	.0000E+00	.2510E+01
5	.0000E+00	.1500E+00

INDEX	TIME LIGHT ON	TIME LIGHT OFF
1	.6000E+01	.1800E+02
2	.3000E+02	.4200E+02
3	.5400E+02	.6600E+02
4	.7800E+02	.9000E+02
5	.1020E+03	.1140E+03

INDEX	TIME RAIN ON	TIME RAIN OFF
1	.0000E+00	.6000E+01
2	.1300E+03	.1400E+03

VIRUS PARAMETERS

DISPLZ= .1000E+01 DLO= .3240E-03 CWIN= .1000E+06 CVGRD= .0000E+00

AIR R.H. (PERCENT)	AIR TEMP (DEG. KELVIN)
.8920E+00	.2817E+03

INITIAL FIELD DISTRIBUTIONS

LAYER	WATER (CM3 WATER/CM-3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.2500E+00	.2817E+03	.0000E+00
2	.2500E+00	.2817E+03	.0000E+00
3	.2500E+00	.2817E+03	.0000E+00
4	.2500E+00	.2817E+03	.0000E+00
5	.2500E+00	.2817E+03	.0000E+00
6	.2500E+00	.2817E+03	.0000E+00
7	.2500E+00	.2817E+03	.0000E+00
8	.2500E+00	.2817E+03	.0000E+00
9	.2500E+00	.2817E+03	.0000E+00
10	.2500E+00	.2817E+03	.0000E+00
11	.2500E+00	.2817E+03	.0000E+00
12	.2500E+00	.2817E+03	.0000E+00
13	.2500E+00	.2817E+03	.0000E+00
14	.2500E+00	.2817E+03	.0000E+00
15	.2500E+00	.2817E+03	.0000E+00
16	.2500E+00	.2817E+03	.0000E+00
17	.2500E+00	.2817E+03	.0000E+00
18	.2500E+00	.2817E+03	.0000E+00
19	.2500E+00	.2817E+03	.0000E+00
20	.2500E+00	.2817E+03	.0000E+00
21	.2500E+00	.2817E+03	.0000E+00
22	.2500E+00	.2817E+03	.0000E+00
23	.2500E+00	.2817E+03	.0000E+00
24	.2500E+00	.2817E+03	.0000E+00
25	.2500E+00	.2817E+03	.0000E+00
26	.2500E+00	.2817E+03	.0000E+00
27	.2500E+00	.2817E+03	.0000E+00
28	.2500E+00	.2817E+03	.0000E+00
29	.2500E+00	.2817E+03	.0000E+00
30	.2500E+00	.2817E+03	.0000E+00
31	.2500E+00	.2817E+03	.0000E+00
32	.2500E+00	.2817E+03	.0000E+00
33	.2500E+00	.2817E+03	.0000E+00
34	.2500E+00	.2817E+03	.0000E+00
35	.2500E+00	.2817E+03	.0000E+00
36	.2500E+00	.2817E+03	.0000E+00
37	.2500E+00	.2817E+03	.0000E+00
38	.2500E+00	.2817E+03	.0000E+00
39	.2500E+00	.2817E+03	.0000E+00
40	.2500E+00	.2817E+03	.0000E+00

41	.2500E+00	.2817E+03	.0000E+00
42	.2500E+00	.2817E+03	.0000E+00
43	.2500E+00	.2817E+03	.0000E+00
44	.2500E+00	.2817E+03	.0000E+00
45	.2500E+00	.2817E+03	.0000E+00
46	.2500E+00	.2817E+03	.0000E+00
47	.2500E+00	.2817E+03	.0000E+00
48	.2500E+00	.2817E+03	.0000E+00
49	.2500E+00	.2817E+03	.0000E+00
50	.2500E+00	.2817E+03	.0000E+00
51	.2500E+00	.2817E+03	.0000E+00
52	.2500E+00	.2817E+03	.0000E+00
53	.2500E+00	.2817E+03	.0000E+00
54	.2500E+00	.2817E+03	.0000E+00
55	.2500E+00	.2817E+03	.0000E+00
56	.2500E+00	.2817E+03	.0000E+00
57	.2500E+00	.2817E+03	.0000E+00
58	.2500E+00	.2817E+03	.0000E+00
59	.2500E+00	.2817E+03	.0000E+00
60	.2500E+00	.2817E+03	.0000E+00
61	.2500E+00	.2817E+03	.0000E+00
62	.2500E+00	.2817E+03	.0000E+00
63	.2500E+00	.2817E+03	.0000E+00
64	.2500E+00	.2817E+03	.0000E+00
65	.2500E+00	.2817E+03	.0000E+00
66	.2500E+00	.2817E+03	.0000E+00
67	.2500E+00	.2817E+03	.0000E+00
68	.2500E+00	.2817E+03	.0000E+00
69	.2500E+00	.2817E+03	.0000E+00
70	.2500E+00	.2817E+03	.0000E+00
71	.2500E+00	.2817E+03	.0000E+00
72	.2500E+00	.2817E+03	.0000E+00
73	.2500E+00	.2817E+03	.0000E+00
74	.2500E+00	.2817E+03	.0000E+00
75	.2500E+00	.2817E+03	.0000E+00
76	.2500E+00	.2817E+03	.0000E+00
77	.2500E+00	.2817E+03	.0000E+00
78	.2500E+00	.2817E+03	.0000E+00
79	.2500E+00	.2817E+03	.0000E+00
80	.2500E+00	.2817E+03	.0000E+00
81	.2500E+00	.2817E+03	.0000E+00
82	.2500E+00	.2817E+03	.0000E+00
83	.2500E+00	.2817E+03	.0000E+00
84	.2500E+00	.2817E+03	.0000E+00
85	.2500E+00	.2817E+03	.0000E+00
86	.2500E+00	.2817E+03	.0000E+00
87	.2500E+00	.2817E+03	.0000E+00
88	.2500E+00	.2817E+03	.0000E+00
89	.2500E+00	.2817E+03	.0000E+00
90	.2500E+00	.2817E+03	.0000E+00
91	.2500E+00	.2817E+03	.0000E+00
92	.2500E+00	.2817E+03	.0000E+00

93	.2500E+00	.2817E+03	.0000E+00
94	.2500E+00	.2817E+03	.0000E+00
95	.2500E+00	.2817E+03	.0000E+00
96	.2500E+00	.2817E+03	.0000E+00
97	.2500E+00	.2817E+03	.0000E+00
98	.2500E+00	.2817E+03	.0000E+00
99	.2500E+00	.2817E+03	.0000E+00
100	.2500E+00	.2817E+03	.0000E+00
101	.2500E+00	.2817E+03	.0000E+00

UNIVERSAL CONSTANTS

GRAV = .1271E+11 R = .5981E+14 SIGMA = .4896E-08

TABLES OF SOIL PROPERTIES

THTAST(I)

.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00	.5500E+00
.5500E+00	.5500E+00	.5500E+00	.5500E+00		
.5500E+00					

TORT(I)

.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00
.6600E+00	.6600E+00	.6600E+00	.6600E+00		
.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00
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.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00
.6600E+00	.6600E+00	.6600E+00	.6600E+00		
.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00
.6600E+00	.6600E+00	.6600E+00	.6600E+00		
.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00	.6600E+00

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.6600E+00 .6600E+00 .6600E+00 .6600E+00
.6600E+00

EPS(I)

.5500E+00 .5500E+00 .5500E+00 .5500E+00 .5500E+00 .5500E+00
.5500E+00 .5500E+00 .5500E+00 .5500E+00
.5500E+00 .5500E+00 .5500E+00 .5500E+00 .5500E+00 .5500E+00
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.5500E+00 .5500E+00 .5500E+00 .5500E+00
.5500E+00

PCTSAN(I)

.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00
.3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00 .3000E+00

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.3000E+00   .3000E+00   .3000E+00   .3000E+00
  .3000E+00   .3000E+00   .3000E+00   .3000E+00   .3000E+00   .3000E+00
.3000E+00   .3000E+00   .3000E+00   .3000E+00
  .3000E+00   .3000E+00   .3000E+00   .3000E+00   .3000E+00   .3000E+00
.3000E+00   .3000E+00   .3000E+00   .3000E+00
  .3000E+00   .3000E+00   .3000E+00   .3000E+00   .3000E+00   .3000E+00
.3000E+00   .3000E+00   .3000E+00   .3000E+00
  .3000E+00

        PCTCLA(I)

  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00   .1000E+00
.1000E+00   .1000E+00   .1000E+00   .1000E+00
  .1000E+00

        PCTSIL(I)

  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
```

```
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00   .6000E+00
.6000E+00   .6000E+00   .6000E+00   .6000E+00
  .6000E+00
```

RHOSOL(I)

```
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01   .2652E+01
.2652E+01   .2652E+01   .2652E+01   .2652E+01
  .2652E+01
```

RHOB(I)

```
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01   .1193E+01
.1193E+01   .1193E+01   .1193E+01   .1193E+01
  .1193E+01
```

SHTSOL(I)

```
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
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.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00   .1750E+00
.1750E+00   .1750E+00   .1750E+00   .1750E+00
  .1750E+00
```

LAMSOL(I)

```
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01   .3430E+01
.3430E+01   .3430E+01   .3430E+01   .3430E+01
  .3430E+01
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ALPTH(I)

```
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
```

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  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04   .1241E+04
.1241E+04   .1241E+04   .1241E+04   .1241E+04
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.1241E+04   .1241E+04   .1241E+04   .1241E+04
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.1241E+04   .1241E+04   .1241E+04   .1241E+04
  .1241E+04

        BETATH(I)

  .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00
.7079E+00   .7079E+00   .7079E+00   .7079E+00
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.7079E+00   .7079E+00   .7079E+00   .7079E+00
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.7079E+00   .7079E+00   .7079E+00   .7079E+00
  .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00
.7079E+00   .7079E+00   .7079E+00   .7079E+00
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.7079E+00   .7079E+00   .7079E+00   .7079E+00
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.7079E+00   .7079E+00   .7079E+00   .7079E+00
  .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00
.7079E+00   .7079E+00   .7079E+00   .7079E+00
  .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00
.7079E+00   .7079E+00   .7079E+00   .7079E+00
  .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00   .7079E+00
.7079E+00   .7079E+00   .7079E+00   .7079E+00
  .7079E+00

        GAMCNS(I)

  .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01
.6500E+01   .6500E+01   .6500E+01   .6500E+01
  .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01
.6500E+01   .6500E+01   .6500E+01   .6500E+01
  .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01
.6500E+01   .6500E+01   .6500E+01   .6500E+01
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  .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01
.6500E+01   .6500E+01   .6500E+01   .6500E+01
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.6500E+01   .6500E+01   .6500E+01   .6500E+01
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.6500E+01   .6500E+01   .6500E+01   .6500E+01
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.6500E+01   .6500E+01   .6500E+01   .6500E+01
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.6500E+01   .6500E+01   .6500E+01   .6500E+01
  .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01
.6500E+01   .6500E+01   .6500E+01   .6500E+01
  .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01   .6500E+01
.6500E+01   .6500E+01   .6500E+01   .6500E+01
  .6500E+01

        KTHSTS(I)

  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00   .6100E+00
.6100E+00   .6100E+00   .6100E+00   .6100E+00
  .6100E+00

        THTRES(I)

  .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01
.2900E-01   .2900E-01   .2900E-01   .2900E-01
  .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01
.2900E-01   .2900E-01   .2900E-01   .2900E-01
  .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01
.2900E-01   .2900E-01   .2900E-01   .2900E-01
  .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01
.2900E-01   .2900E-01   .2900E-01   .2900E-01
  .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01   .2900E-01
.2900E-01   .2900E-01   .2900E-01   .2900E-01
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 .2900E-01  .2900E-01  .2900E-01  .2900E-01  .2900E-01  .2900E-01
.2900E-01  .2900E-01  .2900E-01  .2900E-01
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.2900E-01  .2900E-01  .2900E-01  .2900E-01
 .2900E-01  .2900E-01  .2900E-01  .2900E-01  .2900E-01  .2900E-01
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 .2900E-01  .2900E-01  .2900E-01  .2900E-01  .2900E-01  .2900E-01
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 .2900E-01

      DALPTZ(I)

 .0000E+00  .0000E+00  .0000E+00  .0000E+00  .0000E+00  .0000E+00
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      DBETAZ(I)

 .0000E+00  .0000E+00  .0000E+00  .0000E+00  .0000E+00  .0000E+00
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  .0000E+00    .0000E+00    .0000E+00    .0000E+00    .0000E+00    .0000E+00
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  .0000E+00
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DTHTSZ(I)

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DTHREZ(I)

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.0000E+00

OUTPUT DATA FOR DYNAMIC SYSTEM

*** WATER, TEMP., AND VIRUS CONC., RESPECTIVELY, AT TIME T =1.0000 ***
(DTLAST= .1000)

FIELD DISTRIBUTIONS

LAYER	WATER (CM3/CM3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.2780E+00	.2784E+03	.4090E+05
2	.2774E+00	.2785E+03	.2580E+05
3	.2717E+00	.2795E+03	.1508E+04
4	.2663E+00	.2803E+03	.4823E+02
5	.2616E+00	.2808E+03	.9113E+00
6	.2578E+00	.2812E+03	.1024E-01
7	.2550E+00	.2814E+03	.6823E-04
8	.2531E+00	.2816E+03	.2687E-06
9	.2518E+00	.2816E+03	.6259E-09
10	.2510E+00	.2817E+03	.8731E-12
11	.2506E+00	.2817E+03	.7494E-15
12	.2503E+00	.2817E+03	.4150E-18
13	.2502E+00	.2817E+03	.1588E-21
14	.2501E+00	.2817E+03	.4559E-25
15	.2500E+00	.2817E+03	.1070E-28
16	.2500E+00	.2817E+03	.2203E-32
17	.2500E+00	.2817E+03	.4196E-36
18	.2500E+00	.2817E+03	.7646E-40
19	.2500E+00	.2817E+03	.1360E-43
20	.2500E+00	.2817E+03	.2386E-47
21	.2500E+00	.2817E+03	.4159E-51
22	.2500E+00	.2817E+03	.7219E-55
23	.2500E+00	.2817E+03	.1250E-58
24	.2500E+00	.2817E+03	.2162E-62
25	.2500E+00	.2817E+03	.3734E-66

NODE	PSI	KONTHS	VLZZ
1	-.8527E+03	.5014E-02	.1873E+00
2	-.8563E+03	.4935E-02	.1833E+00
3	-.8905E+03	.4254E-02	.1495E+00
4	-.9246E+03	.3677E-02	.1230E+00
5	-.9554E+03	.3230E-02	.9445E-01
6	-.9811E+03	.2903E-02	.6859E-01
7	-.1001E+04	.2679E-02	.4730E-01
8	-.1014E+04	.2532E-02	.3136E-01
9	-.1023E+04	.2441E-02	.2029E-01
10	-.1029E+04	.2387E-02	.1305E-01
11	-.1032E+04	.2355E-02	.8550E-02

12	-.1034E+04	.2336E-02	.5848E-02
13	-.1035E+04	.2326E-02	.4275E-02
14	-.1036E+04	.2321E-02	.3382E-02
15	-.1036E+04	.2318E-02	.2886E-02
16	-.1036E+04	.2316E-02	.2616E-02
17	-.1037E+04	.2315E-02	.2472E-02
18	-.1037E+04	.2315E-02	.2395E-02
19	-.1037E+04	.2315E-02	.2355E-02
20	-.1037E+04	.2314E-02	.2335E-02
21	-.1037E+04	.2314E-02	.2325E-02
22	-.1037E+04	.2314E-02	.2319E-02
23	-.1037E+04	.2314E-02	.2317E-02
24	-.1037E+04	.2314E-02	.2316E-02
25	-.1037E+04	.2314E-02	.2315E-02

IEVENT(1)= 0   IEVENT(2)= 1

RELATIVE HUMIDITY OF THE OUTER BOUNDARY LAYER AIR= .1000E+01
RELATIVE HUMIDITY AT THE SOIL SURFACE= .9993E+00
SATURATED WATER VAPOR DENSITY IN AIR= .6124E-05
SATURATED WATER VAPOR DENSITY AT AIR-SOIL INTERFACE= .6857E-05
EVAPORATIVE(-) OR CONDENSIVE(+) FLUX=-.6399E-03
AIR TEMP. AT OUTER BOUNDARY LAYER EDGE= .2767E+03
SURFACE INFILTRATION RATE(CM/HR)= .1000E+00
TEMP. RAIN WATER= .2770E+03
SOLAR RADIATION= .0000E+00
EVAPORATIVE(-) OR CONDENSIVE(+) HEAT TRANSFER=-.3794E+00
SENSIBLE HEAT TRANSFER=-.3552E+00
TRANSFER OF HEAT OF RAIN WATER INTO SOIL= .4000E+00

*** WATER, TEMP., AND VIRUS CONC., RESPECTIVELY, AT TIME T = 2.0000***
(DTLAST= .1000)

FIELD DISTRIBUTIONS

LAYER	WATER (CM3/CM3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.2871E+00	.2777E+03	.5940E+05
2	.2866E+00	.2778E+03	.4629E+05
3	.2822E+00	.2786E+03	.5336E+04
4	.2776E+00	.2793E+03	.3677E+03
5	.2732E+00	.2799E+03	.1700E+02
6	.2689E+00	.2804E+03	.5377E+00
7	.2650E+00	.2808E+03	.1175E-01
8	.2615E+00	.2811E+03	.1768E-03
9	.2586E+00	.2813E+03	.1818E-05
10	.2562E+00	.2814E+03	.1266E-07
11	.2543E+00	.2815E+03	.5921E-10
12	.2529E+00	.2816E+03	.1850E-12
13	.2520E+00	.2817E+03	.3862E-15
14	.2513E+00	.2817E+03	.5429E-18
15	.2508E+00	.2817E+03	.5222E-21
16	.2505E+00	.2817E+03	.3530E-24

17	.2503E+00	.2817E+03	.1742E-27
18	.2502E+00	.2817E+03	.6576E-31
19	.2501E+00	.2817E+03	.2003E-34
20	.2501E+00	.2817E+03	.5187E-38
21	.2500E+00	.2817E+03	.1196E-41
22	.2500E+00	.2817E+03	.2550E-45
23	.2500E+00	.2817E+03	.5164E-49
24	.2500E+00	.2817E+03	.1012E-52
25	.2500E+00	.2817E+03	.1943E-56

NODE	PSI	KONTHS	VLZZ
1	-.8001E+03	.6333E-02	.1826E+00
2	-.8029E+03	.6255E-02	.1786E+00
3	-.8276E+03	.5601E-02	.1499E+00
4	-.8544E+03	.4977E-02	.1387E+00
5	-.8813E+03	.4426E-02	.1228E+00
6	-.9079E+03	.3949E-02	.1062E+00
7	-.9331E+03	.3547E-02	.8912E-01
8	-.9561E+03	.3220E-02	.7247E-01
9	-.9761E+03	.2963E-02	.5707E-01
10	-.9927E+03	.2768E-02	.4363E-01
11	-.1006E+04	.2625E-02	.3249E-01
12	-.1015E+04	.2522E-02	.2372E-01
13	-.1022E+04	.2451E-02	.1710E-01
14	-.1027E+04	.2403E-02	.1230E-01
15	-.1031E+04	.2371E-02	.8914E-02
16	-.1033E+04	.2350E-02	.6599E-02
17	-.1034E+04	.2336E-02	.5050E-02
18	-.1035E+04	.2328E-02	.4035E-02
19	-.1036E+04	.2322E-02	.3381E-02
20	-.1036E+04	.2319E-02	.2967E-02
21	-.1036E+04	.2317E-02	.2709E-02
22	-.1036E+04	.2316E-02	.2550E-02
23	-.1037E+04	.2315E-02	.2454E-02
24	-.1037E+04	.2315E-02	.2396E-02
25	-.1037E+04	.2315E-02	.2361E-02

IEVENT(1)= 0 IEVENT(2)= 1

RELATIVE HUMIDITY OF THE OUTER BOUNDARY LAYER AIR= .1000E+01
RELATIVE HUMIDITY AT THE SOIL SURFACE= .9994E+00
SATURATED WATER VAPOR DENSITY IN AIR= .6131E-05
SATURATED WATER VAPOR DENSITY AT AIR-SOIL INTERFACE= .6528E-05
EVAPORATIVE(-) OR CONDENSIVE(+) FLUX=-.3555E-03
AIR TEMP. AT OUTER BOUNDARY LAYER EDGE= .2767E+03
SURFACE INFILTRATION RATE(CM/HR)= .1000E+00
TEMP. RAIN WATER= .2770E+03
SOLAR RADIATION= .0000E+00
EVAPORATIVE(-) OR CONDENSIVE(+) HEAT TRANSFER=-.2109E+00
SENSIBLE HEAT TRANSFER=-.1974E+00
TRANSFER OF HEAT OF RAIN WATER INTO SOIL= .4000E+00

*** WATER, TEMP., AND VIRUS CONC., RESPECTIVELY, AT TIME T = 3.0000*** (DTLAST= .1000)

FIELD DISTRIBUTIONS

LAYER	WATER (CM3/CM3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.2931E+00	.2772E+03	.7458E+05
2	.2926E+00	.2773E+03	.6307E+05
3	.2889E+00	.2781E+03	.1059E+05
4	.2849E+00	.2787E+03	.1096E+04
5	.2809E+00	.2793E+03	.7991E+02
6	.2770E+00	.2798E+03	.4212E+01
7	.2731E+00	.2802E+03	.1636E+00
8	.2694E+00	.2806E+03	.4710E-02
9	.2660E+00	.2809E+03	.1003E-03
10	.2629E+00	.2811E+03	.1572E-05
11	.2601E+00	.2813E+03	.1799E-07
12	.2578E+00	.2814E+03	.1488E-09
13	.2558E+00	.2815E+03	.8829E-12
14	.2543E+00	.2816E+03	.3731E-14
15	.2531E+00	.2816E+03	.1119E-16
16	.2522E+00	.2817E+03	.2380E-19
17	.2515E+00	.2817E+03	.3610E-22
18	.2510E+00	.2817E+03	.3948E-25
19	.2507E+00	.2817E+03	.3167E-28
20	.2505E+00	.2817E+03	.1911E-31
21	.2503E+00	.2817E+03	.8955E-35
22	.2502E+00	.2817E+03	.3381E-38
23	.2501E+00	.2817E+03	.1070E-41
24	.2501E+00	.2817E+03	.2949E-45
25	.2501E+00	.2817E+03	.7331E-49

NODE	PSI	KONTHS	VLZZ
1	-.7673E+03	.7348E-02	.1798E+00
2	-.7697E+03	.7269E-02	.1758E+00
3	-.7900E+03	.6628E-02	.1481E+00
4	-.8124E+03	.5994E-02	.1414E+00
5	-.8352E+03	.5416E-02	.1302E+00
6	-.8585E+03	.4889E-02	.1188E+00
7	-.8818E+03	.4418E-02	.1066E+00
8	-.9047E+03	.4003E-02	.9383E-01
9	-.9267E+03	.3646E-02	.8095E-01
10	-.9471E+03	.3345E-02	.6834E-01
11	-.9655E+03	.3097E-02	.5641E-01
12	-.9815E+03	.2898E-02	.4556E-01
13	-.9950E+03	.2742E-02	.3605E-01
14	-.1006E+04	.2623E-02	.2803E-01
15	-.1014E+04	.2533E-02	.2150E-01
16	-.1021E+04	.2468E-02	.1635E-01
17	-.1026E+04	.2420E-02	.1240E-01

18	-.1029E+04	.2387E-02	.9440E-02
19	-.1031E+04	.2363E-02	.7276E-02
20	-.1033E+04	.2347E-02	.5722E-02
21	-.1034E+04	.2336E-02	.4626E-02
22	-.1035E+04	.2328E-02	.3863E-02
23	-.1036E+04	.2323E-02	.3341E-02
24	-.1036E+04	.2320E-02	.2987E-02
25	-.1036E+04	.2318E-02	.2751E-02

IEVENT(1)= 0   IEVENT(2)= 1

RELATIVE HUMIDITY OF THE OUTER BOUNDARY LAYER AIR= .1000E+01
RELATIVE HUMIDITY AT THE SOIL SURFACE= .9994E+00
SATURATED WATER VAPOR DENSITY IN AIR= .6131E-05
SATURATED WATER VAPOR DENSITY AT AIR-SOIL INTERFACE= .6355E-05
EVAPORATIVE(-) OR CONDENSIVE(+) FLUX=-.2015E-03
AIR TEMP. AT OUTER BOUNDARY LAYER EDGE= .2767E+03
SURFACE INFILTRATION RATE(CM/HR)= .1000E+00
TEMP. RAIN WATER= .2770E+03
SOLAR RADIATION= .0000E+00
EVAPORATIVE(-) OR CONDENSIVE(+) HEAT TRANSFER=-.1196E+00
SENSIBLE HEAT TRANSFER=-.1126E+00
TRANSFER OF HEAT OF RAIN WATER INTO SOIL= .4000E+00
*** WATER, TEMP., AND VIRUS CONC., RESPECTIVELY, AT TIME T = 4.0000*** (DTLAST=
.1000)

FIELD DISTRIBUTIONS

LAYER	WATER (CM3/CM3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.2980E+00	.2769E+03	.8707E+05
2	.2976E+00	.2770E+03	.7689E+05
3	.2942E+00	.2777E+03	.1678E+05
4	.2906E+00	.2783E+03	.2310E+04
5	.2870E+00	.2789E+03	.2290E+03
6	.2833E+00	.2794E+03	.1687E+02
7	.2797E+00	.2798E+03	.9463E+00
8	.2761E+00	.2802E+03	.4087E-01
9	.2726E+00	.2805E+03	.1364E-02
10	.2693E+00	.2808E+03	.3514E-04
11	.2662E+00	.2810E+03	.6964E-06
12	.2633E+00	.2812E+03	.1054E-07
13	.2608E+00	.2813E+03	.1210E-09
14	.2586E+00	.2814E+03	.1044E-11
15	.2567E+00	.2815E+03	.6718E-14
16	.2551E+00	.2816E+03	.3206E-16
17	.2539E+00	.2816E+03	.1129E-18
18	.2529E+00	.2816E+03	.2930E-21
19	.2521E+00	.2817E+03	.5609E-24
20	.2515E+00	.2817E+03	.7967E-27
21	.2511E+00	.2817E+03	.8481E-30
22	.2508E+00	.2817E+03	.6870E-33
23	.2505E+00	.2817E+03	.4323E-36
24	.2504E+00	.2817E+03	.2167E-39
25	.2503E+00	.2817E+03	.8914E-43

NODE	PSI	KONTHS	VLZZ
1	-.7410E+03	.8296E-02	.1775E+00
2	-.7430E+03	.8218E-02	.1740E+00
3	-.7608E+03	.7570E-02	.1493E+00
4	-.7804E+03	.6922E-02	.1443E+00
5	-.8005E+03	.6321E-02	.1353E+00
6	-.8212E+03	.5762E-02	.1263E+00
7	-.8424E+03	.5247E-02	.1166E+00
8	-.8637E+03	.4778E-02	.1064E+00
9	-.8849E+03	.4358E-02	.9578E-01
10	-.9057E+03	.3987E-02	.8496E-01
11	-.9255E+03	.3663E-02	.7416E-01
12	-.9442E+03	.3386E-02	.6365E-01
13	-.9611E+03	.3154E-02	.5370E-01
14	-.9762E+03	.2963E-02	.4453E-01
15	-.9892E+03	.2808E-02	.3634E-01
16	-.1000E+04	.2685E-02	.2923E-01
17	-.1009E+04	.2589E-02	.2323E-01
18	-.1016E+04	.2516E-02	.1831E-01
19	-.1022E+04	.2460E-02	.1435E-01
20	-.1026E+04	.2419E-02	.1125E-01

21	-.1029E+04	.2389E-02	.8861E-02
22	-.1031E+04	.2367E-02	.7053E-02
23	-.1033E+04	.2351E-02	.5707E-02
24	-.1034E+04	.2340E-02	.4717E-02
25	-.1035E+04	.2332E-02	.4000E-02

IEVENT(1)= 0   IEVENT(2)= 1

RELATIVE HUMIDITY OF THE OUTER BOUNDARY LAYER AIR= .1000E+01
RELATIVE HUMIDITY AT THE SOIL SURFACE= .9994E+00
SATURATED WATER VAPOR DENSITY IN AIR= .6111E-05
SATURATED WATER VAPOR DENSITY AT AIR-SOIL INTERFACE= .6213E-05
EVAPORATIVE(-) OR CONDENSIVE(+) FLUX=-.9010E-04
AIR TEMP. AT OUTER BOUNDARY LAYER EDGE= .2766E+03
SURFACE INFILTRATION RATE(CM/HR)= .1000E+00
TEMP. RAIN WATER= .2770E+03
SOLAR RADIATION= .0000E+00
EVAPORATIVE(-) OR CONDENSIVE(+) HEAT TRANSFER=-.5350E-01
SENSIBLE HEAT TRANSFER=-.5151E-01
TRANSFER OF HEAT OF RAIN WATER INTO SOIL= .4000E+00

*** WATER, TEMP., AND VIRUS CONC., RESPECTIVELY, AT TIME T = 5.0000***
(DTLAST= .1000)

FIELD DISTRIBUTIONS

LAYER	WATER (CM3/CM3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.3022E+00	.2766E+03	.9741E+05
2	.3019E+00	.2767E+03	.8834E+05
3	.2987E+00	.2773E+03	.2353E+05
4	.2954E+00	.2779E+03	.4036E+04
5	.2920E+00	.2785E+03	.5056E+03
6	.2886E+00	.2790E+03	.4790E+02
7	.2852E+00	.2794E+03	.3525E+01
8	.2818E+00	.2798E+03	.2043E+00
9	.2784E+00	.2802E+03	.9399E-02
10	.2751E+00	.2804E+03	.3440E-03
11	.2719E+00	.2807E+03	.1001E-04
12	.2688E+00	.2809E+03	.2306E-06
13	.2660E+00	.2811E+03	.4185E-08
14	.2633E+00	.2812E+03	.5946E-10
15	.2610E+00	.2814E+03	.6563E-12
16	.2589E+00	.2814E+03	.5587E-14
17	.2571E+00	.2815E+03	.3642E-16
18	.2556E+00	.2816E+03	.1808E-18
19	.2543E+00	.2816E+03	.6808E-21
20	.2533E+00	.2816E+03	.1940E-23
21	.2525E+00	.2817E+03	.4183E-26
22	.2519E+00	.2817E+03	.6854E-29
23	.2514E+00	.2817E+03	.8589E-32
24	.2510E+00	.2817E+03	.8321E-35
25	.2507E+00	.2817E+03	.6327E-38

NODE	PSI	KONTHS	VLZZ
1	-.7193E+03	.9178E-02	.1758E+00
2	-.7211E+03	.9101E-02	.1725E+00
3	-.7371E+03	.8446E-02	.1501E+00
4	-.7546E+03	.7790E-02	.1462E+00
5	-.7726E+03	.7172E-02	.1387E+00
6	-.7913E+03	.6590E-02	.1313E+00
7	-.8105E+03	.6045E-02	.1233E+00
8	-.8301E+03	.5540E-02	.1148E+00
9	-.8499E+03	.5075E-02	.1059E+00
10	-.8698E+03	.4653E-02	.9667E-01
11	-.8895E+03	.4273E-02	.8722E-01
12	-.9086E+03	.3936E-02	.7769E-01
13	-.9270E+03	.3641E-02	.6828E-01
14	-.9442E+03	.3386E-02	.5917E-01
15	-.9599E+03	.3170E-02	.5054E-01
16	-.9740E+03	.2989E-02	.4256E-01
17	-.9864E+03	.2841E-02	.3537E-01
18	-.9969E+03	.2720E-02	.2904E-01
19	-.1006E+04	.2624E-02	.2360E-01
20	-.1013E+04	.2548E-02	.1903E-01
21	-.1019E+04	.2489E-02	.1527E-01
22	-.1023E+04	.2444E-02	.1223E-01
23	-.1027E+04	.2409E-02	.9824E-02
24	-.1029E+04	.2384E-02	.7939E-02
25	-.1031E+04	.2364E-02	.6485E-02

IEVENT(1)- 0   IEVENT(2)- 1

RELATIVE HUMIDITY OF THE OUTER BOUNDARY LAYER AIR- .1000E+01
RELATIVE HUMIDITY AT THE SOIL SURFACE- .9994E+00
SATURATED WATER VAPOR DENSITY IN AIR- .6069E-05
SATURATED WATER VAPOR DENSITY AT AIR-SOIL INTERFACE- .6091E-05
EVAPORATIVE(-) OR CONDENSIVE(+) FLUX--.1567E-04
AIR TEMP. AT OUTER BOUNDARY LAYER EDGE- .2765E+03
SURFACE INFILTRATION RATE(CM/HR)- .1000E+00
TEMP. RAIN WATER- .2770E+03
SOLAR RADIATION- .0000E+00
EVAPORATIVE(-) OR CONDENSIVE(+) HEAT TRANSFER--.9309E-02
SENSIBLE HEAT TRANSFER--.1051E-01
TRANSFER OF HEAT OF RAIN WATER INTO SOIL- .4000E+00
*** WATER, TEMP., AND VIRUS CONC., RESPECTIVELY, AT TIME T -6.0000 ***
(DTLAST- .1000)

FIELD DISTRIBUTIONS

LAYER	WATER (CM3/CM3 SOIL)	TEMPERATURE (DEG. KELVIN)	VIRUS (PFU/ML)
1	.3059E+00	.2763E+03	.1061E+06
2	.3056E+00	.2764E+03	.9794E+05
3	.3026E+00	.2770E+03	.3055E+05

4	.2995E+00	.2776E+03	.6254E+04
5	.2964E+00	.2781E+03	.9466E+03
6	.2932E+00	.2786E+03	.1097E+03
7	.2899E+00	.2791E+03	.1001E+02
8	.2867E+00	.2795E+03	.7306E+00
9	.2835E+00	.2798E+03	.4309E-01
10	.2802E+00	.2802E+03	.2063E-02
11	.2771E+00	.2804E+03	.8033E-04
12	.2740E+00	.2807E+03	.2540E-05
13	.2710E+00	.2809E+03	.6503E-07
14	.2682E+00	.2810E+03	.1342E-08
15	.2655E+00	.2812E+03	.2218E-10
16	.2631E+00	.2813E+03	.2918E-12
17	.2609E+00	.2814E+03	.3034E-14
18	.2589E+00	.2815E+03	.2478E-16
19	.2572E+00	.2815E+03	.1579E-18
20	.2558E+00	.2816E+03	.7813E-21
21	.2545E+00	.2816E+03	.2990E-23
22	.2535E+00	.2816E+03	.8835E-26
23	.2527E+00	.2817E+03	.2015E-28
24	.2521E+00	.2817E+03	.3559E-31
25	.2516E+00	.2817E+03	.4890E-34

NODE	PSI	KONTHS	VLZZ
1	-.7009E+03	.1001E-01	.1743E+00
2	-.7025E+03	.9930E-02	.1713E+00
3	-.7171E+03	.9272E-02	.1505E+00
4	-.7330E+03	.8608E-02	.1475E+00
5	-.7494E+03	.7980E-02	.1411E+00
6	-.7663E+03	.7381E-02	.1347E+00
7	-.7839E+03	.6815E-02	.1280E+00
8	-.8019E+03	.6282E-02	.1207E+00
9	-.8203E+03	.5786E-02	.1131E+00
10	-.8390E+03	.5325E-02	.1052E+00
11	-.8578E+03	.4903E-02	.9693E-01
12	-.8766E+03	.4519E-02	.8848E-01
13	-.8950E+03	.4173E-02	.7992E-01
14	-.9129E+03	.3866E-02	.7138E-01
15	-.9299E+03	.3596E-02	.6299E-01
16	-.9459E+03	.3362E-02	.5491E-01
17	-.9606E+03	.3162E-02	.4728E-01
18	-.9738E+03	.2992E-02	.4022E-01
19	-.9855E+03	.2852E-02	.3383E-01
20	-.9955E+03	.2736E-02	.2816E-01
21	-.1004E+04	.2642E-02	.2324E-01
22	-.1011E+04	.2567E-02	.1904E-01
23	-.1017E+04	.2507E-02	.1554E-01
24	-.1022E+04	.2461E-02	.1266E-01
25	-.1025E+04	.2424E-02	.1032E-01

IEVENT(1)= 0 IEVENT(2)= 1

RELATIVE HUMIDITY OF THE OUTER BOUNDARY LAYER AIR= .1000E+01
RELATIVE HUMIDITY AT THE SOIL SURFACE= .9995E+00
SATURATED WATER VAPOR DENSITY IN AIR= .6016E-05
SATURATED WATER VAPOR DENSITY AT AIR-SOIL INTERFACE= .5983E-05
EVAPORATIVE(-) OR CONDENSIVE(+) FLUX= .3717E-04
AIR TEMP. AT OUTER BOUNDARY LAYER EDGE= .2764E+03
SURFACE INFILTRATION RATE(CM/HR)= .1000E+00
TEMP. RAIN WATER= .2770E+03
SOLAR RADIATION= .0000E+00
EVAPORATIVE(-) OR CONDENSIVE(+) HEAT TRANSFER= .2208E-01
SENSIBLE HEAT TRANSFER= .1920E-01
TRANSFER OF HEAT OF RAIN WATER INTO SOIL= .4000E+00

APPENDIX V: DISTRIBUTION OF SOFTWARE

The VIRTUS model software may be obtained from the Robert S. Kerr Environmental Research Laboratory. Please send a written request with either a 3.5 inch low density (720 KB) or a 5.25 inch low density (360 KB) diskette to the following address. The diskette needs to be preformatted and MS-DOS compatible.

VIRTUS Distribution
Robert S. Kerr Environmental Research Laboratory
U. S. Environmental Protection Agency
P. O. Box 1198
Ada, OK 74821-1198
USA

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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7. AUTHOR(S) [1]M.V. Yates, [2]S.R. Yates, and [1]Y. Ouyang		8. PERFORMING ORGANIZATION REPORT NO.
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15. SUPPLEMENTARY NOTES

Project Officer: David M. Walters FTS: 743-2261

16. ABSTRACT

As a result of the recently-proposed mandatory ground-water disinfection requirements to inactivate viruses in potable water supplies, there has been increasing interest in virus fate and transport in the subsurface. Several models have been developed to predict the fate of viruses in ground water, but few include transport in the unsaturated zone, and all require a constant virus inactivation rate. These are serious limitations in the models, as it has been shown that considerable virus removal occurs in the unsaturated zone, and inactivation rate of viruses is dependent on environmental conditions. The purpose of this research was to develop a predictive model of virus fate and transport in unsaturated soils that allows the virus inactivation rate to vary based on changes in soil temperature. The model was developed based on the law of mass conservation of a contaminant in porous media and couples the flow of water, viruses, and heat through the soil. Model predictions were compared to measured data of virus transport in laboratory column studies, and were within the 95% confidence limits of the measured concentrations. Model simulations were performed to identify variables that have a large effect on the results.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Virus Transport Unsaturated Zone Modeling Pathogens Virus Heat Transport		

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 148
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