DISSERTATION

TRANSPORT OF COPIOTROPHIC BACTERIA IN OLIGOTROPHIC COARSE SOILS--A MONTE CARLO ANALYSIS

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY THOMAS CHARLES PETERSON

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ABSTRACT OF DISSERTATION

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On-site wastewater treatment systems placed in coarse-grained, oligotrophic soils such as those typically found in the mountainous regions of the West are designed and installed with the assumption that most pathogenic microorganisms will not pass unaltered through an unsaturated zone located in the soil below each system.

Studies have shown that 0.6 to 1.2 m of unsaturated soil below an on-site system drainfield is sufficient to remove most bacteria and viruses in most environments.

Little is known of the transport of pathogenic, copiotrophic bacteria in coarse-grained soils below on-site drainfields placed in mountainous soil environments thought to be oligotrophic.

A stochastic bacterial transport model was developed to analyze bacterial translocation in coarse-grained, mountainous soils beneath a hypothetical drainfield/soil interface. Specific model parameters were randomly generated using a procedure known to produce either a normal or log-normal distribution of random numbers. Numerous computer simulation runs were completed for hypothetical sandy and loamy sand soils subjected to a 10 year and 100

year rain storm. The resulting output was used to generate cumulative frequency distributions.

Results from these simulations indicate that copiotrophic, enteric bacteria have the potential to travel great distances in oligotrophic, coarse-grained soils. The copiotrophic bacteria are likely to travel beyond the arbitrary 1.2 m of soil under conditions typically occurring in mountainous regions. The extent of bacterial transport and the bacterial concentration at any point in the soil is largely the result of the initial bacterial concentration, the impact of straining and clogging by the soil, and the bacterial die-off.

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I. INTRODUCTION

Population shifts in many areas of the West and emigration from industrial centers to rural areas of the East are leading to development pressures for new homes, second homes, and recreational facilities in mountainous areas throughout the United States. Developments are often located in regions where water supplies are limited and easily contaminated because soils are typically of coarse-grained texture or shallow in depth. Construction of centralized sewer facilities to serve these areas is often financially infeasible because of topographic variability, bedrock outcrops, low density housing, and reduced government funding of construction grants. Individual on-site systems, typically a septic tank and leachfield, are often the only alternative.

Mountainous and poor soil regions contain many areas which are severely limited in regard to the placement of on-site systems. These areas include both steep mountain slopes with coarse, shallow soils as well as valleys commonly filled with coarse river alluvium. These coarse soils have limited clay fractions and organic matter, resulting in poor filtration, adsorption, and degradation of pathogenic and non-pathogenic microorganisms commonly released from these on-site systems. Rapid microbial

transport through coarse alluvium or fractured bedrock may result in extensive contamination of the groundwater. State and county governments regulate these on-site systems, yet little is known about the removal efficiency of on-site systems in coarse soils during either normal environmental conditions or during "adverse" conditions. Bacterial flux in these soils under adverse conditions has not been determined.

A. Problem Statement

Glaciation in many areas removed much of the existing soil cover leaving steep mountain slopes with bedrock surfaces and valley floors filled with morainal and outwash sediments. Fluvial processes on the valley floors caused these sediments to be reworked. These dynamic processes removed much of the finer sediment leaving numerous paleochannels within terrace and valley floor deposits. These coarse-grained paleochannels, usually masked on the surface, have often served as groundwater sources. The characteristics that make them good groundwater sources, such as proximity to the surface, recharge potential, and apparent specific yield, are those which also make them easily contaminated and difficult to control.

Soil development on mountain slopes is slow. There is a natural downslope movement of surface sediments, so the development, depth, and fertility of soils on mountain slopes is often severely limited. Often the soil has a

preponderance of coarse fragments resulting in an excess of large pores that tends to be droughty (Williams et al., 1978). Beneath this veneer of surface litter and soil is fractured bedrock or a thick layer of macro-crystalline gravel ("grus") overlying the fractured bedrock below (Mueller, 1979).

On-site wastewater systems placed in these environments are designed and installed with the assumption that most pathogenic organisms will not pass unaltered through an unsaturated zone located below each system. Estimated seasonal fluctuations of the water table are to be incorporated in all designs.

The presence of an unsaturated, aerobic zone is essential to bacterial die-off and to minimal movement of microorganisms (Carlile, 1983). Because intestinal microorganisms survive best under anaerobic conditions and die off rapidly when competing with aerobic organisms, any conditions that cause saturated soil near leachfield trenches increase the potential for survival of intestinal microbes. The result is a greater probability of transport to the groundwater (Carlile et al., 1981).

That saturated or near saturated conditions aid in bacterial transport and survival is a well documented concept (Olivieri, 1983; Reneau et al., 1975; Hagedorn et al., 1978) and others have commented on the major distances traveled by indicator organisms after rainfall events--usually the result of a rainfall elevated water table.

Stenstrom and Hoffner (1982) suggested that dosing with large volumes of low ionic strength water (such as rain water) aided in microorganism transport. Bacterial movement at rates of 1 m/h to more than 10 m/h has been recorded (Rahe et al., 1978; McCoy and Hagedorn, 1980; Allen and Morrison, 1973).

Transport of most contaminants can be effectively limited by a good soil profile of sufficient depth with adequate amounts of clay, silts, fine sands and organic matter (Gerba et al., 1975). Studies have shown that 0.6 m to 1.2 m (2 ft to 4 ft) of unsaturated soil below a septic tank drainfield is sufficient to remove bacteria and viruses; greater depths are necessary for coarse, permeable soils (Otis et al., 1980; Hagedorn et al., 1981; Nichols et al., 1983).

Many states have adopted standards establishing a minimum soil depth to bedrock or the highest level reached by the water table for installation of a septic tank-leachfield system (Baker, 1978). These standards are chosen with little information regarding the maximum depth of unsaturated soil necessary for proper treatment under the range of environmental conditions that may occur at a particular site (McCoy and Hagedorn, 1979).

Although regulations vary from state to state, most require soil percolation rates greater than 3 cm/h (60 min/in) and less than 30 cm/h (5 min/in) and 1.2 m (4 ft) depth

between the bottom of the leachfield trench and bedrock high water table.

The choice of 1.2 m (4 ft) depth below the leachfield was not the result of scientific study. After World War II, the U.S. Federal Housing Authority (FHA) suffered major financial losses through mortgage defaults when people vacated houses with malfunctioning septic tank-leachfield systems. With the U.S. Public Health Service (USPHS), the FHA launched investigations into septic tank practices. The investigations began in the mid-1940's and ended in the early 1960's with the publication of the Manual of Septic Tank Practices by the USPHS. During the early USPHS field studies, investigators found houses with troubled systems were often located in sub-surface drainage swales or topographic basins. Evidently local practices failed to identify trouble spots. The investigators chose a depth of 1.2 m (4 ft) above the seasonal high water table elevation, hoping that fewer incorrect placements would occur (Winneberger, 1984). The 1.2 m (4 ft) depth became embedded in the literature. Subsequent research efforts were directed toward validating the existing regulation, rather than investigating its validity.

B. Objectives

Little is known of the transport of pathogenic, copiotrophic bacteria in coarse soils below on-site leachfields located in mountainous and poor soil

environments thought to be oligotrophic. (Note: Copiotrophic bacteria require high nutrient concentrations, while oligotrophic bacteria can survive and reproduce in low nutrient concentrations. Further elaboration on the concepts of oligotrophy and copiotrophy can be found in Appendix A.)

There has been no scientific verification that 1.2 m (4 ft) of coarse soils is adequate to remove pathogenic bacteria leaving on-site systems.

The objectives of this study are to:

1. Develop a state of the art mathematical model of bacterial transport of copiotrophic bacteria in a oligotrophic, coarse-grained soil environment.
2. Determine, using the bacterial transport model and Monte Carlo simulation procedures, whether 1.2 m (4 ft) of soil depth is adequate for removing fecal coliform bacteria during extreme rainfall events.
3. Provide management or regulatory guidelines for those conditions where water contamination is expected.

C. Scope

The governing hypothesis of this research is that under the influence of adverse rainfall events commonly occurring in the spring, fecal coliform bacteria leaving on-site

wastewater leachfield trenches will travel beyond the 1.2 m depth in coarse soils.

Computer, model, and time constraints require numerous assumptions and simplifications. Many of these are noted in this section and explained in Appendix B.

Coarse soils will be defined as sand and loamy sand as determined from the U.S. Department of Agriculture soil texture triangle (Cosby et al., 1984).

Both rainwater and wastewater will be delivered simultaneously at a hypothetical surface at the base of a leachfield trench. The wastewater load will be 5 cm/d (0.208 cm/hr). The design storms are the 100 yr-6 h (9 cm) storm and the 10 yr-6 h (6.4 cm) storm.

Soil water flow is assumed to be one-dimensional in the vertical direction. Hysteresis is not considered nor is the presence of macropores. The water table is located at 150 cm depth.

Only fecal coliform bacteria transport is simulated. Inherent error in mean wastewater bacterial concentrations and sampling procedures is assumed. The potential ramification on human health as a result of water contamination is beyond the scope of this study.

The development of a biological clogging layer in the leachfield trench/soil interface and its impact on bacterial activity and soil physical properties are not addressed.

II. RATIONALE FOR MONTE CARLO ANALYSIS

The physical and chemical properties of soil are not constant in a natural environment. The soil hydraulic properties that are controlled by the physical and chemical properties of a field soil will vary spatially and temporally. This variability is irregular and imperfectly known. As a result, the assumption of soil homogeneity commonly applied to small laboratory columns is inapplicable to field situations (Russo and Bresler, 1982; Bresler and Dagan, 1981)

Because the soil hydraulic properties are subject to uncertainty, they can be treated as random variables and be defined in terms of their statistical moments (Philip, 1980; Dagan and Bresler, 1983). These soil hydraulic properties are not completely disordered (statistically independent) in the field, so, ideally, their statistical description should incorporate the spatial structure of the properties (Russo and Bresler, 1981a). Therefore, each soil hydraulic property should be characterized statistically by a probability density function and by an autocorrelation function expressing the rate of loss of correlation of variables between any two points of given vector separation (Philip, 1980; Russo and Bresler, 1981b).

If soil hydraulic properties are treated as random variables, the soil water and bacterial transport processes, governed by these hydraulic properties are considered stochastic processes. The parameters used to describe soil water and bacterial transport are also considered random variables, each characterized by a probability density function and autocorrelation function. To account for the correlations between the soil hydraulic properties and their mutual impact on soil water and bacterial transport, a multivariate normal density function can be developed. This function can then be used to generate parameter values.

Bacterial population dynamics are also governed by stochastic processes. The factors that affect the growth (and death) of microorganisms such as ambient environmental variables, parasitism, competition, predation, and availability of food also vary spatially and temporally.

The stochastic nature of microbiological population dynamics is apparent if one accepts the "concept of discrete microhabitats" presented by Stotzky (1974). This concept is derived from the fact that soil is heterogeneous, discontinuous, and dominated by a solid phase of varying sized particles. The variability and discontinuity in particle size results in soil being a composite of numerous small microbial communities each with its own ambient environment. These particles form aggregates with water surrounding each aggregate and forming bridges with adjacent aggregates. Given the presence of discrete microhabitats,

it is possible to accept the concept of the diversity of microhabitats, and by extension, the variability in the microbial composition between even adjacent microhabitats. The physical and chemical characteristics will differ between microhabitats and the types of microbes entering and persisting will vary. The parameters commonly used to describe microbial activity, such as the Monod and die-off coefficients, will also vary. There is spatial dependence, but one parameter value cannot be applied throughout a heterogeneous field. The parameters are random variables.

Accurately modeling a complex, heterogeneous soil environment would require a large number of samples taken over time. Because this is impractical, simplification is necessary.

A major simplification is to assume parameters are stationary--the mean and variance do not vary with time (Andersson and Shapiro, 1983). Multivariate density functions are complex and require numerous parameter values. To simplify, multivariate density functions can be reduced to univariate density functions. As an example, the multivariate parameter distribution of the four parameter Smith-Hebbert (1983) hydraulic conductivity function specifying the relationship between hydraulic conductivity and water content can be reduced to a univariate parameter distribution. This is accomplished by assuming that only saturated hydraulic conductivity is spatially variable, while the other three parameters (saturated water content,

residual water content, and lambda) are constant. The assumption is that the variability of saturated hydraulic conductivity over a vertical field is greater than with the other soil water parameters. Previous statistical analysis (Russo and Bresler, 1982) indicated that the variability of these soil water parameters is limited (Dagan and Bresler, 1983). By assuming that one probability density function for a specific variable will describe the variation in the vertical field, one removes the complexity of a probability density function for each point in the field.

The noted assumptions allow the soil to be described as homogeneous and non-uniform. The medium is homogeneous because a monomodal probability density function characterizes a random variable, as opposed to a multimodal distribution. Non-uniformity implies a distribution of parameter values as opposed to one value.

When working with a natural system, the inherent physical, chemical, and biological variability would suggest the need for long-term monitoring to obtain reliable estimates of soil water movement and bacterial transport. A valid alternative to monitoring is a Monte Carlo simulation (Haith, 1985). Monte Carlo simulation "is used to solve problems which depend in some important way upon probability--problems where physical experimentation is impracticable and the creation of an exact formula is impossible. The Monte Carlo method tries to use probability to find an answer to a physical question (McCracken, 1955)."

Monte Carlo simulations are often employed to analyze the effects of random disribution of soil properties on the hydrologic performance of a specific system (Smith and Hebbert, 1979), be it a watershed or a hypothetical soil column. Typically, a large number of Monte Carlo runs are completed for each situation being analyzed. For each run the parameters and sometimes the boundary conditions are chosen from probabilistic distributions. Therefore the output variables are also probabilistic distributions that reflect the uncertainties of the system being modeled (Freeze, 1975; Dettinger and Wilson, 1981; and Haith, 1985). A Monte Carlo simulation is actually a special type of sampling because it is performed on a model instead of a real life object (Kleijnen, 1974). Monte Carlo simulations have been applied in numerous porous media studies by several authors, including Warren and Price (1961), Freeze (1975), and Smith and Freeze (1979).

In this study a soil water transport model is coupled to a bacterial transport model. Specific model parameters are randomly generated using a procedure known to produce either a normal or log-normal distribution of random numbers. Numerous simulation runs are completed, and the resulting output is used to generate a cumulative frequency distribution.

III. THEORETICAL BACKGROUND

A. Soil Water Transport

The mass balance equation for soil water transport in the vertical direction, assuming no soil water source or sink, is

$$\frac{\partial \theta}{\partial t} = - \frac{\partial q_w}{\partial z} \qquad \text{(III.1)}$$

where

θ = volumetric water content (L^3/L^3)

q_w = soil water flux (L/T)

z = depth in soil, positive downward (L)

t = time (T)

Soil water flux is proportional to the hydraulic gradient and is described by Darcy's Law

$$q_w = - K \frac{\partial H}{\partial z} \qquad \text{(III.2)}$$

where

K = hydraulic conductivity (L/T)

H = hydraulic head (L).

Hydraulic head is a combination of the gravitational head, z, and pressure head, h. The gravitational head is taken as negative below the reference elevation (soil surface). Therefore

$$H = h - z \qquad \text{(III.3)}$$

Assuming $\theta = \theta(h)$, the combination of equations (III.1), (III.2), and (III.3) results in the well known pressure head form of the Richard's equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z} \qquad \text{(III.4)}$$

If the relation between θ and h is known, one may apply the chain rule to the left side of equation (III.4)

$$\frac{\partial \theta}{\partial t} = \frac{d\theta}{dh}\frac{\partial h}{\partial t} = C(h)\frac{\partial h}{\partial t} \qquad \text{(III.5)}$$

where

C(h) = specific capacity (/L)

The specific capacity of a soil represents the change in volumetric water content per incremental change in pressure head.

Combining equations (III.4) and (III.5) results in

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] - \frac{\partial K(h)}{\partial z} \qquad \text{(III.6)}$$

This is the governing, one-dimensional, partial differential equation for both unsaturated and saturated flow in layered soils.

The pressure head form of the Richard's equation is preferable to the diffusivity form [$h=h(\theta)$]. In saturated systems or where $d\theta/dh$ tends to 0, the diffusivity becomes infinite. In cases of mixed saturated and unsaturated flow (non-uniform flow), the pressure head equation must be used (Klute, 1969).

There is ample evidence in the literature of the validity of the Richard's flow equation under various boundary and initial conditions (Selim et al., 1983).

B. Bacterial Transport

Bacterial transport in soil is a function of many complex and dependent factors. It is influenced by the specific bacterial species of interest, and by the variables affecting the viability of that species such as moisture, temperature, food supply, and competition with or inhibition by other microbial species. Bacterial transport is influenced by the length of wet and dry periods as well as their intensity and by the rate of soil water flow which is a function of head (Crane and Moore, 1984).

Studies of bacterial transport and contamination from on-site systems in saturated and unsaturated soils have been reviewed by Hagedorn et al. (1981) and Canter and Knox (1985). Most studies involved the passage of bacteria through fine-grained soils over distances of 0.8 to 15 m. The results indicate slow rate of movement and fairly rapid attenuation of effluent bacteria (Sinton, 1986). Few of the studies considered the special nature of the physical and chemical environment; few considered the biological processes influencing transport.

Few mathematical models of bacterial transport in soils have been reported. Matthess and Pekdeger (1981) and Corapcioglu and Haridas (1984 and 1985) have presented

deterministic microbial transport models. Jang et al. (1983) used a first order rate equation to predict bacterial removal in sandstone.

Matthess and Pekdeger (1981) provide a conceptual model for bacterial transport in groundwater using the equation of hydrodynamic dispersion provided by Bear (1972). No solutions were provided. Corapcioglu and Haridas (1984 and 1985) developed governing equations for bacterial transport and fate, and an analytical Laplace transform solution, and a Galerkin finite element solution. The models of Matthess and Pekdeger (1981) and Corapcioglu and Haridas (1984 and 1985) consider many of the processes included in the mathematical model presented below. The processes, and the importance given to each, differ with each model. The application of the models is dissimilar as well.

Jang et al. (1983) studied bacterial transport in sterilized sandstone cores. They determined a clean bed filter coefficient by measuring effluent concentration and back-calculating, using a first order rate equation. Processes involved in bacterial removal were not analyzed.

Filtration studies using deep-bed porous media filters have been reported over the years. Data from these studies are not directly applicable to groundwater and soil water flow conditions, although some of the concepts are useful. Flow velocities in fluidized beds are often greater than 100 m/d. Soil water flow velocities are usually one or two orders of magnitude less (McDowell-Boyer et al., 1986).

Filter media are uniform in size, often uniform in shape, and often of man-made material.

1. Governing Equations

The conservation equation for transport of bacteria in the vertical direction is

$$\frac{\partial \theta C}{\partial t} + \frac{\partial \rho C_a}{\partial t} = - \frac{\partial q_b}{\partial z} \qquad \text{(III.7)}$$

where

C = concentration of suspended bacteria per unit bulk volume of soil ($/L^3$)

C_a = concentration of adsorbed or strained bacteria per mass of soil ($/M$)

q_b = flux of bacteria ($/L^2\ T$)

ρ = mass of soil per unit bulk volume of soil (bulk density) (M/L^3)

The conservation equation for suspended bacteria is

$$\frac{\partial \theta C}{\partial t} = - \frac{\partial q_b}{\partial z} + G_{su} \qquad \text{(III.8)}$$

where

G_{su} = source/sink term for suspended bacteria ($/L^3\ T$)

Within the continuum of interest, bacteria are subject to growth, decay, and removal by particle surfaces (adsorption and straining). Thus

$$G_{su} = - G_a + f(su) \qquad \text{(III.9)}$$

where

G_a = source/sink term for adsorbed/strained bacteria ($/L^3$ T)

f(su) = functions accounting for growth and decay of suspended bacteria ($/L^3$ T)

For adsorbed/strained bacteria,

$$- G_a = \frac{\partial \rho C_a}{\partial t} + f(a) \qquad \text{(III.10)}$$

where

f(a) = functions accounting for growth and decay of adsorbed/strained bacteria ($/L^3$ T)

The conservation equation for adsorbed/strained bacteria assumes reversible equilibrium. Bacterial release and retention to particle surfaces occur simultaneously.

Combining equations (III.8), (III.9), and (III.10) results in the governing equation for bacterial transport

$$\frac{\partial \theta C}{\partial t} = - \frac{\partial q_b}{\partial z} + f(su) - \frac{\partial \rho C_a}{\partial t} + f(a) \qquad \text{(III.11)}$$

To account for growth and death of the suspended bacteria,

$$f(su) = \mu_g \theta C \frac{1 - C/C'}{1 - C/C''} - \mu_p \theta C \frac{P}{K + C} - k_d \theta C \qquad \text{(III.12)}$$

where

μ_g = parameter related to growth velocity (/T)

μ_p = predation rate constant (/T) (assimilation rate constant, related to metabolic demand of predator)

C' = maximum bacterial concentration allowed by a limiting nutrient supply ($/L^3$)

C'' = parameter related to the amount of nutrient and its uptake efficiency by an organism (units of bacterial concentration) ($/L^3$)

C'/C'' = efficiency of nutrient uptake, 0 to 1

k_d = specific die-off rate constant ($/T$)

P = predator concentration ($/L^3$)

K_p = predation efficiency constant (units of prey concentration) ($/L^3$)

(Cui and Lawson, 1982; Cui et al., 1984; Cui and Lu, 1985).

The three terms in equation (III.12) represent growth, predation, and starvation leading to death, respectively. The derivation of the the growth ("Cui") equation from the Monod form of the Michaelis-Menten equation is given in Appendix C.

The Cui equation attempts to explain the relationship between population increase and limiting resources. The population dynamics of oligotrophic and copiotrophic bacteria are often analyzed using the Monod saturation constant, K_s. The value of the saturation constant is indicative of the ability of an organism to utilize a resource (the "affinity" for the nutrient). Oligotrophic bacteria tend to have high affinity and low specificity for nutrients, while copiotrophs have low affinity and high specifity for nutrients. Saturation constant values for

oligotrophs are low relative to the high values for copiotrophs (Cui and Lawson, 1982 and Poindexter, 1981).

When the value of K_s is small, C'/C" approaches 1, and the nutrient uptake efficiency of an organism is high. When the value of K_s is large, C'/C" approaches 0, which indicates that bacterial growth is restricted by limited nutrient availability. When the total amount of nutrient that can be utilized by the bacterial population, S_m is large, then C'/C" approaches 1, and nutrient uptake efficiency is high. When S_m is limited, C'/C" is much less than 1, and a longer time is required for population increase (Cui et al., 1984). When C'/C" approaches 1 and growth is not restricted, the growth curve approaches an exponential form. When C'/C" approaches 0 and growth is nutrient-limited, the growth curve approaches a logistic form (Cui and Lawson, 1982 and Cui et al., 1984).

The second term in equation (III.12) is a sink term for predation. Its form is also similar to the Monod equation. The predation efficiency constant relates to the efficiency of prey utilization by a predator. It is function of two parameters

$$K_p = {}_u{}_p / v_p \qquad \text{(III.13)}$$

where

v_p = capture rate constant (L^3/T)

A low capture rate constant and a high assimilation rate constant would mean large K_p. This would imply that predatory activity would have a noticeable impact on the

bacterial population. Low K_p means the specific predator requires only a low density of prey (a low demand for prey) (Cui and Lu, 1985).

The second term in equation (III.12) is limited in application because a set of parameters is required for each predator and a set of equations is required for growth and death of each predator. The equation is useful in general terms for system analysis.

The third term in equation (III.12) is a sink term for starvation and death, both of which connote a degenerating state for the bacterial population as a whole and are a function of nutrient availability. It is impossible to account for the varying metabolic state of each individual organism. It is assumed that aging and decay are occurring in the population. Starvation and decay imply permanent removal from the population.

The equation for bacterial flux is

$$q_b = - D_d \theta \frac{\partial C}{\partial z} - D_b \theta \frac{\partial C}{\partial z} + q_w C + q_s C - \mu_m \theta \frac{\partial C}{\partial z} + \mu_c (s) C \frac{\partial s}{\partial z} \quad \text{(III.14)}$$

where

D_d = mechanical dispersion (L^2/T)

D_b = Brownian diffusion (L^2/T)

q_w = soil water flux (L/T)

q_s = sedimentation (gravitational) flux of suspended bacteria (L/T)

μ_m = random motility coefficient (L^2/T)

$\mu_c(s)$ = chemotactic coefficient $(L^2/T)/s$

(represents the strength of the chemotactic movement caused by a unit chemical concentration gradient)

s = nutrient concentration (M/L^3).

(Corapcioglu and Haridas, 1984; Lauffenberger et al., 1982; Lauffenberger et al., 1984; and Rosen, 1983b)

2. Bacterial Transport Processes in a Competitive Environment

The environment of interest in this study is one of coarse-grained soils and oligotrophic bacteria into which copiotrophic, enteric bacteria are introduced. These coarse-grained, partially weathered soils, typically found in mountains of the West, are likely to be nutrient-limited. These soils are young in age and are coarse-grained because of limited chemical and physical weathering.

Fahey and Knight (1986) and Yavitt and Fahey (1986) reported that in lodgepole pine ecosystems (typical of mountain regions in the West), most nutrients were assimilated in the surface layers of the soil. Soluble organic compounds had a short residence time in the forest floor.

These mountain soils are probably deficient in organic matter. The limited nutrients available for bacteria living at depths below 1 m would be those that leached from the surface soil.

Copiotrophic, enteric bacteria introduced into this environment would be at a competitive disadvantage. For them to persist in these coarse-grained soils they must be able to tolerate abiotic stresses, to maintain viability in the absence of nutrients, and to coexist with antagonists (Liang et al., 1982). [NOTE: Bacteria are viable "if they demonstrate the ability to reproduce on agar plates with nutrients" (Kurath and Morita, 1983)]. Bacteria which survive have the potential of being transported great distances.

Several factors tend to facilitate or restrict bacterial transport through these soils. These factors include growth, starvation, death, filtration, predation, sedimentation, diffusion, motility and chemotaxis, dispersion, and advective flow. The importance of each of these on bacterial transport and on the governing equations of bacterial transport will be discussed in the sections that follow.

a. Growth, Starvation, and Death

To survive, bacteria must compete successfully for nutrients. Each bacterial species has its threshold of nutrient requirement which governs its ability to reproduce, become dormant, or die (Morita, 1982). Crane and Moore (1984) suggest that the major reason for bacterial die-off in a foreign environment is the inability of the introduced organisms to lower their metabolic requirements in a situation of lower nutrient availability. If the bacteria

lack nutrient reserves or lack the ability to enter a resting state, they starve to death.

A first postulate of this paper is that these coarse-grained soils beneath leachfield trenches are nutrient-limited, specifically carbon-limited, for copiotrophic bacteria.

Research indicates that activated sludge, trickling filter, oxidation ditch, and irrigation ditch pond effluents derived from domestic wastewater are carbon-limited for microbial growth (Jenkins and Richard, 1982 and Moore et al., 1981).

Viraraghavan (1976) found a 78% reduction in soluble organic carbon (SOC) to 105 mg/l between the influent and effluent ports of septic tanks. Viraraghavan and Warnock (1976) found a 75 to 90% reduction in SOC between the effluent port of a septic tank and a soil lysimeter sampling point located at 1.07 m depth (42 cm below an experimental drainage pipe). The approximate SOC ranged from 2.4 to 47.5 mg/l . Thomas and Bendixen (1969), using 0.9-m lysimeters filled with silica sand, found that 14% of the organic carbon passed through the sand in the liquid percolate, 9% remained in the sand as an undegraded residue, and 77% of the organic carbon applied was degraded. Namkung and Rittmann (1986) reported that 85% of the effluent SOC from biological treatment processes contained soluble microbial products, while the remainder was residual influent substrate, and non- or slowly biodegradable organic

materials. They indicated that the soluble microbial products were mainly high molecular weight organic compounds rather than low molecular weight organic compounds.

Some macromolecules are hydrolyzed slowly under the action of extracellular enzymes. Such molecules may be considered recalcitrant. The organic carbon in these molecules would be unavailable for utilization by bacteria (Button, 1985). One may note that glucose (a low molecular weight compound) is a preferred carbon and energy source for growth of enteric bacteria (Harder et al., 1984).

It is reasonable to assume that the soil beneath a leachfield trench is carbon-limited for copiotrophs. The nutritional situation in the soil would be more analogous to a nutrient-limited continuous culture than to a batch culture where cells would grow at maximum specific growth rates (Gray and Williams, 1971). In this carbon-limited environment, oligotrophs that do well at low substrate concentrations would have a selective, competitive advantage over enteric copiotrophs adapted to growth at higher nutrient levels (Jannasch, 1967; Klein and Casida, 1967; Poindexter, 1981; and Pfennig, 1984). Bacterial cells placed in this nutrient-limited environment would be subject to the stress of starvation, and they would shift their metabolic activities away from biosynthesis and reproduction toward acquisition of energy for existing biological functions (endogenous metabolism or respiration)(Kurath and Morita, 1983).

Starving copiotrophic bacteria undergo a sequence of processes which lead to the production of a high number of small cells called "dwarfs" (Humphrey et al., 1983) or "ultramicrocells" (filterable bacteria-diameter less than .0003 mm)(Morita, 1982). Laboratory studies of the starvation/dwarfing process (Kjelleberg et al., 1983) indicate that dwarfing occurs over the first 4-5 h after introduction into a nutrient limited environment. The process is divided into two distinct phases--(1) fragmentation [division without growth (Kjelleberg and Hermansson (1984)] , which results in an increase in cell numbers during the first 1 to 2 h, and (2) continuous size reduction of the fragmented cells, but no further increase in numbers.

Novitsky and Morita (1976) provided an indication of the potential increase in cell numbers during starvation. They subjected marine vibrio cells to an organic-nutrient-free solution and noted that during the first week of exposure to starvation, the number of viable cells increased. After the first week, the number of cells countable by microscopy remained at a high level, but the viable count dropped. They noted an increase of up to 400% in cell numbers during the first week. The increase in cell number apparently was dependent on the initial concentration. The lower the number, the higher the percentage that survived (Morita, 1982). Kurath (1980) noted that the viable population dropped to 0.1% of the

initial population after 25 days. It is quite apparent that the number of viable cells dropped off rapidly.

During the period of size reduction there is little or no metabolic activity, but there is a slow loss in viability. Dawson et al. (1981) found endogenous respiration of washed lag-phase bacteria was about 150 ng atoms oxygen/10^9 viable cells/min . Taking this value as 100%, the oxygen consumption rates for 5 h-, 5 day-, and 8 day-starved bacteria were 59, 6, and 4%, respectively. The size reduction of the dwarfs was up to 39% after 22 h (Kjelleberg and Hermansson, 1984). Novitsky (1977) calculated the volume of a starved cell to be .09 of the volume of a non-starved cell. A distinction should be made between cells becoming small as a result of aging and those becoming small from starvation. Dawson et al. (1981) reported half-lives of 68 h for starved cells but only 18 h for aged cells.

Although the formation of and the increase in number of small cells during starvation apparently is a regular feature of marine copiotrophs (Dawson et al., 1981 and Kjelleberg et al., 1982), whether the same process occurs with aquatic copiotrophs in a nutrient-limited soil environment is uncertain. The assumption in this study is that the processes are similar in both environments, although the extent of cell reduction and increase in cell numbers may be reduced in the soil.

Ensign (1970) provided a comparison of half-life starvation times for several oligotrophic (O) and copiotrophic (C) bacterial species in a nutrient-limited medium, as shown in Table III.1.

Table III.1. Comparison of the half-life starvation times for several bacterial species.

ORGANISM	50% SURVIVAL TIME (h)
Streptococcus sp. (C)	30
Escherichia coli (C)	36
Pseudomonas aeruginosa (C)	84
Arthrobacter sp. (O)	1680

The growth rate for arthrobacter is considerably slower than that of many of their natural competitors (Ensign, 1970), but they are better adapted to utilizing the limited nutrients that are available. In a nutrient-limited environment, copiotrophic bacterial growth may cease.

In addition to reduction in cell size and increase in cell number, bacteria subject to starvation conditions generally show an increase in cell hydrophobicity (Rosenberg and Kjelleberg, 1986)(see Appendix D) . Associated with this increase in hydrophobicity is an increased potential for adsorption. Adsorption may be viewed as a "tactic in starvation survival"(Dawson et al., 1981). Studies (Harvey and Young, 1980 and Kirchman and Mitchell, 1982) indicate that attached bacteria were more metabolically active than their free-living counterparts. There is evidence that nutrient availability to bacteria at surfaces can differ

from that of the bulk fluid (Fletcher and Marshall, 1982)(see Appendix D). Studies (Kjelleberg and Hermansson, 1984) suggest that some copiotrophic bacteria can increase their hydrophobicity during starvation.

Small, starved bacteria respond immediately to nutrient-enriched surfaces (Kjelleberg et al., 1982). Fresh surfaces may be colonized by small starved copiotrophs. Once provided with adequate nutrients, these small starved bacteria return to their normal size (approx. .001 mm in diameter) before cell division occurs. Hendricks (1974) found that enteric bacteria adsorbed to glass surfaces were more metabolically active than organisms in free suspension. Heukelekian and Heller (1940) showed that the growth of Escherichia coli at low carbon levels was possible only in the presence of a surface. Ellwood et al. (1982) found that bacteria with high affinity uptake systems might recognize molecules of the limiting nutrient concentrated at a surface.

In a natural soil environment, oligotrophic bacteria are probably established on particle surfaces. The particle surfaces are probably not nutrient-rich, although nutrients are likely to concentrate on these surfaces. Oligotrophic bacteria, not copiotrophic bacteria, have high affinity uptake systems (Poindexter, 1981). If a nutrient-rich environment were to develop, or if a nutrient pulse were to enter the system, utilization of those nutrients would be rapid. This would then lead to a nutrient-deficient

condition that would favor oligotrophs (Fletcher and Marshall, 1982). More likely, nutrient pulses would be utilized primarily by the oligotrophic and zymogenous bacteria (defined in Appendix A) because they probably have the enzyme capacity to adjust quickly, and because of their larger biomass. Copiotrophic bacteria would probably not have rapid enzyme production capability.

Tempest et al. (1983) concluded from ecophysiological criteria that, for microorganisms, the size of the genome must necessarily be kept to a minimum. This would support the idea that the genetic capability to produce both "high-geared" and "low-geared" enzymes is unlikely to occur in a single microorganism. The energy cost of enzymes for fast and slow catalysis in a nutrient-poor and nutrient-rich environment would be too high (Andrews and Harris, 1986). Copiotrophs with low substrate affinity and high substrate specificity are "low-geared" organisms. Data thus far obtained indicate that the bacteria which have the ability to survive long periods of time in the absence of appropriate substrate also have the "expensive protein synthesizing machinery" necessary for immediate use of any substrate that might be encountered in the natural environment (Morita, 1982). The bacteria with the competitive advantage are the "high-geared" oligotrophs.

This leads to the second and third postulates of this paper--(a) that based on the assumption of carbon-limited leachfield soils, the copiotrophic, enteric coliforms

introduced into these soils are subject to starvation, reduction in size, and possibly an increase in number, and (b) that these enteric coliforms are not competitive at soil particle surfaces because they do not have the necessary enzyme systems needed to compete with surface-attached oligotrophs in a carbon-limited soil environment.

As a result of the reduction of bacterial cell volume, potential increase in cell number, and reduced adsorptive potential, fecal coliform bacteria may have an increased probability of being transported with water flow in the coarse soil environment. This increased probability of transport assumes that most soil particle surfaces are colonized by indigenous oligotrophs. Copiotrophic, enteric bacteria would not be successful competitors for available nutrients that may exist at soil particle surfaces, because the nutrient concentrations would be inadequate to support copiotrophic bacterial growth.

An assumption of this thesis is that growth and death of copiotrophic, enteric coliform bacteria that are strained by or possibly adsorbed to soil particles are in equilibrium. Therefore, f(a) in equation (III.11) is equal to zero, and the governing equations for bacterial transport of copiotrophic, enteric coliform bacteria provide terms for growth and death of suspended bacteria only.

b. Predation

Bacteria in soil are subject to predation from other bacteria (myxobacter, streptomycetes, and numerous other soil bacteria such as Bdellovibrio), bacteriophages (host-specific viruses) and larger soil fauna such as protozoa and nematodes.

Protozoa and Bdellovibrio are the most numerous bacterial predators in most soils (Alexander, 1977 and Clarholm, 1981), while nematodes may be more limited in distribution (Yeates and Coleman, 1982). Protozoa and nematodes are ubiquitous in soils and are as much as 96% by weight of the soil microfauna (Overgaard-Neilsen, 1949; Anderson et al., 1978). Only a small proportion of nematodes are found with any frequency in soils where major decomposition activity is not common (Kuhnelt, 1976). The size of nematodes (0.3 to 2.5 mm) also limits their distribution (Freckman, 1982). As a result, their presence and growth is less in fine-textured soils than in coarse-textured, and their distribution in the soil reflects the distribution of organic matter (Yeates and Coleman, 1982).

Free-living protozoa are concentrated in surface litter in association with decaying vegetation (Stout, 1973) and in the rhizosphere where food is in ample supply (Clarholm, 1981). They are generally limited to pores with a diameter greater than .003 mm. (Darbyshire et al., 1985). Typical

soil protozoan predators are shelled and naked amoebae and ciliates.

Most ciliate species are specialized feeders of bacteria-sized food particles (.0002 to .001 mm in diameter) and they require high concentrations of food. Fenchel (1980) found that the minimum concentration of bacteria for sustaining growth of two species of ciliates--Colpidium campylum and Tetrahymena vorax--was around 10 cells/ml in the case of Escherichia coli. Ciliates are highly mobile compared to other protozoa, they have a short generation time, and they encyst (Fenchel, 1980).

Bdellovibrio are obligate aerobes (Dawes, 1976) whose prey is specifically gram-negative bacteria (Starr and Huang, 1976). The concentration of potential prey may be a limiting factor for Bdellovibrio. Bacterial cell densities as high as 10^6 cells/ml do not ensure the existence of Bdellovibrio (Varon et al., 1984).

Predators require a relatively large population of prey, yet the host population seldom drops below certain levels. Prey densities below which ciliates and amoebae will not multiply vary between 10^6 and 10^7 cells/ml (Fenchel, 1980; Anderson et al., 1978). Studies indicate that organisms introduced into soil often decline to a certain level, and the extent of the decline varies with the initial cell number (density-dependent). If the number added is greater than the steady-state level, the population declines to that level. If the adundance of added organisms is below

the steady-state level, there is little or no decline as a result of predation (Alexander, 1981).

It has been suggested that significant numbers of free bacteriophages will exist in soil only under circumstances that allow for large numbers of host cells (Reanny and Nash, 1973). As an example, Chao et al. (1977) found that lytic bacteriophages did not reduce Escherichia coli population density below 10^4 to 10^5 cells/ml.

Mallory et al. (1983) proposed that in an environment with two or more species, predators will eliminate one prey species when the second prey species concentration is above the threshold (steady-state) level, and the other species is not viable, or is growing at a rate less than the predation rate. They found that Salmonella typhimurium and Klebsiella pneumoniae died as a result of protozoan predation. Pseudomonas species were able to proliferate because they grew rapidly on the low level of nutrients present.

This presents a complicated scenario. Will the copiotrophic, enteric bacteria be eliminated in the soil environment as they were eliminated in the study of Mallory et al. (1983), or are the numbers of enteric bacteria sufficiently below the threshold value such that potential predators will not be stimulated? An important determinant is the variety and numbers of potential predators in the soil. The exact nature of predatory activity in most soils, including those below leachfields, is not known. No

literature on predators or predatory activity in leachfield soils was found.

c. Filtration (Straining and Adsorption)

Filtration in a coarse soil environment can be divided into two processes--straining and adsorption.

In straining, three processes can work independently or together depending on the soil particle size distribution and average pore volume size in the soil. These three processes are, (1) actual filtration by the solid matrix, (2) sedimentation of bacteria in the soil pores, (3) "bridging" where previously filtered bacteria reduce the permeability of the soil (Crane and Moore, 1984).

Hagedorn et al. (1981) suggested that straining of bacteria by soil particles was the main limitation to transport of bacteria in soil. Butler et al. (1954) concluded that removal of bacteria from a percolating liquid is inversely proportional to the particle size of the soil. Column studies using uniform spherical material indicate that straining occurred when the diameter of suspended particles moving through a medium was more than 0.2 times the diameter of particles of the medium itself (Bouwer, 1984). This would suggest that straining in coarse, sandy soils may occur at or near soil particle contact points.

If one were to determine a ratio between the diameter of the media and the diameter of the particle (bacteria)--dm/dp--the values would range from about 165 to 4000. This assumes a range of media particle sizes of 0.5

to 2.0 mm (the size range of coarse sands) and of bacteria sizes of .0005 to .003 mm. Sakthivadivel (1969) concluded that for a dm/dp ratio greater than 20, only 2 to 5% of the pore volumes were occupied by strained particles. Herzig et al. (1970) indicated little straining was expected for dm/dp greater than 12.

Particles that collect on porous media form a deposit which can alter water flow properties and decrease permeability (McDowell-Boyer et al., 1986). Sakthivadivel (1969) found permeability reductions were limited to 10 to 50% of clean media values. Note that his studies were with plastic particles in mineral oil. It would be very difficult to estimate in situ permeability reductions that were the result of strained bacteria.

While a straining mechanism is often mentioned as a cause of particle removal in groundwater and soil water flow environments, little quantitative analysis has been attempted (McDowell-Boyer et al., 1986).

Adsorption of bacteria to a soil surface can be a factor in restricting bacterial transport. Gerba et al. (1975) suggested that adsorption is important in soils that contain clay.

Bacterial surface changes may aid in adsorption. Bacterial hydrophobicity and adsorption potential were mentioned earlier and in Appendix D. Development of extracellular material, found to aid in adsorption, is energy intensive, yet Dawson et al. (1981) found that

dwarfing was accompanied by changes in the outer surface of bacteria, especially the appearance of bridging polymers. Stenstrom and Kjelleberg (1985) noted that the presence of fimbriae resulted in a higher degree of adsorption than with non-fimbriated bacteria. Fimbriae are filamentous appendages common to gram-negative bacteria (Pelczar and Reid, 1965). Whether they are present or maintained by starving coliforms in a soil environment is uncertain.

Empirical equations for determining virus adsorption constants have been developed based on the surface area of soils (Reddy et al., 1981; Enfield et al., 1976; and Zantua et al., 1977). These equations assume zero adsorption for soils with a clay content less than 18%. Gerba et al. (1975) suggested that adsorption was a greater factor with viruses than bacteria. Results from an investigation of bacterial adsorption to sand, silt loam, and clay show no adsorption to sand (Hendricks et al., 1979). Matthess and Pekdeger (1985) report that autochthonous bacteria (defined in Appendix A) are more likely to adsorb to particles while enteric bacteria show hardly any growth and should show minimal adsorption. They suggest that attachment (adsorption) is most intensive during the exponential growth phase. They inferred that because enteric bacteria show little growth, active attachment should be at a minimum. As postulated earlier in this paper, enteric bacteria may have an increased propensity for adsorption, but they may not

compete successfully for adsorption sites. It is assumed that most sites are colonized by oligotrophs.

Accepting these results allows one to suggest that adsorption of bacteria is limited in sand, loamy sand, and sandy loam soils. This assumption is made based on the clay content of these soils (Cosby et al., 1984). Straining is most likely the primary filtration process. The extent of straining in removing bacteria from suspension may depend on the potential reduction in size or the potential production of extracellular material by the coliform bacteria.

d. Sedimentation

Sedimentation or gravitational settling is important for the accumulation of inorganic mineral suspension (density about 2.5 g/cm^3), but not for microorganisms less than .005 mm in diameter size, with a density of around 1 g/cm^3 (Pekdeger and Matthess, 1983 and Yao et al., 1971). The gravitational velocity of a bacterial cell of .005 mm diameter is on the order of groundwater flow velocity (Corapcioglu and Haridas, 1984).

e. Motility and Chemotaxis

Motile bacteria are capable of self-propulsion, mainly by the action of flagella. Escherichia coli cells have flagella randomly distributed over the cell surface. The flagella, individually or as a bundle, rotate like a corkscrew causing forward motion (Berg, 1983). In a nutrient-rich laboratory culture, coliform bacteria may swim

as fast as 10 cm/hr (Rowberry et al., 1983). Most of the swimming movement is random in occurrence and direction, roughly analogous to Brownian motion (Berg, 1975). The swimming is mixed with tumbling (erratic behavior caused by a reversal of the direction of rotation or unbundling of flagella)(Berg,1983).

Random motility causes the dispersal of bacteria from areas of high density to areas of low density. This process would tend to cause net bacterial movement from regions of high nutrients to nutrient-poor regions (Lauffenburger et al., 1981).

Chemotaxis is a directional movement toward or away from higher chemical concentrations. Seymour and Doetsch (1973) suggested that while positive chemotactic responses may be of occasional value to bacteria under natural environmental condition; negative chemotactic responses nearly always develop toward lethal or hostile chemical gradients. Chet and Mitchell (1976) suggested that bacteria are chemotactically attracted to many chemicals, most of which could serve as nutrients. However, they also suggested that there was no correlation between the energy production of a particular substance and its ability to attract bacteria. Some organic compounds such as glycerol, gluconate, succinate, and fumerate are metabolized by, but not attractive to Escherichia coli. In other instances, these bacteria were attracted to compounds they could not metabolize.

Rosen (1983a) noted that Escherichia coli swim with a motion biased in the direction of increasing oxygen when placed in a medium with less oxygen than other vital substances. Mesibov and Adler (1972) noted that not all substrates transported by permeases would generate a chemotactic response in coliform bacteria. These studies would support the suggestions of Chet and Mitchell (1976).

One should note that nearly all motility and chemotaxis investigations are performed in the laboratory, not in situ. Whether coliform bacteria are motile in the natural soil environment, and whether it offers a competitive advantage is not known. There are significant energy requirements for production and maintenance of motility apparatus, and this could be significant in a low nutrient environment (Lauffenburger et al., 1981).

Purcell (1977) estimated the Reynolds number (ratio of inertial to viscous forces) in fluids near particles in unsaturated porous media to be on the order of 10^{-4}. The viscous forces would dominate. He estimated that the energy needed to move in this viscous environment was such that bacteria were better off remaining in one place, not searching for nutrients.

There is experimental evidence that bacterial motility and chemotaxis can affect the net bacterial flux in the presence of convective flow up to 2 cm/min (Lauffenburger et al., 1982). Again, this study was performed in a laboratory without soil. Starving coliform bacteria in soil

are unlikely to respond as they would in a laboratory culture. The relative impacts of random motility and chemotaxis are probably minor at a macroscopic scale.

f. Dispersion, Diffusion, and Advective Flow

Hydrodynamic dispersion is a function of diffusion, dispersion, bacterial motility, and the heterogeneity of the porous media (Matthess and Pekdeger, 1985). The equation for hydrodynamic dispersion is

$$D = D_d + D_b \qquad \text{(III.15)}$$

where

D_d = mechanical dispersion (L^2/T)

D_b = bacterial diffusion (L^2/T).

Bacterial diffusion is small relative to mechanical dispersion. Using the Stokes-Einstein diffusion equation (Cussler, 1984), the predicted value of the diffusion coefficient for an idealized bacteria of .001 mm in diameter, is on the order of $10^{-9} cm^2/s$. Fecal coliform are rod-shaped and range in size from .0005 to .003 mm in length (Zinsser Microbiology, 1984). The bacterial size and the small value for bacterial diffusion would suggest that bacterial diffusion is much less than mechanical dispersion, which is on the order of 10^0 to 10^1.

Mechanical dispersion should be treated in both the microscopic (pore scale) and macroscopic or megascopic (field scale) sense. At the microscopic scale mechanical dispersion is caused by three mechanisms--differential water velocities across a pore cross-section as a result of drag

at the boundaries, pore size differential along the water flow path, and the tortuosity or branching of the pore channels (Freeze and Cherry, 1979). One would need to measure the trajectories of individual parcels of water or particulates. This is impractical; therefore the system is typically treated as a continuum and viewed at the macroscopic or megascopic (field) scale. One attempts to account for heterogeneities in the porous media which cause variations in hydraulic conductivity and soil water velocities (McWhorter, 1983).

Dispersion, resulting from porous media heterogeneity, would cause bacteria to be transported at variable rates in different pores. Bacteria would tend to spread out laterally, and some bacteria would be transported at rates greater than the mean soil water velocity.

The equation for hydrodynamic dispersion, assuming no diffusion, is

$$D = \alpha v \qquad \text{(III.16)}$$

where

α = dispersivity (L)

v_w = soil water velocity (L/T).

Dispersivity is defined as the characteristic mixing length, an indication of the dispersion or spreading of bacteria carried by bulk flow (Anderson, 1979). It is usually very difficult to obtain realistic measurements of dispersivity, so it is often treated as an unknown and

determined during model calibration (Anderson, 1979), or it is chosen based on model stability criteria.

The validity of the hydrodynamic dispersion equation is a subject of great controversy. It is generally accepted as an empirical equation for laboratory studies of solute transfer through saturated soil columns. The equation seems to apply to unsaturated media as well, although dispersivity appears to be much higher than with saturated column studies (DeSmedt et al., 1986).

When dispersivity is underestimated, bacterial transport would be slower, and the concentration front would be sharper, more like plug flow. Higher dispersivity values would allow the bacteria to travel further, but the concentration front would be "smeared"--i.e. lower concentrations traveling greater distances.

Beese and Wierenga (1983)(in Sposito et al., 1986) have reviewed a number of laboratory and field studies which support the accuracy of the dispersion equation when applied to one-dimensional transport at water flow velocities greater than .01 m/d. Smiles et al. (1981) suggest 1.0 m/d as a lower bound. Velocities of this magnitude can be expected in coarse-grained soils.

Additional consideration to the problem of dispersivity is provided in Chapter IV - Numerical Solution Procedure.

The process by which bacteria are carried along with the bulk motion of the flowing water is advection (Freeze and Cherry, 1979).

3. Modifications of Bacterial Transport Governing Equations

Assuming that the impact of bacterial diffusion, sedimentation, random motility, and chemotaxis would be small relative to advective flow, these terms may be eliminated from the bacterial flux equation.

Combining equations (III.11), (III.12), and (III.14), accounting for growth and death of suspended bacteria only, and accepting the simplifications of the previous paragraph gives

$$\frac{\partial \rho C_a}{\partial t} + \frac{\partial (\theta C)}{\partial t} = \frac{\partial}{\partial z}\left[D\theta \frac{\partial C}{\partial z} \right] - \frac{\partial (q_w C)}{\partial z} - k_d \theta C + \mu_g \theta C \frac{1 - C/C'}{1 - C/C''} - \mu_p \theta C \frac{P}{K_p + C} \qquad \text{(III.17)}$$

The determination of the individual effects of adsorption and straining or clogging in an in-situ soil environment is extremely difficult. No attempt to differentiate between the two was made.

Expanding the derivatives of the first, second, and fourth terms of equation (III.17), assuming constant soil bulk density, and recognizing the equality given in equation (III.1), the transport equation becomes

$$\rho \frac{\partial C_a}{\partial t} + \theta \frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left[D\theta \frac{\partial C}{\partial z} \right] - q_w \frac{\partial C}{\partial z} - k_d \theta C + \mu_g \theta C \frac{1 - C/C'}{1 - C/C''} - \mu_p \theta C \frac{P}{K_p + C} \qquad \text{(III.18)}$$

Using the chain rule,

$$\frac{\partial C_a}{\partial t} = \frac{dC_a}{dC}\frac{\partial C}{\partial t} \qquad \text{(III.19)}$$

The graphical relation between C_a and C is referred to as an isotherm. The slope of the isotherm, dC_a/dC, represents the partitioning of bacteria between the solution and the soil matrix. The slope term is known as the distribution coefficient, k_{ac}. The equation

$$C_a = k_{ac} C \qquad \text{(III.20)}$$

is commonly referred to as the linear Freundlich isotherm. It is important to note that the distribution coefficient is valid only if partitioning reactions between liquid and solids are fast and reversible, and the isotherm is linear (Freeze and Cherry, 1979).

Using equations (III.19) and (III.20), and dividing both sides by , equation (III.18) can be simplified to

$$\left(\frac{\rho k_{ac}}{\theta} + 1\right)\frac{\partial C}{\partial t} = \frac{1}{\theta}\frac{\partial}{\partial z}\left[D\theta\frac{\partial C}{\partial z}\right] - \left(\frac{q_w}{\theta}\right)\frac{\partial C}{\partial z} -$$

$$k_d C + \mu_g C\frac{1 - C/C'}{1 - C/C''} - \mu_p C\frac{P}{K_p + C} \qquad \text{(III.21)}$$

If growth is thought to have limited impact on the bacterial population, and predation cannot be separated from population decrease due to starvation and death, the equation can be further simplified to

$$\left(\frac{\rho k_{ac}}{\theta} + 1\right)\frac{\partial C}{\partial t} = \frac{1}{\theta}\frac{\partial}{\partial z}\left[D\theta\frac{\partial C}{\partial z}\right] - \left(\frac{q_w}{\theta}\right)\frac{\partial C}{\partial z} - k_d C \qquad \text{(III.22)}$$

This equation was used for most simulations.

IV. NUMERICAL SOLUTION PROCEDURE

A. Numerical Solution Strategy

For purposes of numerical solution, the soil profile is treated as a hypothetical, one-dimensional soil column. This column is divided into 150 units or grids, each of which is 1 cm in depth. Each grid has an initial pressure head from which water content is determined. Each grid has an initial bacterial concentration of zero.

The transport equations, the hydraulic conductivity equations, the water content and capacity equations, the hydrodynamic dispersion equation, and the retardation equation are solved at each time step in each grid.

The initial values for the bacterial die-off coefficient, the bacterial distribution coefficient, the saturated hydraulic conductivity coefficient, and the initial input bacterial concentration are randomly determined at the beginning of the numerical simulation.

B. Parameter Generation

1. Input Random Variables

Four input parameters were randomly generated for the Monte Carlo simulations. The bacterial die-off coefficient and the bacterial distribution coefficient values were

assumed to have a normal distribution. The saturated hydraulic conductivity values and the input coliform concentration were assumed to have a log-normal distribution (Freeze, 1975 and Otis et al., 1975).

Normally distributed random numbers were generated using a pseudo-random number generator. The values are "pseudo" random numbers because they are generated deterministically (Rubinstein, 1981). The pseudo-random number generator is

$$X = \sigma \left[\sum_{i=1}^{12} r_i - 6 \right] + \mu \qquad \text{(IV.1)}$$

where

X = normal random number

r_i = uniform random number

μ = known sample mean of particular parameter being generated

σ = known sample standard deviation of particular parameter being generated

(Hartley, 1976)

Log-normally distributed random numbers were generated using

$$X = X_o + \exp(\mu + \sigma R_n) \qquad \text{(IV.2)}$$

where

X = log-normal random number

X_o = location parameter (lowest value, often set = 0)

R_n = normal random number

μ = mean of ln $(X-X_o)$ of sample (also called location parameter)

σ = standard deviation of ln $(X-X_o)$ of sample (also called scale parameter)

(Salas, 1983)

When the values of μ and σ were determined prior to log transformation of the data set, then one must determine the correct values of μ and σ to be used in the log normal random number generator. The location and scale parameters were determined using

$$\overline{X} = \exp\left(\mu + \frac{1}{2}\sigma^2\right) \qquad \text{(IV.3)}$$

and

$$s^2 = \exp(2\mu + \sigma^2)(\exp[\sigma^2] - 1) \qquad \text{(IV.4)}$$

where

$\overline{X}$ = known mean of parameter of interest

s^2 = known variance of parameter of interest

(Aitchison and Brown, 1957)

Solving for μ and σ results in

$$\mu = \ln \overline{X} - (\ln s^2 / 6) \qquad \text{(IV.5)}$$

and

$$\sigma = (\ln s^2 / 3)^{\frac{1}{2}} \qquad \text{(IV.6)}$$

These values are used in equation (IV.2) to generate a log-normally distributed value of either saturated hydraulic conductivity or the input concentration of bacteria.

Equation (IV.1) is used to generate normally distributed values of the bacterial distribution coefficient and die-off coefficient.

a. Bacterial Die-off Coefficient

Bacterial die-off is typically treated as a first order decay reaction. Literature data on the correlations of other models to die-off in soil-water systems are limited (Crane and Moore, 1986).

Reddy et al.(1981) and Crane and Moore (1986) report fecal coliform decay or die-off values ranging from .005/h to .028/h in the soil environment. Using the range of values provided by Reddy et al. (1981), a mean fecal coliform die-off value of .016/h was determined. Likewise, a standard deviation of .008/h was determined. These values were used in equation (IV.1) to determine a bacterial die-off coefficient for each simulation.

b. Bacterial Distribution Coefficient

The bacterial distribution coefficient represents the partitioning of bacteria between the solution phase and the solid phase. This partitioning would be accomplished by adsorption and straining. Research has not yet provided a means to determine relative contributions of all the processes influencing the distribution of bacteria between the solid and solution phases. In a field situation it would be impossible to determine if bacteria removal from the solution phase was the result of adsorption, straining,

predation, or normal death accompanied by cellular lysis. On theoretical grounds, one must recognize that the processes are different and separate.

Typically, the factor ($\rho k_{ac} / \theta + 1$) in equations (III.21) and (III.22) is referred to as retardation, R. Research on retardation of bacteria in soils is limited. Field studies have shown that values for the retardation factor range from 1 to 2 for Escherichia coli and Serratia marcesans (Matthes and Pekdeger, 1985 and Pekdeger, 1984). Solving the retardation equation for k_{ac} results in

$$k_{ac} = (\theta / \rho)(R - 1) \qquad \text{(IV.7)}$$

Therefore, for retardation between 0 and 1, k_{ac} ranges from 0 to θ_s / ρ .

Equation (IV.1) was used to generate a normal random number between 1 and 2. This value was used in equation (IV.7) to determine a distribution coefficient for each simulation.

c. Saturated Hydraulic Conductivity Coefficient

Saturated hydraulic conductivity was the only randomly generated parameter of the five parameters used in the soil water characteristic equation and the hydraulic conductivity equation.

Cosby et al. (1984) statistically analyzed soil samples from 35 localities in 23 states. Their regression studies of 14 sand samples and 30 loamy samples indicated saturated hydraulic conductivity means and standard deviations for sandy soils to be 16.79 and 5.08 cm/h, and

for loamy sand soil, 6.23 and 8.23 cm/h, respectively. Equation (IV.2) was used to generate a value of saturated hydraulic conductivity for each simulation.

d. Input Bacterial Concentration

Published reports of fecal coliform bacterial concentration in domestic wastewater are limited. Few have quantified bacterial concentrations at the pipe/soil interface.

Typically, one of two methods is utilized when sampling soil microbial populations. In one procedure, soil water leachate is collected, bacteria are enumerated. The populations are expressed as number of cells per milliliter of solution. In the second procedure, typically 1 g of soil is dispersed in 99 ml of buffer solution, then shaken or stirred (Brown et al., 1979). The bacterial abundance is expressed as number of cells per gram of soil.

Population counts can be estimated using any of several indirect or direct methods. Typical indirect methods are the dilution plate count method and the MPN technique (Doxtader, 1985). The AODC (acridine orange direct count) method is commonly used (Wilson et al., 1983).

Investigators often use only one enumeration procedure. A difference of several orders of magnitude may be observed between the direct (total) and indirect (viable) counting procedures. There are several reasons for this difference. The cells may be inactive in the natural state, they may grow too slowly to produce visible colonies, cells may be

inactivated by other cells in the vicinity, the cells may be inactive as a result of environmental stress, cells may adhere to sampling apparatus, and cells frequently occur as colonies in soils (Van Es and Meyer-Reil, 1982; Alexander, 1977). These colonies may not disintegrate when soil dilutions are shaken or stirred (Alexander, 1977), so the assumption that one cell forms one colony may not be valid (Doxtader, 1985).

These factors, and others, indicate that reported bacterial concentrations are subject to error which may be large, and the error is usually one of underestimation--possibly by several orders of magnitude.

Reported fecal coliform concentrations associated with on-site systems are variable. Brown et al. (1979) reported mean effluent concentrations of 11080 cells/ml solution. Reneau et al. (1975) reported a range of 240,000 cells/ml to <3 cells/ml solution in cases where septic effluent was coming to the surface without passing through any soil material. Reneau and Pettry (1975) reported fecal coliform concentrations up to 11000 cells/ml solution at 145 cm depth below a drainfield located in loamy sand soil.

Siegrist (1977) reported 94 fecal coliform samples from 5 septic tanks. The mean and standard deviation were 4210 cells/ml solution and 926.2 cells/ml, respectively. An E.P.A. (1978) study reported 151 fecal coliform samples from 7 septic tanks. The approximate mean and standard

deviation were 50000 cells/ml of solution and 20000 cells/ml, respectively.

Concentrations expressed as number of cells per milliter soil solution may be expressed as cells per cubic centimeter soil bulk volume if the soil water content is known or can be estimated. Concentrations expressed as cells per gram of soil may be expressed as cells per cubic centimeter soil bulk volume if the soil bulk density is known or can be estimated. The calculations are as follows:

$$\text{cells/cm}^3 \text{ soil bulk volume} = \theta * \text{cells/ml soil solution} \quad \text{(IV.8)}$$

where θ is volume of soil water per unit bulk volume of soil; and

$$\text{cells/cm}^3 \text{ soil bulk volume} = \rho * \text{cells/g soil} \quad \text{(IV.9)}$$

where ρ is the soil bulk density in grams per cubic centimeter soil bulk volume.

For this study, input bacterial concentrations of 4210 cells/cubic centimeter soil bulk volume (approx. 12200 cells/ml soil solution), 50000 cells/cubic centimeter soil bulk volume (approx. 145000 cells/ml soil solution), and 17250 cells/cubic centimeter soil bulk volume (50000 cells/ml soil solution) were used for sandy soils. These conversions were based on a saturated soil water content of 0.345. For loamy sand soils, assuming a water content of 0.41, the input bacterial concentrations were 50000 cells/cubic centimeter soil bulk volume (approx. 122000 cells/ml) and 4210 cells/cubic centimeter soil bulk volume

(approx. 10200 cells/ml). For stochastic simulations, an input bacterial concentration was generated using equation (IV.2).

2. Soil Water Characteristic Model

Soil water retention properties are described using the Brooks-Corey model (Brooks and Corey, 1964). The model has been widely used (McCuen et al., 1981). The Brooks-Corey model is

$$\theta(h) = [\theta_s - \theta_r] \left[\frac{h_d}{h}\right]^{\lambda} + \theta_r \qquad \text{(IV.10)}$$

where

θ = volumetric water content

θ_s = water content at saturation

θ_r = residual water content

h_d = displacement pressure head (L)

h = pressure head (L)

λ = parameter related to pore distribution.

Brooks-Corey parameters were optimally fitted to a water content-pressure head relationship for sand as reported in a study by Haverkamp et al. (1977). The Brooks-Corey model was then compared to the Haverkamp model of the pressure head-water content relationship. As shown in Table IV.1, the results from each model were similar.

Parameter values were chosen from the results of a statistical study reported by McCuen et al (1981). They analyzed 11 soil textural classes and provided mean values for soil water characteristic parameters for each class. Their results, based on 19 sand samples and 69 loamy sand

Table IV.1. Comparison of Haverkamp and Brooks-Corey Soil Water Properties Models.

Pressure Head	Haverkamp		Brooks-Corey	
	$\theta(h)$	$K(\theta)$	$\theta(h)$	$K(\theta)$
0	.287	34.0	.287	34.0
10	.286	32.5	.287	34.0
30	.222	3.56	.164	7.0
50	.124	.35	.122	.034
80	.084	.038	.101	.002
100	.079	.013	.094	.0005
120	.077	.006	.090	.0002
150	.076	.002	.087	.00007

Note: Pressure head units are -cm. Hydraulic conductivity units are cm/h.

samples, were as follows: for water content at saturation with sands and loamy sands, .345 and .41; for residual water content for sands and loamy sands, .016 and .024; for displacement head in sands and loamy sands, -15.78 cm and -9.71 cm; and for lambda in sands and loamy sands, .533 and .449. The value reported for lambda is very similar to the value (.58) reported by El-Kadi (1985).

The specific capacity, C(h), of equations (III.5) and (III.6) is determined by taking the derivative of equation (IV.10) with respect to the pressure head, h:

$$\frac{d\theta}{dh} = -\frac{\lambda}{h_d}(\theta_s - \theta_r)\left(\frac{h_d}{h}\right)^{\lambda+1} \qquad \text{(IV.11)}$$

Soil bulk density is assumed to be constant at 1.55 g/cm^3. Studies by Rawls and Brakensiek (1985) suggest soil bulk density values for sand and loamy sand range from 1.40 to 1.65 g/cm^3.

3. Hydraulic Conductivity Model

The soil hydraulic conductivity model is a modified form of the equation presented by Brooks and Corey (1964). It is based on extensive laboratory studies of porous media (Smith and Hebbert, 1983).

The Smith-Hebbert modification is

$$K(\theta) = K_{sh}\left[\frac{\theta - \theta_r}{\theta_s - \theta_r}\right]^{\varepsilon} \qquad \text{(IV.12)}$$

where

K_{sh} = hydraulic conductivity at saturation (L/T)

ε = parameter related to λ, where $\varepsilon = (2+3\lambda)/\lambda$

Values of K_{sh} were generated for various water contents using the optimized parameters in the Brooks-Corey soil water characteristic function mentioned above. These values were compared to those generated using the Haverkamp et al. (1977) soil water characteristic function and hydraulic conductivity function. The results were similar from pressure head of 0 to about -40 cm. After -40 cm they began to diverge. The Smith-Hebbert modification underestimated hydraulic conductivity at pressure head values of less than -30 cm. (See Table IV.1)

4. Dispersivity Coefficient

Dispersivity is scale dependent. Field tracer tests have shown that longitudinal dispersivity is not constant, but increases as the distance between the source and

observation point increases. At some point the dispersivity stops increasing. This increase of dispersivity with travel distance is the scale effect (Sudicky et al., 1983 and Molz et al., 1983).

The scale effect is accounted for in model stability criteria, which require that dispersivity be greater than or equal to 1/2 the grid size (Warner, 1986). Warner (1981) has shown that variation in the dispersivity value by a factor of 2 or 3 has little impact on the shape of breakthrough curves. Two simulations of the bacterial transport model with dispersivities varying by a factor of 10, are shown in Figure IV.1.

Bresler and Dagan (1981) suggest that the variability of dispersivity has little impact upon the statistical moments (mean, variance, etc.) of solute concentrations.

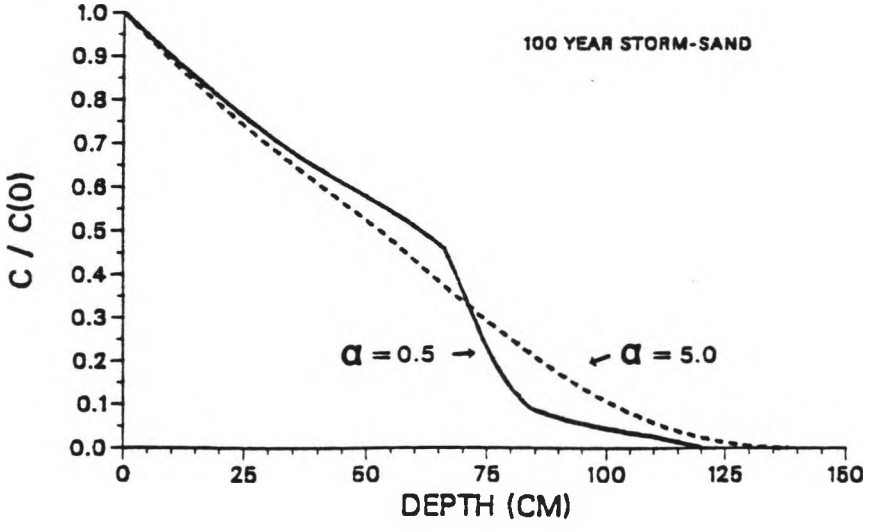

Figure IV.1. Comparison of bacterial transport simulations with dispersivities of 0.5 cm and 5.0 cm. C(0) = 50000 cells/cubic centimeter soil.

For this study a value of dispersivity of 0.5 cm, which is equal to 1/2 the grid size, is used. This will give greater weight to the convective flux.

Transverse dispersivity is not included in soil water flow in one dimension because only the z-component of pore water velocity is known.

C. Numerical Simulation Model

1. Initial Conditions

No fecal coliform bacteria are assumed to be present in the soil at the beginning of each simulation.

Initial soil water content is assumed to represent a state where gravitational water has drained. The soil water condition is static, therefore the initial pressure head distribution is the negative of the elevation head, with h=0 at the water table, located at 150 cm depth.

2. Boundary Conditions

For the soil surface the boundary condition is that of water flux

$$q(t) = -K(h)\frac{\partial h}{\partial z} + K(h) \quad \text{at } z = 0 \qquad \text{(IV.13)}$$

This is Darcy's equation in the vertical direction.

The boundary condition at bottom (z = 150 cm) is a water table. The soil is saturated at all times. Therefore the pressure head condition is

$$h = 0 \quad \text{at } z = 150 \text{ cm} \qquad \text{(IV.14)}$$

At the soil surface the bacterial concentration is treated as a constant prescribed source.

$$C = C_o \qquad \text{at } z = 0 \qquad \text{(IV.15)}$$

where C_o is the concentration at the soil surface.

At a defined depth, the bacterial concentration remains zero. Thus, the boundary condition at the bottom of the soil profile is

$$\frac{\partial C}{\partial z} = 0 \qquad \text{at } z = 150 \text{ cm} \qquad \text{(IV.16)}$$

3. Method of Solution

The soil water and bacterial transport equations are non-linear partial differential equations. They cannot be solved analytically, but approximate solutions can be obtained by numerical analysis. The method of solution of the transport equations was by an explicit-implicit finite difference approximation. The complete solution procedure is provided in Selim and Iskandar (1980). The stability and convergence criteria were satisfied at all times (Selim et al., 1983). A mass balance was maintained as a check on the numerical results (Selim and Iskandar, 1981). An expanded overview of the solution procedure is provided in Appendix E.

4. Model Verification

The soil water flux model used in this study is a modified version of the Selim-Iskandar model (Selim and Iskandar, 1980 and 1981; Iskandar and Selim, 1981; Selim et

al., 1983). The model was first used for transient, unsaturated flow by Selim (1978) and is a modification and extension of work originally done by Selim and Kirkham (1973). The model has been verified, validated, and used many times (Iskandar and Selim, 1981 and Selim et al., 1983).

The modified version of the model was verified under conditions of high flux rates at the surface, with data obtained from the Haverkamp et al. (1977) study. Optimized parameters in the Brooks-Corey soil properties functions were used, and a simulation was run at surface flux rates of 13.69 cm/h--rainfall rates in excess of those used in the study. The results of the simulation verified that the modified model produced good results at high flux rates. The model overestimated water movement at lower soil depths at early times--less than one hour. These results are comparable to those found by Iskandar and Selim (1981). They found that, "for the first 0.2 d the model somewhat underestimated the rate of water movement in the top soil layer, but overestimated it for the lower soil depths."

Verification of the bacterial transport model was confined to one data set because of limited information on bacterial movement in soils. Most field and column studies reported only input and output concentrations, and few provided specific information on soil physical properties.

A study by Dazzo et al. (1973) provided sufficient information to run comparative simulations. They applied

fecal coliform bacteria (2.4×10^5 cells/ml) in a cow manure slurry to a column of Scranton fine sand at a rate of 0.0298 cm/h (5 cm per week). After two weeks (336 h), samples were removed at several depths and analyzed for fecal coliform bacteria. Their results are shown--solid line connecting empty squares--in Figure IV.2.

Several verification simulations of the bacterial transport model (equation III.22) were completed. The hydraulic conductivity of Scranton fine sand was estimated to be 15 cm/h, an average value for a fine sand (Daly, 1982). Retention and die-off were treated as irreversible processes, so the distribution coefficient was equal to zero. The results of two simulations are shown for comparative purposes in Figure IV.2.

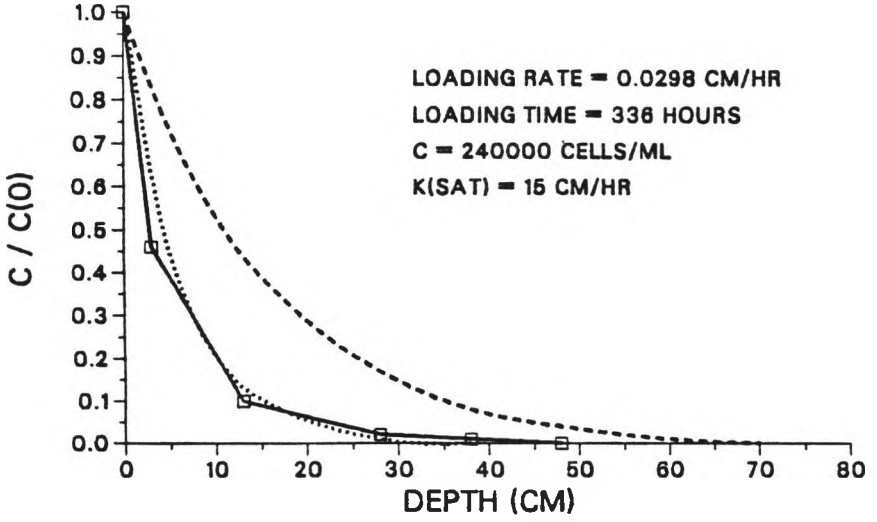

Figure IV.2. Comparison of bacterial transport in a soil column with simulations made with bacterial transport model. Solid curve - Dazzo et al. (1973), Dashed curve - die-off = 0.016/h, Dotted curve - die-off and clogging = 0.054/h.

The dashed line represents the results when the model is run with a mean value for the die-off coefficient--0.016/h. The dotted line is the result of adding a clogging constant of 0.038/h to the die-off coefficient. Polprasert and Hoang (1983) determined this clogging constant for filters composed of crushed stone of 20 mm in diameter.

The goal of the bacterial transport verification was not to determine a best fitting curve. Sampling errors, the method of measurement for bacterial numbers (MPN technique), and stressed organisms are but a few of the factors that would lead to imperfectly fit curves.

The goal was to determine if reasonable results could be obtained with the bacterial transport model. That goal was met.

5. Model Sensitivity Analysis

Model sensitivity was investigated by varying specific parameter values and noting the effect on model results. Individual changes in parameter values, not changes in combinations of parameters, were analyzed. The parameters analyzed were limited to those that were randomly generated during the Monte Carlo simulations--input bacterial concentration, bacterial die-off coefficient, saturated hydraulic conductivity, and bacterial distribution coefficient. During each sensitivity analysis, each parameter, other than the one under analysis, was fixed at

the mean values mentioned previously. Sensitivity analysis was limited to sandy soils and the 100 year storm.

a. Initial Concentration of Bacteria

The maximum depth of bacterial transport is dependent, in part, on the initial concentration reaching the soil. As the concentration of bacteria increased, the probability of organisms reaching lower soil depths also increased. Bacteria seldom reached depths greater than 100 cm when the initial concentration was less than 4000 cells/cm^3 soil. Figure IV.3 shows the change in maximum depth of bacterial penetration in the soil after 72 h as the initial bacterial abundance changes from 5000 to 100000 cells/cm soil.

Bacteria first reached the 120 cm^3 depth when the initial concentration was 30000 cells/cm^3 soil, and the time elapsed was between 120 and 144 h.

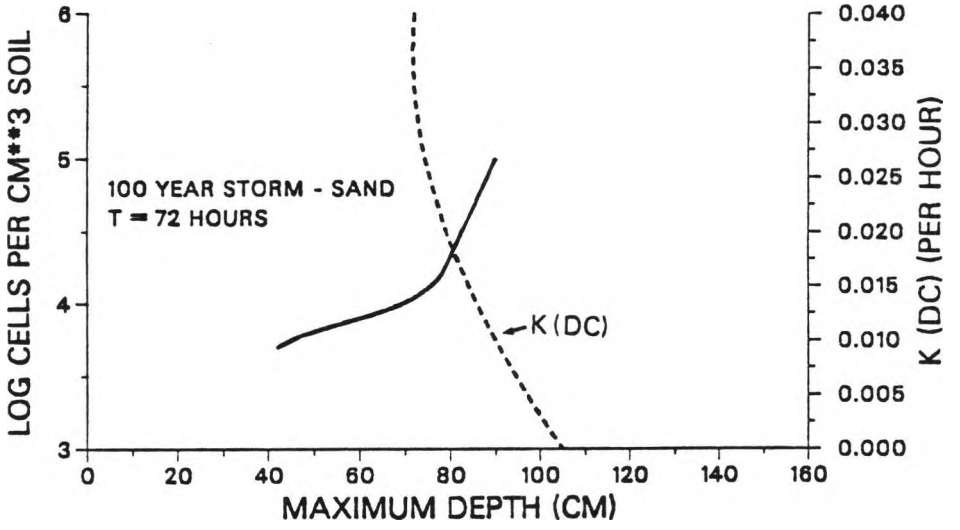

Figure IV.3. Sensitivity analysis of the input bacterial concentration and bacterial decay coefficient.

The initial bacterial concentration became less important to distance traveled at concentrations greater than 100000 cells/cm ^{3} soil. After 110 hours, maximum depth of transport for an initial concentration of 100000 cells/cm ^{3} soil was 114 cm; for an initial concentration of 170000 cells/cm ^{3} soil, maximum depth was 117 cm.

b. Bacterial Die-off Coefficient

The bacterial die-off coefficient is time-dependent. At early times, the value of the die-off coefficient has little impact on the depth of bacterial penetration. As shown in Figure IV.4, as time increases, the effects of bacterial die-off are more noticeable.

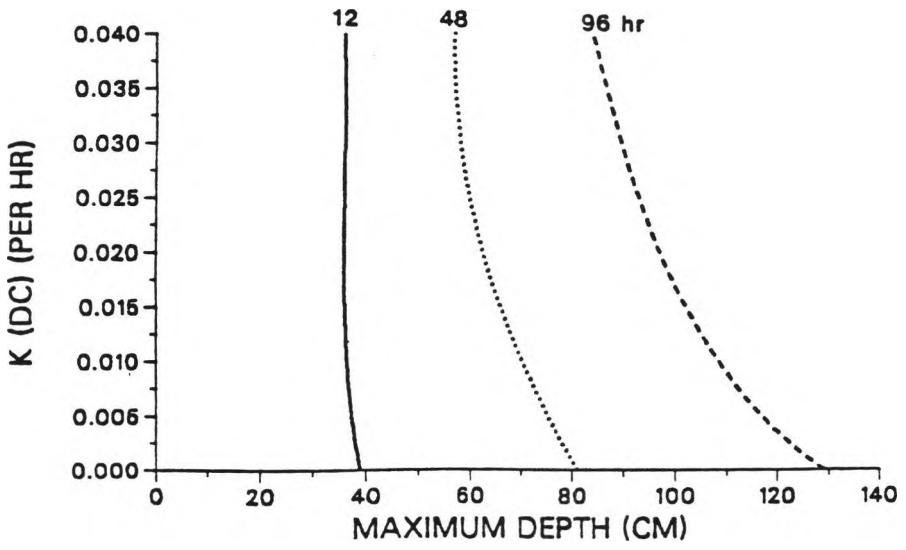

Figure IV.4. Sensitivity analysis of the bacterial die-off coefficient at 12-,48-,and 96-h.

Computer costs limited the length of the sensitivity simulations. Because die-off is time-dependent, bacteria

would be expected to reach 120 cm depth eventually, except at very high die-off rates. Results did indicate that when die-off was 0.010/h, bacteria reached 120 cm in 96 to 110 h.

c. Saturated Hydraulic Conductivity Coefficient

Changing the saturated hydraulic conductivity from 60 to 600 cm/h had little impact on the depth of bacterial penetration. This is not surprising given the low wastewater loading rate. The impact may be more apparent during the three hours of rainfall. As shown in Figure IV.5, low values of saturated hydraulic conductivity did influence the maximum depth of penetration, although the impact was limited relative to other parameters analyzed. For coarse-grained soils subject to the storms used in this study, the specific value of the saturated hydraulic conductivity has little influence on the depth of bacterial transport.

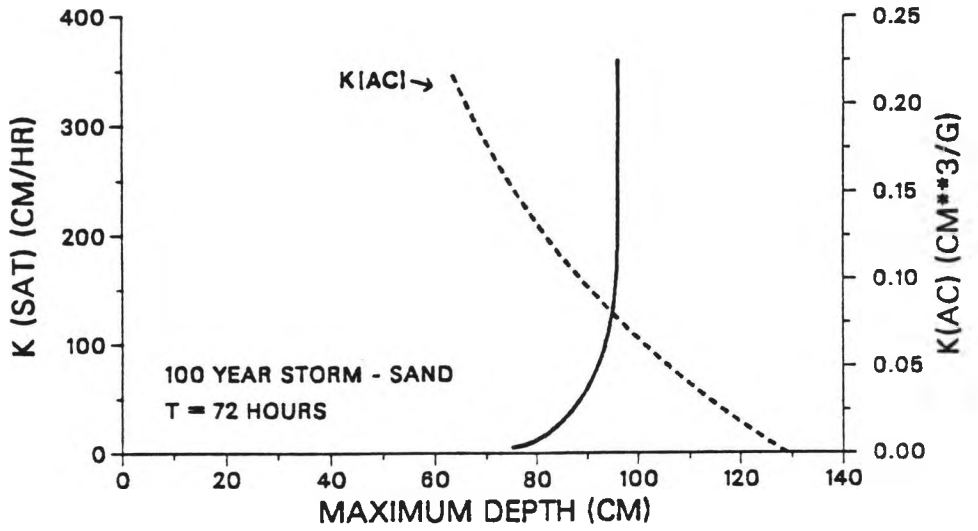

Figure IV.5. Sensitivity analysis of saturated hydraulic conductivity and bacterial distribution coefficient.

d. Bacterial Distribution Coefficient

As shown in Figure IV.5, an increase in the value of the distribution coefficient has a noticeable impact on the maximum depth of penetration. An increase in the distribution coefficient from 0.00 to 0.02 results in a 12 h lag in the time required for bacteria to penetrate to 120 cm--62 to 74 h.

The impact of the bacterial distribution coefficient on the governing transport equation is a function of the water content of the soil, not time. As shown in Figure IV.6, the shapes of the distribution coefficient curves do not change in time, as they did with the die-off coefficient.

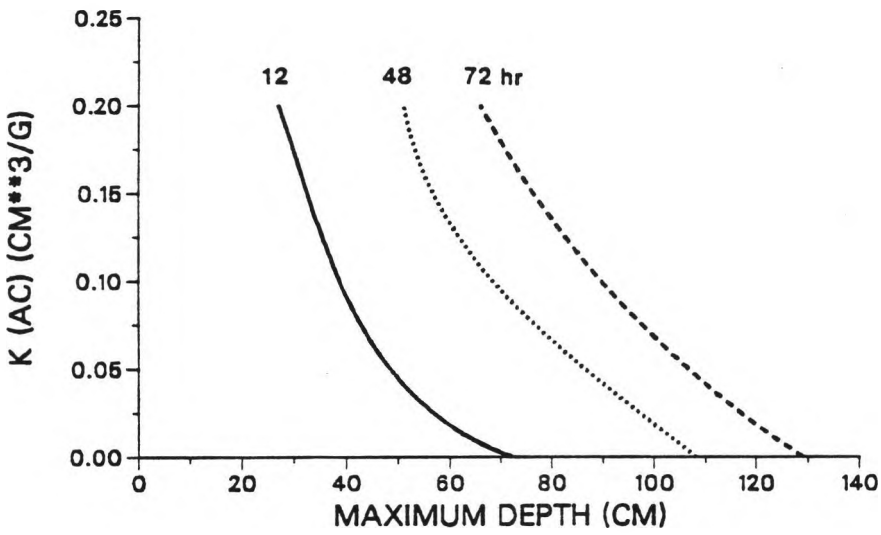

Figure IV.6. Sensitivity analysis of the bacterial distribution coefficient at 12-, 48-, and 72 h.

Within the range of values expected for this study, the initial bacterial concentration and the bacterial distribution coefficient have the greatest influence on bacterial transport distance in coarse-grained soils.

V. RESULTS AND ANALYSIS OF BACTERIAL TRANSPORT SIMULATIONS

The bacterial transport computer model was used for both deterministic and stochastic simulations. Deterministic simulations were performed to compare model performance for specific initial and boundary conditions using mean values for the various input parameters. Stochastic simulations were performed to determine the probability of bacteria being transported to specific soil depths and to determine the probability of a specific bacterial concentration at those specified depths. Results specified in probabilities are suggested because average ("generic") soil physical and hydrologic properties are unlikely in a natural (in situ) environment.

A. Deterministic Simulations

The results of the deterministic simulations allowed several generalizations to be made:

(1) Bacterial Transport--Alternative Conductivities. There were limited differences in bacterial transport between the average saturated hydraulic conductivities and the specified percolation rates for sandy and loamy sand soils provided in the EPA Design Manual (Otis et al., 1980).

(2) Bacterial Transport--Alternative Storms.

There was no appreciable difference in bacterial transport between the 10 year storm and the 100 year storm.

(3) Bacterial Transport--Alternative Soils.

There was a noticeable difference in bacterial transport between sandy soils and loamy sand soils.

(4) Bacterial Transport--Alternative Concentrations.

There was an appreciable difference in bacterial transport between an initial bacterial cell concentration of 4210 and 50000 cells/cm^3 soil.

(5) Bacterial Transport--Alternative Parameters.

There was an appreciable impact on bacterial concentrations at various depths when the bacterial die-off and distribution coefficients, individually or combined, were excluded from the bacterial transport equation.

(6) Bacterial Transport--No Storm.

Bacteria traveled appreciable distances without the benefit of high intensity storms.

(7) Bacterial Transport--Random Motility.

Including random motility in the equation for bacterial flux (III.14) had minimal impact on the distribution and concentration of bacteria.

NOTE: Unless otherwise stated, mean parameter values were used for the deterministic simulations. These values were

50000 cells/cm^3 soil for the initial bacterial cell concentration, 0.016/h for the die-off coefficient, 0.113 cm^3 /g for the distribution coefficient, and for saturated hydraulic conductivity--16.79 cm/h for sandy soil and 5.08 cm/h for loamy sand.

1. Bacterial Transport--Alternative Conductivities.

Deterministic simulations were performed to compare relative bacterial concentrations at various depths using the mean values for saturated hydraulic conductivity and the suggested EPA percolation rates provided in Otis et al. (1980). The upper limits on percolation rates suggested in Otis et al. (1980) are 1 min/in (152.4 cm/h) for coarse to medium sand and 6 min/in (25.4 cm/h) for fine sand and loamy sand. Typically, percolation tests are performed to determine wastewater application rates.

Comparisons between sandy and loamy sand soils are provided in Figures V.1 and V.2. At any given depth the relative concentration is greater at the EPA design percolation rates than at the mean rate developed from the USDA soil texural triangle.

Bacterial transport was greater with the EPA design rates. The greatest differences in relative concentrations are 0.18 at 54 cm for sandy soils and 0.09 at 48 cm for loamy sands. The design percolation rates were 5 to 9 times greater than the mean hydraulic conductivity rates, so these results were expected.

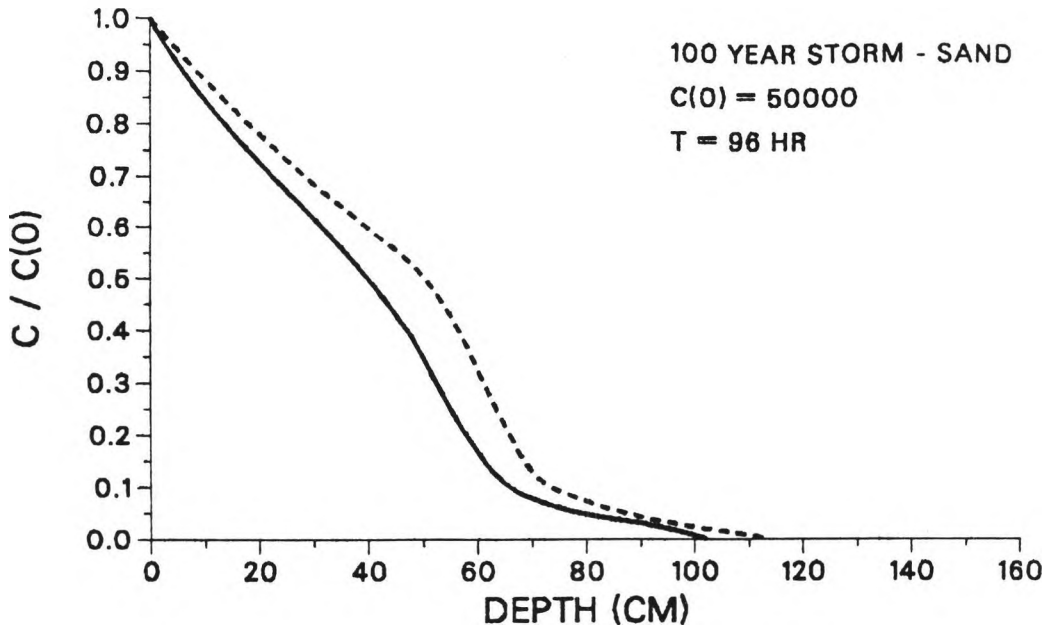

Figure V.1. Comparison between the mean saturated hydraulic conductivity 16.79 cm/h (solid line) and the EPA design percolation rate 152.4 cm/h (dashed line) for sandy soils.

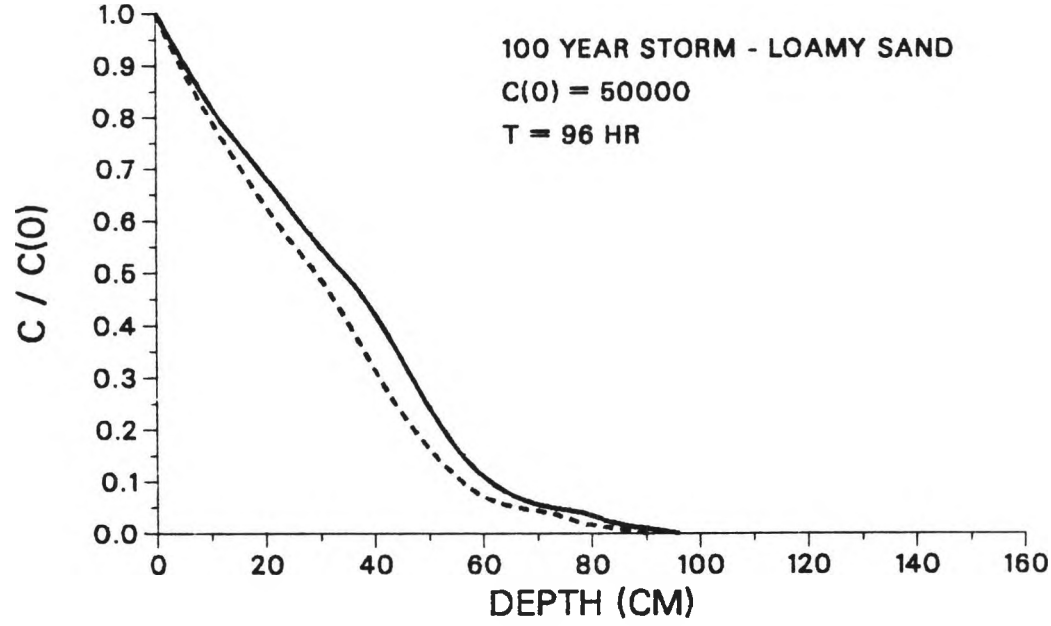

Figure V.2. Comparison between the mean saturated hydraulic conductivity 5.08 cm/h (dashed line) and the EPA design percolation rate 25.4 cm/h (solid line) for loamy sand soils.

2. Bacterial Transport--Alternative Storms.

A deterministic simulation was performed to compare the impact of the the 100 year and 10 year storms on bacterial transport in sandy soil. As shown in Figure V.3, the curves of relative concentration at various depths were quite similar for both the 10 year and 100 year storm.

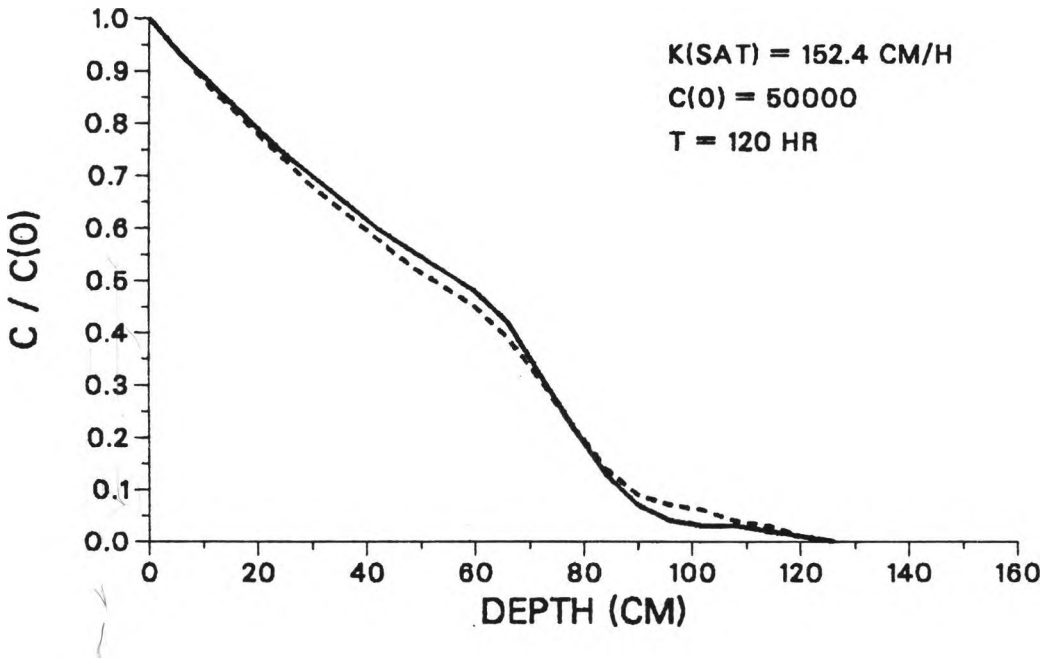

Figure V.3. Comparison of 100 year storm (dashed line) and 10 year storm (solid line) on relative concentrations of bacteria at various depths.

The difference was probably the result of dispersion. At 12 cm depth and t=1 h, soil water velocity during the 100 year storm simulation was 23 cm/h, while during the 10 year storm simulation it was 17 cm/h. At 30 cm depth and t=4 h, during the 100 year storm, soil water velocity was 2.5 cm/h; during the 10 year storm the velocity was zero.

As shown in Figures V.4 and V.5, the distribution of water at various times was similar, although the volume of water was different. NOTE: The water content distributions at t = 1,2,3 h were not available at the EPA design rate. The patterns of distribution should be similar, and the water volume was the same.

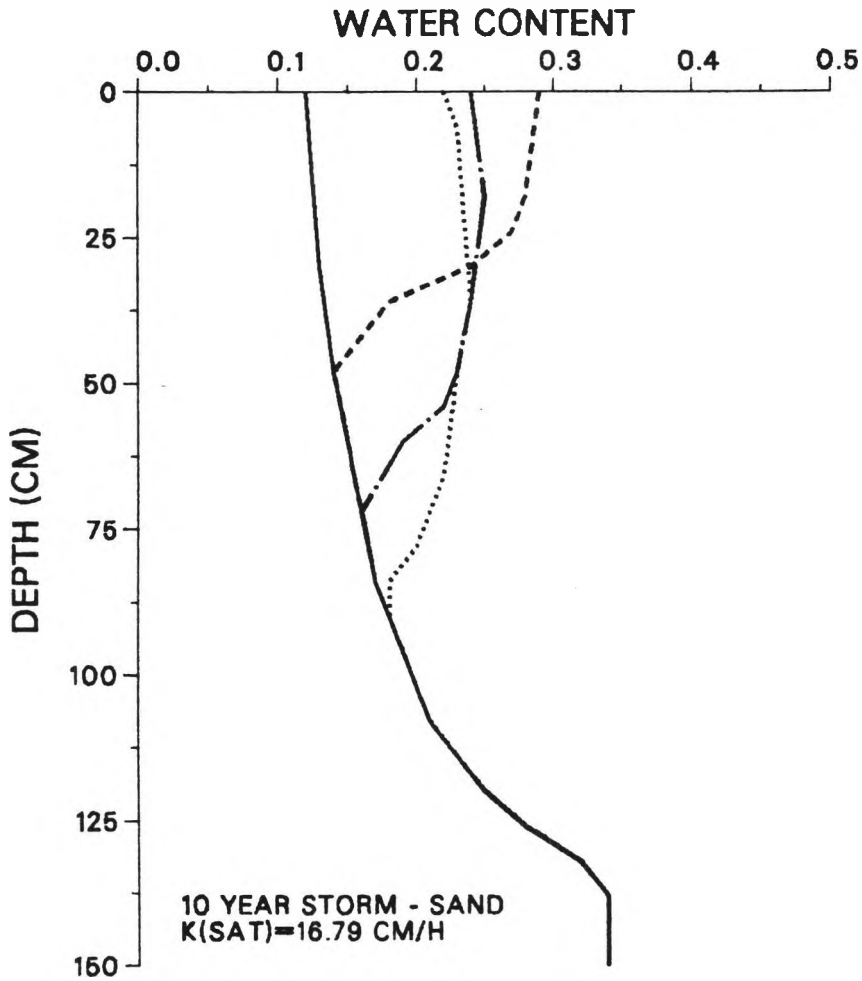

Figure V.4. Water content distribution with depth at 0 h (solid line), 1 h (dashed line), 2 h (chain-dot line), and 3 h (dotted line) for the 10 year storm.

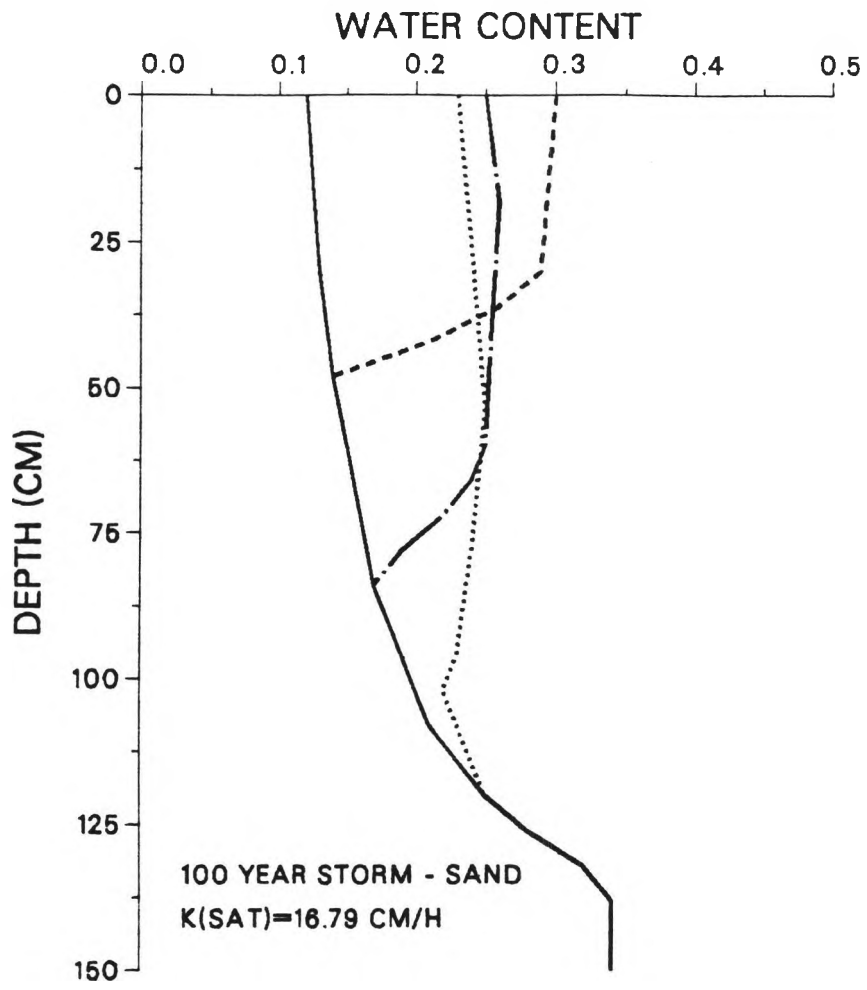

Figure V.5. Water content distribution with depth at 0 h (solid line), 1 h (dashed line), 2 h (chain-dot line), and 3 h (dotted line) for the 100 year storm.

3. Bacterial Transport--Alternative Soils.

Comparative simulations between sandy and loamy sands indicated noticeable differences in relative concentrations with depth and distance traveled. As shown in Figure V.6, the relative concentrations at all depths were greater in the sandy soil. This was expected because of the greater hydraulic conductivity of sand. The greatest difference in relative concentration was 0.23 at 60 cm depth.

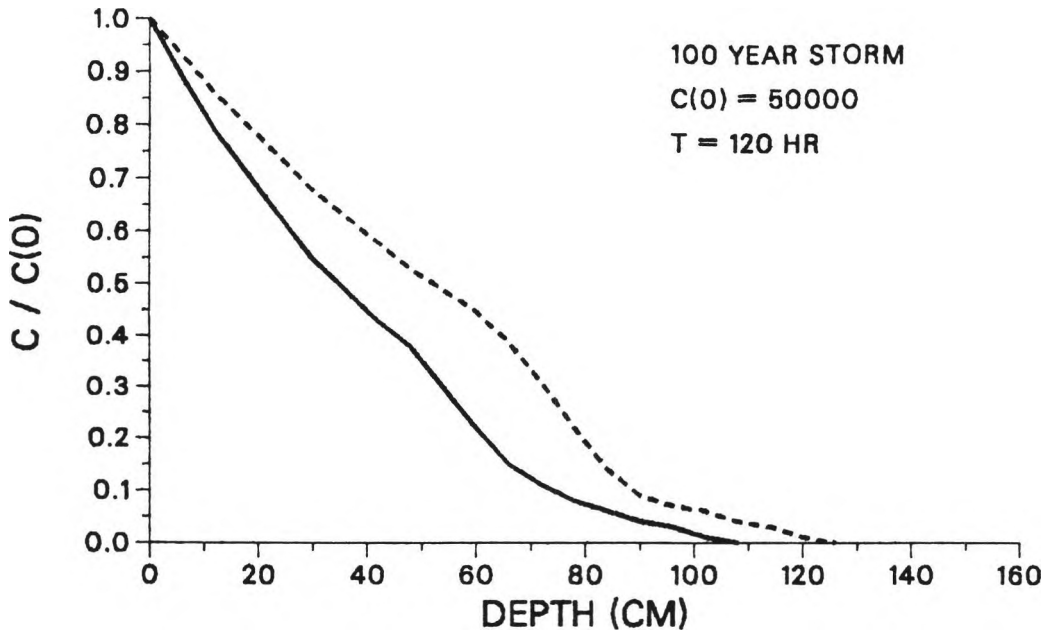

Figure V.6. Comparison of relative bacterial concentration versus depth for loamy sand soil (solid line) and sandy soil (dashed line) at the EPA design percolation rates-sand 152.4 cm/h and loamy sand 25.4 cm/h.

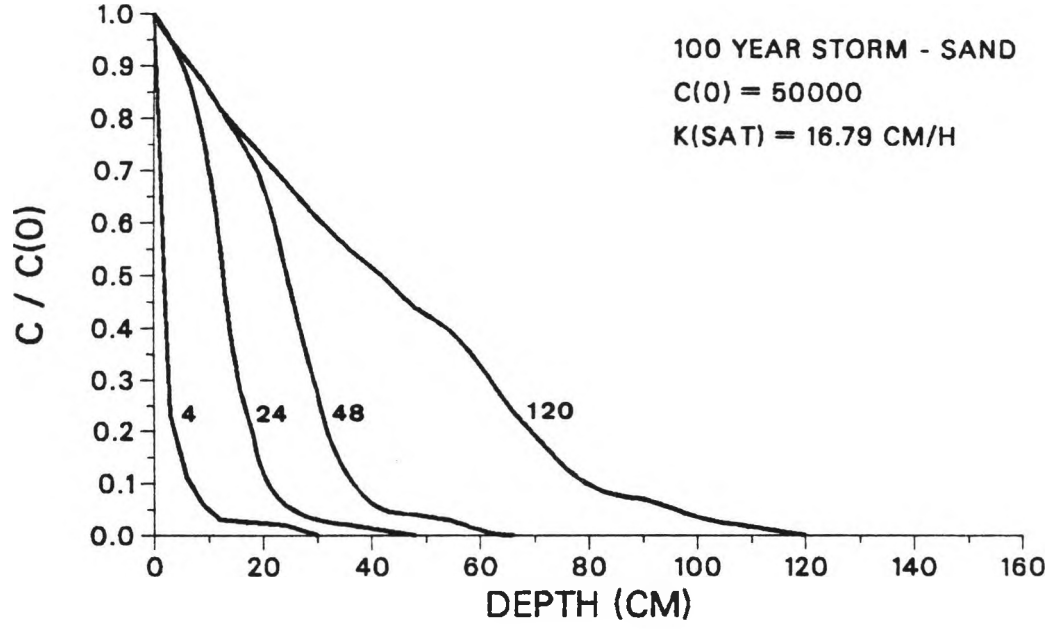

Figure V.7. Relative concentration profiles versus depth using the mean saturated hydraulic conductivity rate--sandy soil at 4-,24-,48-,120 h.

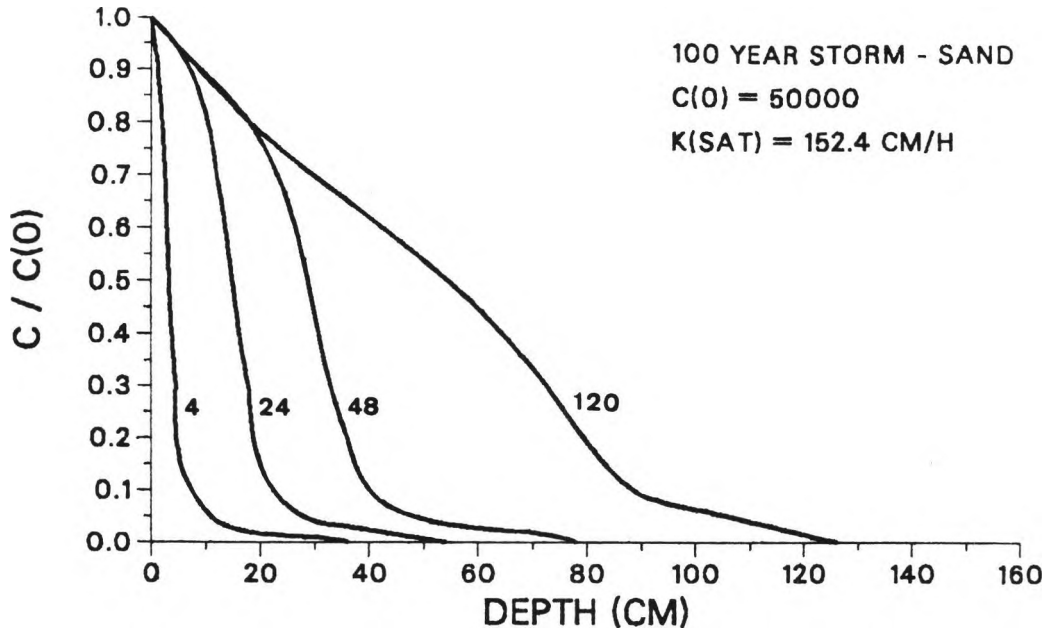

Figure V.8. Relative concentration profiles versus depth using the EPA design percolation rate--sandy soil at 4-, 24-, 48-, 120 h.

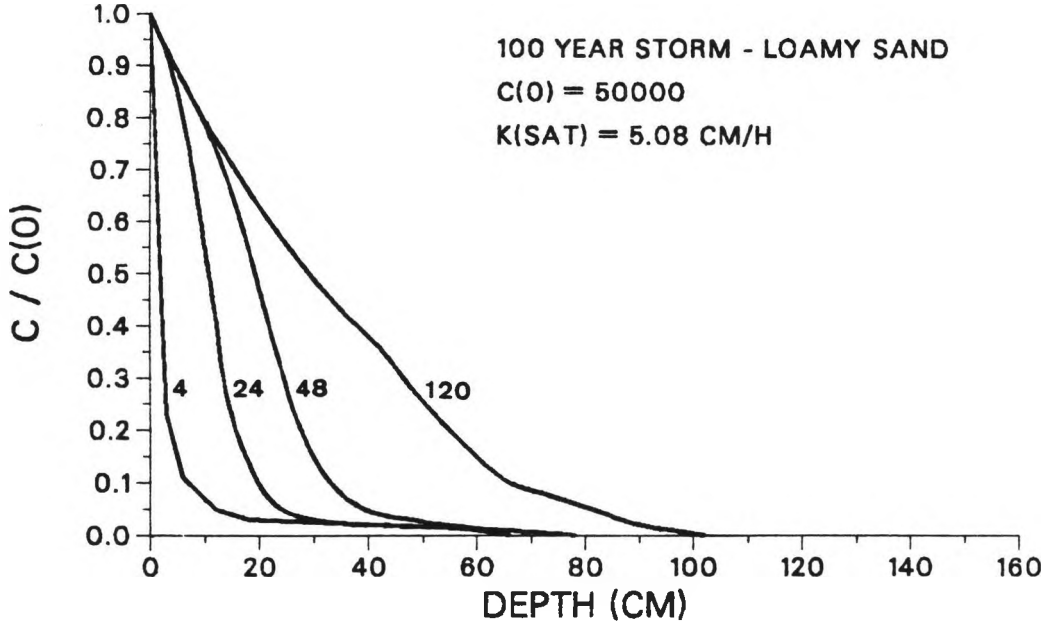

Figure V.9. Relative concentration profiles versus depth using the mean saturated hydraulic conductivity rate--loamy sand soil at 4-, 24-, 48-, 120 h.

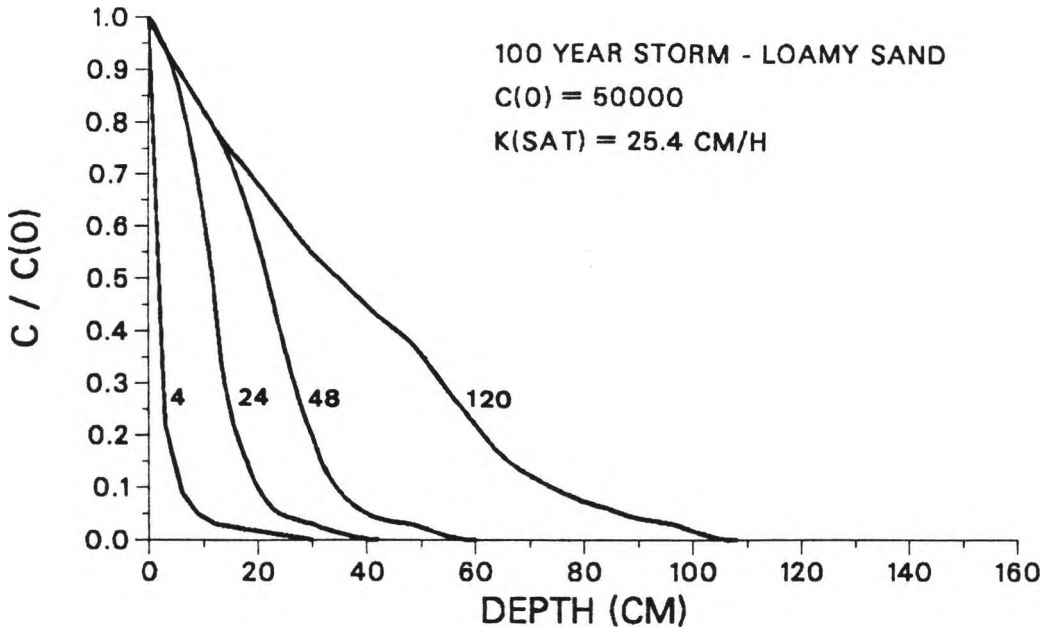

Figure V.10. Relative concentration profiles versus depth using the EPA design percolation rate--loamy sand soil at 4-, 24-, 48-, 120 h.

For comparative purposes the concentration profiles at 4, 24, 48, and 120 h are provided for sandy soil and loamy sand soil at both the mean hydraulic conductivity rates and the EPA design percolation rates. These profiles are provided in Figures V.7, V.8, V.9, and V.10.

At 120 h the sandy soils, with greater conductivity, had higher concentrations of bacteria than loamy sands. For comparison, the relative concentrations at 60 cm depth at 120 h in Figures V.7, V.8, V.9, and V.10, respectively were 0.33, 0.45, 0.15, and 0.22. At early time (4 h) the concentration profiles were similar. The exception is shown in Figure V.9--the loamy sand soil with saturated hydraulic conductivity of 5.08 cm/h. The rainfall rate of 6.8 cm/h

during the first hour of the storm was greater than the saturated hydraulic conductivity. This caused a positive pressure head in a saturated soil. The high soil water velocities would increase dispersion. Small concentrations of bacteria would travel further under these conditions. As shown in Figure V.9, bacteria approached 70 cm and 80 cm depths at 4 h and 24 h, respectively. Figure V.11 shows the saturated water conditions at early times.

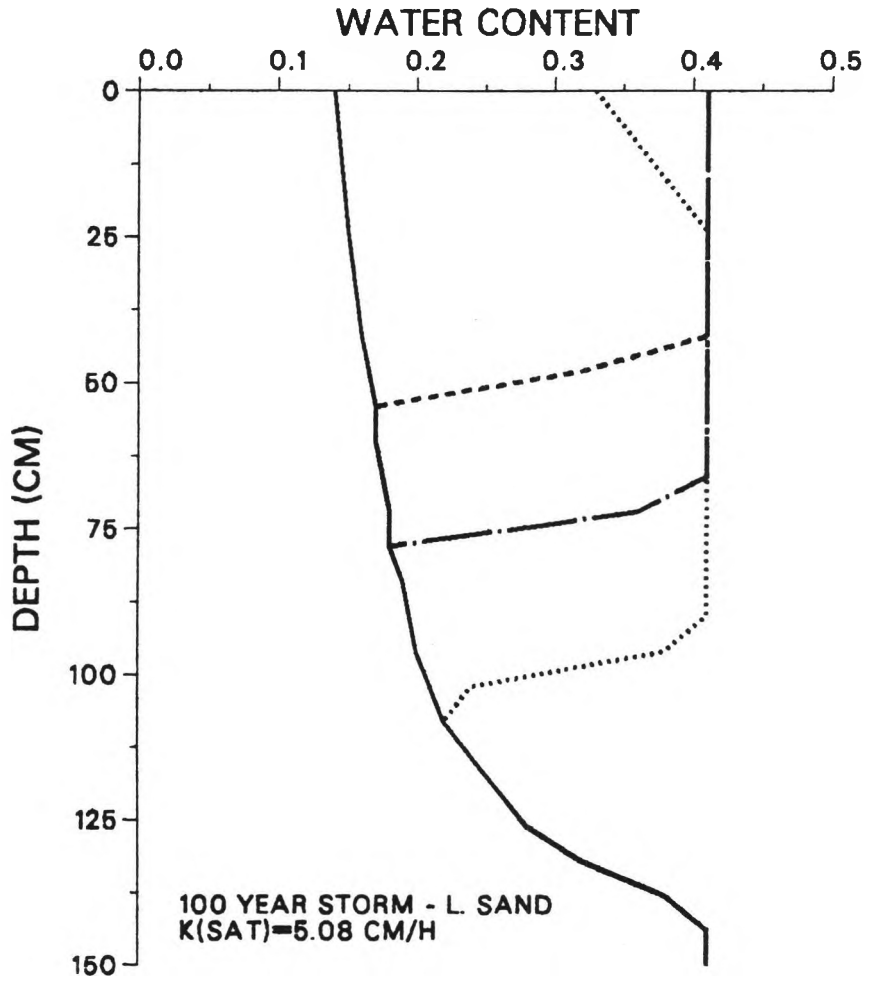

Figure V.11. Water content profiles at early times in loamy sand using the mean saturated hydraulic rate- 0 h (solid line), 1 h (dashed line), 2 h (chain-dot line), 3 h (dotted line).

The water content profiles at 0, 4, 12, 120 h for each example shown in Figures V.7, V.8, V.9, and V.10 are provided for comparison. Saturated water flow occurs only with loamy sand soil with a mean saturated hydraulic conductivity of 5.08 cm/h--as shown in Figure V.14.

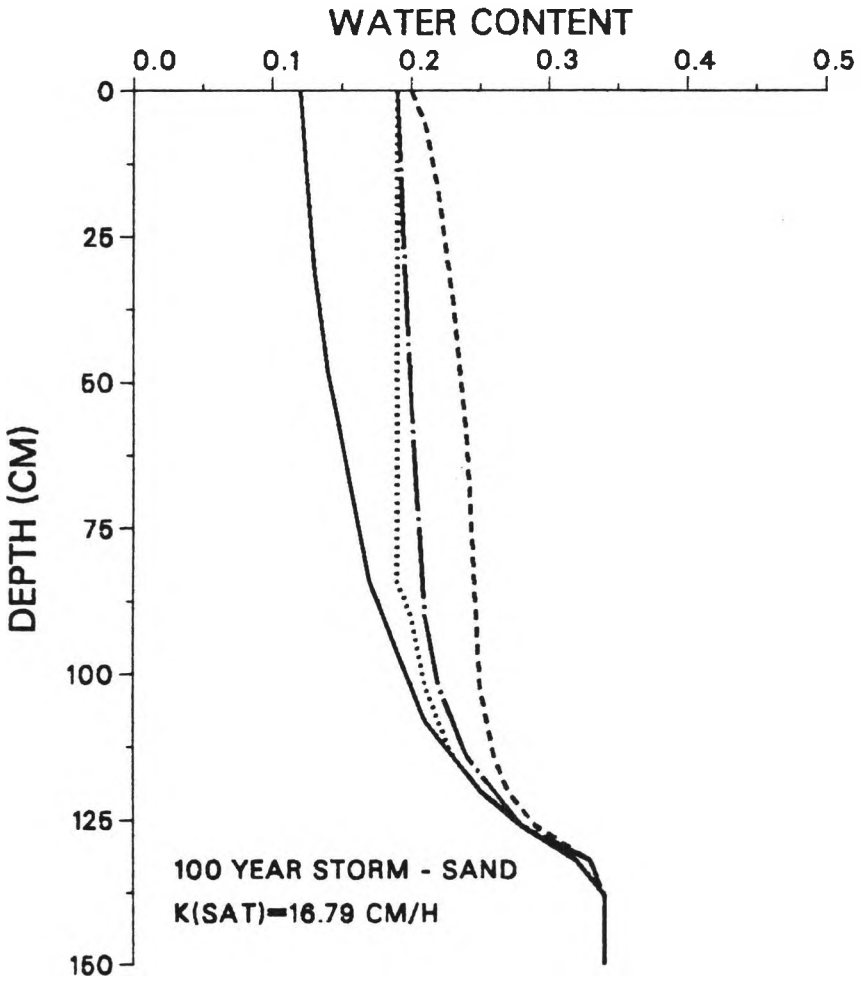

Figure V.12. Water content profiles using the mean saturated hydraulic conductivity. 0 h (solid line), 4 h (dashed line), 12 h (chain-dot line), and 120 h (dotted line). NOTE: The profiles at 24 h, 96 h, and 120 h are similar.

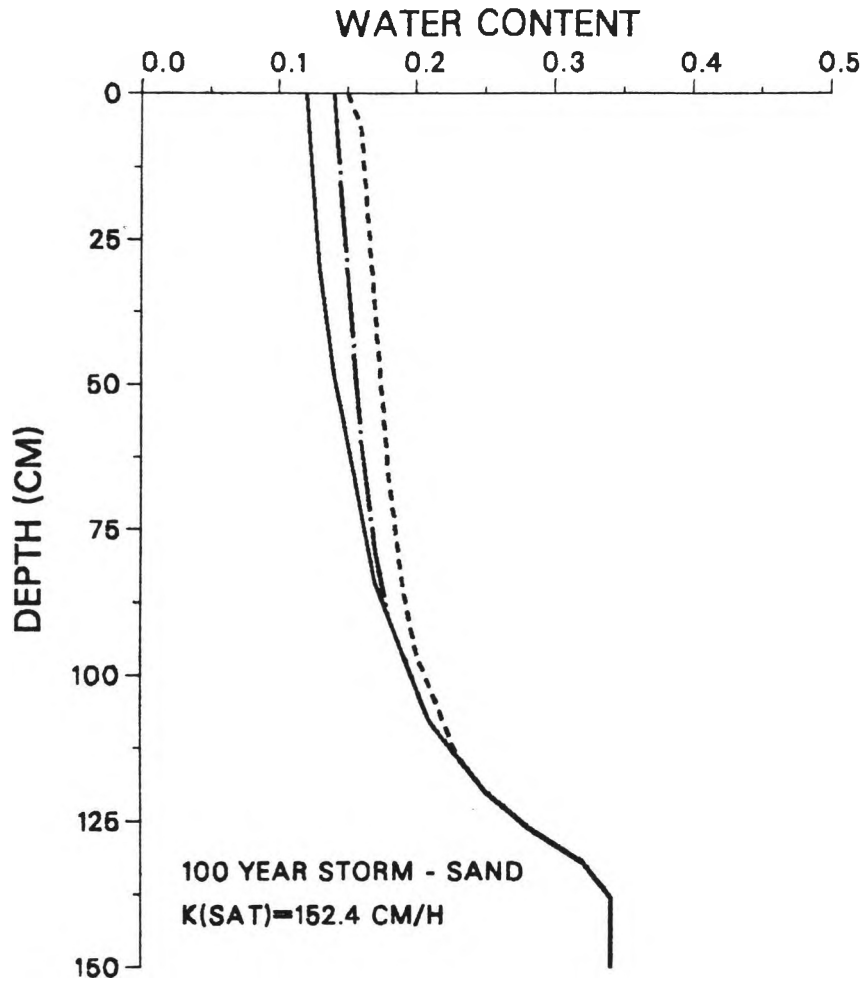

Figure V.13. Water content profiles using the EPA design percolation rate. 0 h (solid line), 4 h (dashed line), 12 h (chain-dot line). NOTE: The profiles at 12 h, 24h, 96 h, and 120 h are similar.

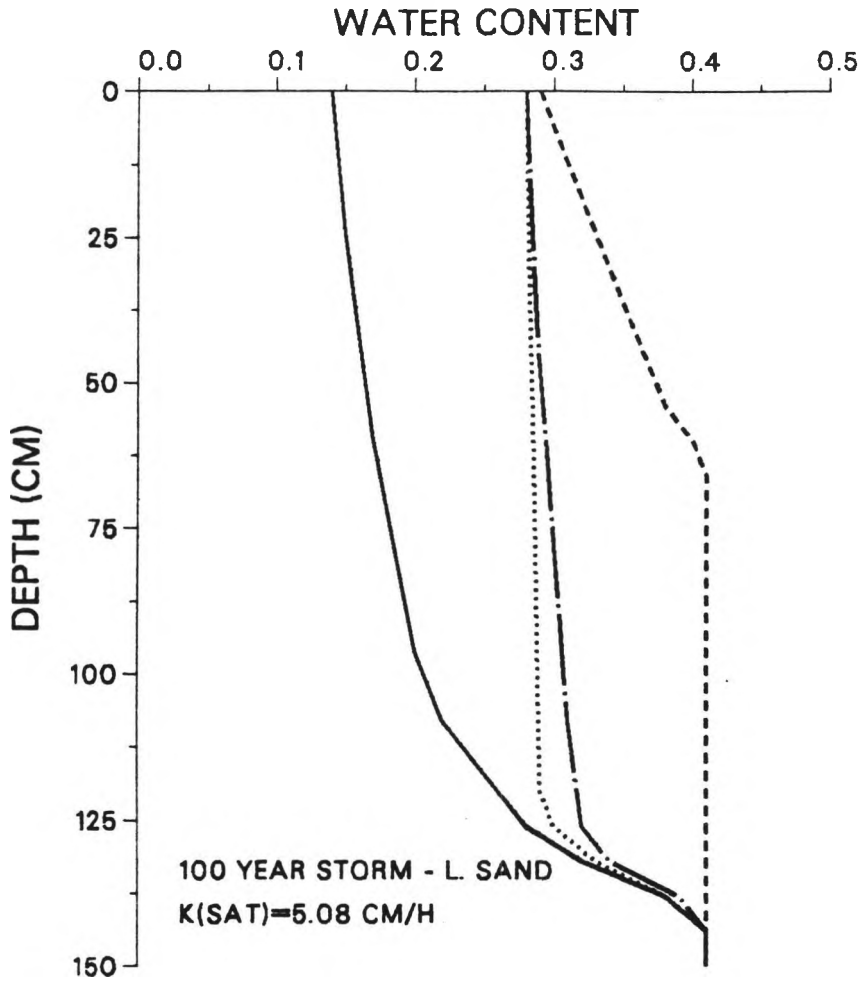

Figure V.14. Water content profiles using the mean saturated hydraulic conductivity rate. 0 h (solid line), 4 h (dashed line), 12 h (chain-dot line), and 120 h (dotted line). NOTE: The profiles at 24 h, 96 h, and 120 h are similar.

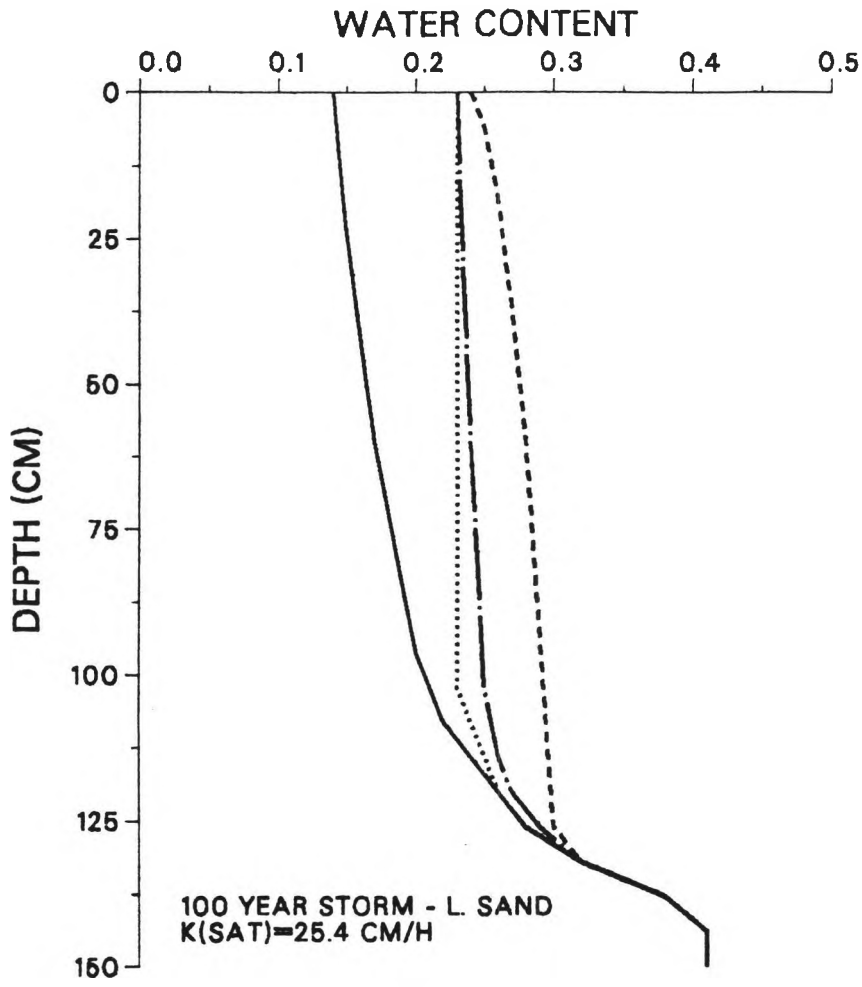

Figure V.15. Water content profiles using the EPA design percolation rate. 0 h (solid line), 4 h (dashed line), 12 h (chain-dot line), and 120 h (dotted line). NOTE: The profiles at 24 h, 96 h, and 120 h are similar.

4. Bacterial Transport--Alternative Concentrations.

When the initial bacterial cell concentration was 4210 cells/cm ^{3} soil, transport distance was limited. Limited travel was evident with both sandy and loamy sand soils and with both the mean saturated hydraulic conductivity rate and the EPA design rate. Figure V.16 shows the relative concentrations with depth for both sandy and loamy sand soils at the higher EPA design percolation rates.

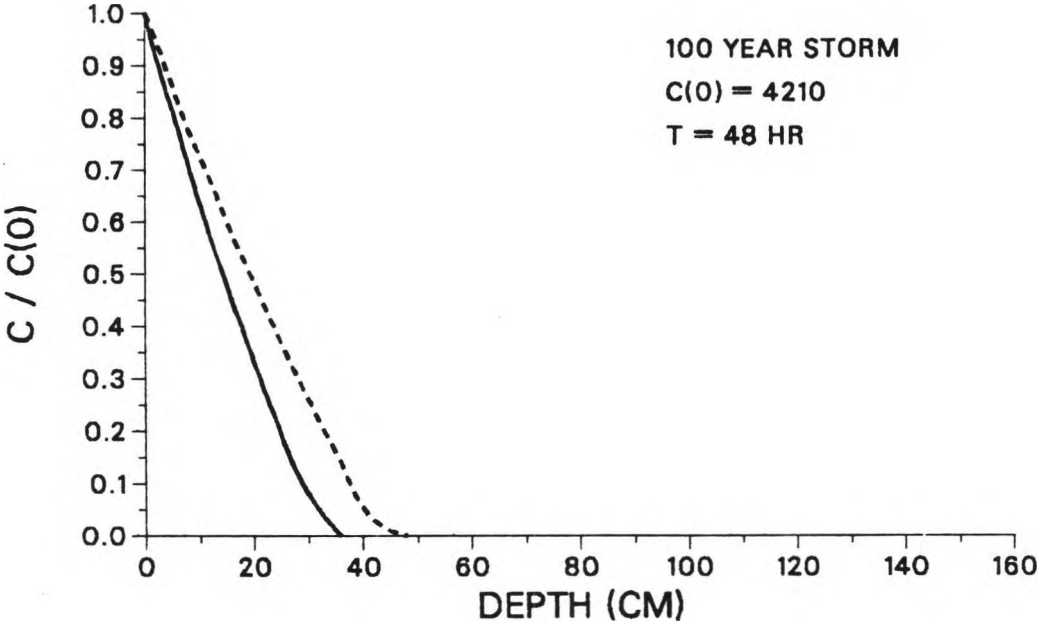

Figure V.16. Relative concentration profiles versus depth for low initial bacterial cell concentrations in soil at the EPA design percolation rate. Loamy sand soil (solid line) and Sandy soil (dashed line).

The relative concentration profiles were the same at both 48 h and 120 h when the EPA design percolation rate was used. Bacteria traveled no further than 48 cm. In loamy sand subject to the 5.08 cm/h saturated hydraulic

conductivity rate and saturated flow, bacteria traveled further in early times, but at 120 h the curves were similar to the other soils. Bacteria traveled no further than 51 cm.

When the initial bacterial cell concentration was 17250 cells/cm^3 soil, the relative concentration profiles were similar to those when initial concentrations were 50000 cells/cm^3 soil. Compare Figures V.7 and V.17. Bacteria did not travel beyond 110 cm at the lower concentration, and they did not exceed 120 cm depth at the higher concentration. The big difference is numbers. At 90 cm depth, the concentration was 3252 cells/cm^3 soil for the higher inital bacterial concentration, and the concentration was 1583 cells/cm^3 soil for the lower initial concentration.

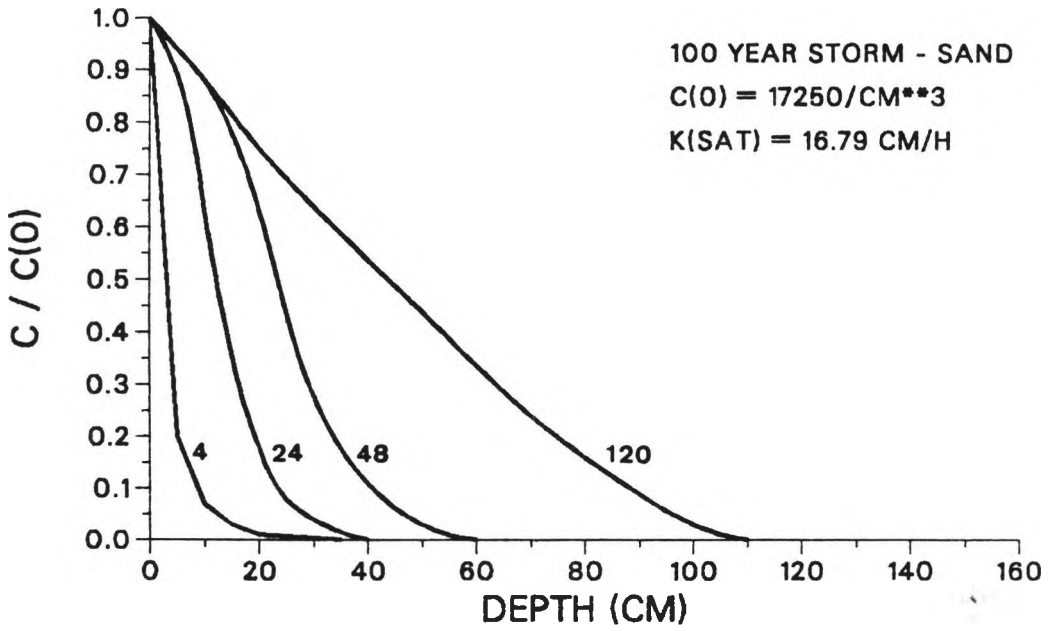

Figure V.17. Relative concentration profiles versus depth using the mean saturated hydraulic conductivity rate--sandy soil. Initial bacterial cell concentration 17250 cells per cubic centimeter soil at 4-, 24-, 48-, 120 h.

5. Bacterial Transport--Alternative Parameters.

When both the distribution and die-off coefficient were set equal to zero and the initial bacterial cell concentration was 4210 cells/cm^3 soil, the distance of bacterial travel remained limited. At equilibrium in sand, bacteria traveled no further than 93 cm. In loamy sand travel was limited to 66 cm. When the initial concentration was 50000 cells/cm^3 soil, bacteria reached 120 cm depth at 29 h in sandy soil and 48 h in loamy sand.

Both the distribution and die-off coefficient had substantial impact on the results at higher initial bacterial cell concentrations. Figure V.18 shows the impact on relative concentration profiles when the distribution and die-off coefficient were set equal to zero, individually or combined.

When the effects of retardation (distribution coefficient) are discounted, bacteria would travel with the same velocity as soil water, although they would remain subject to die-off during transit. One would expect bacteria, at higher relative concentrations, to travel further when retardation is not a factor. As shown in Figure V.18, that fact is evident. When die-off is not a factor, but retardation is, then one would expect the relative concentration profiles to resemble plug flow. As shown in Figure V.18, both the dotted and the chain-dot curves resemble plug flow.

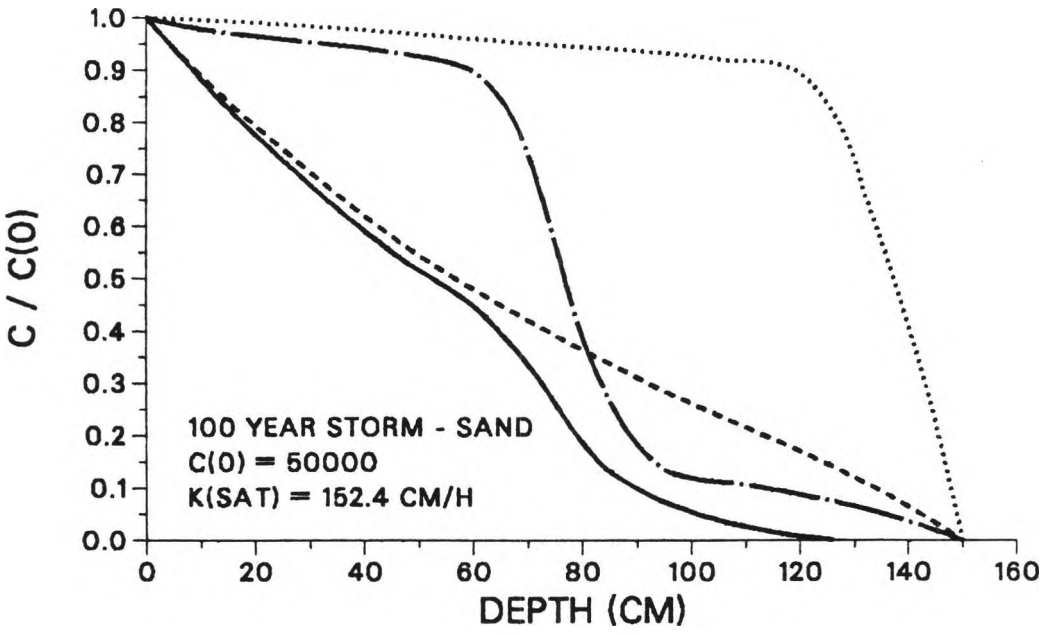

Figure V.18. Comparison of relative concentration profiles when distribution and die-off coefficients are equal to zero. Mean parameter values (solid line); distribution coefficient equal to zero (dashed line); die-off coefficient equal to zero (chain-dot line); and both die-off and distribution values are set equal to zero (dotted line). T = 96 h.

6. Bacterial Transport--No Storm.

Wastewater loading, without rainfall, at a rate of 5 cm/d (0.208 cm/h) was sufficient to allow bacteria to travel great distances. Bacteria traveled 141 cm in 168 h (7 days) when the initial concentration was 50000 cells/cm^3 soil and 125 cm when the initial concentration was 17250 cells/cm^3 soil. Rainfall would carry bacteria further, but results indicate that the wetting front was far in advance of the bacterial front during heavy rainfall.

Results, based on initial bacterial cell concentration of 50000 cells/cm^3 soil, show that the soil loaded with wastewater but no rain remained at the initial soil water condition at soil depths below 51 cm at 4 h, and bacteria traveled only 9 cm. When rainfall was included with wastewater loading, the complete column was affected by the change in soil water. The complete soil column water content distribution had changed at 4 h, and bacteria traveled 33 cm.

Within 24 h the soil loaded with wastewater only had changed water content at all depths. At 48 h the water content profiles for both wastewater only and waterwater with rain were similar. Bacteria had traveled 57 cm in the

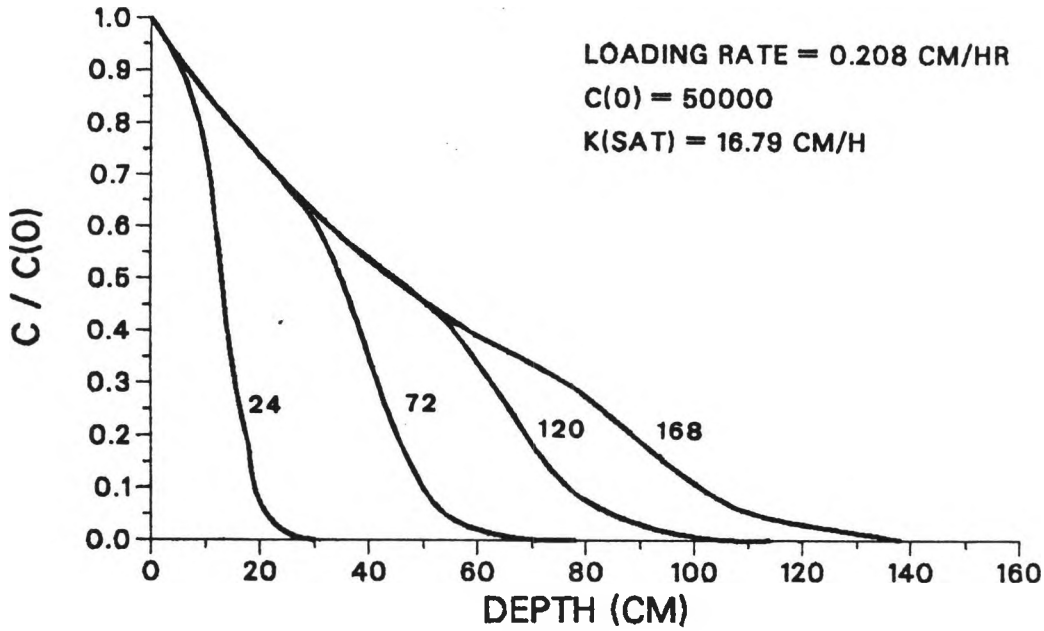

Figure V.19. Relative concentrations versus depth at various times, when sand was subjected to wastewater loading only. Concentration in cells per cubic centimeter soil at 24-, 72-, 120-, 168 h.

wastewater only column and 66 cm in the wastewater with rain column. By 120 h the distances were 114 cm and 117 cm, respectively. The relative concentrations versus depth over time are shown in Figure V.19. The shape of the curves in Figures V.7 and V.19 are similar except at low concentration. Higher flux carried the bacteria further. As shown in the two graphs, bacteria traveled 45 cm in 24 h at higher flux rates, while only 30 cm at lower flux rates. Although the general form of the relative concentration curves are similar at both concentrations--17250 and

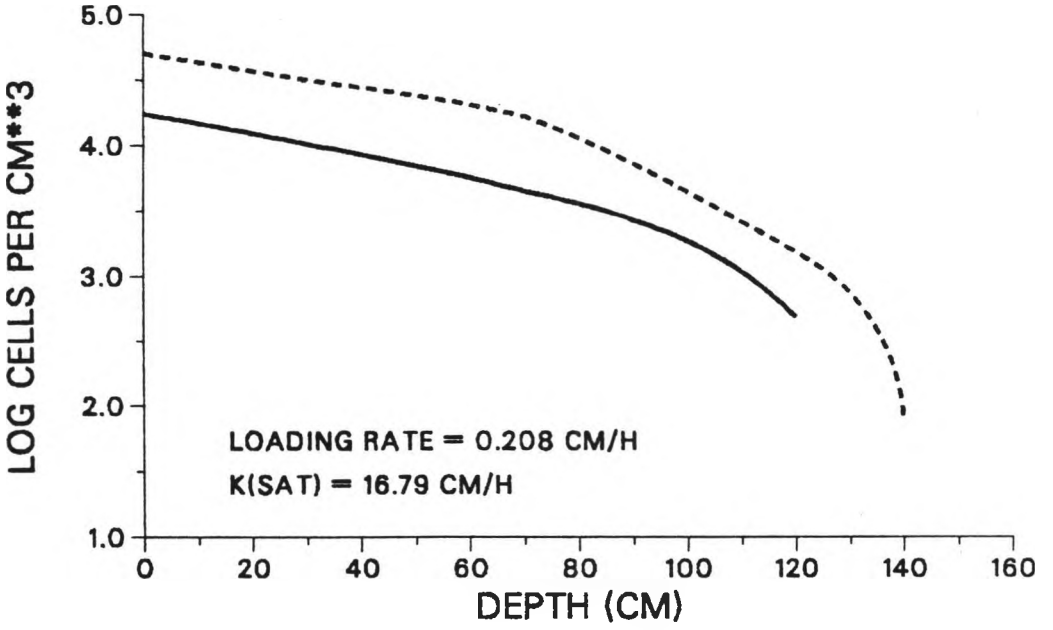

Figure V.20. Comparison of bacterial concentration and depth in sandy soils subjected to wastewater loading only. Dashed line--initial bacterial concentration 50000 cells per cubic centimeter soil. Solid line--initial concentration 17250 cells per cubic centimeter soil. T = 168 h.

50000 cells/cm^3 soil, the populations differ. As shown in Figure V.20., the bacterial populations at each depth differ by as much as one half log cells.

7. Bacterial Transport--Random Motility.

When random motility was included in the bacterial transport equation, the impact on the results was insignificant. One simulation was completed with a random motility coefficient of 0.0032 cm^2 /h. This value was suggested by Rosen (1983b) for the case of aerobic, motile Escherichia coli in an aqueous medium that contained less oxygen than other substances. Simulations of bacterial transport in sandy soil subjected to the 100 year storm and an initial bacterial concentration of 50000 cells/cm^3 soil, with and without motility as a factor, were compared. Comparison of relative concentration profiles at 120 h indicated that the greatest difference in concentration occurred at 87 cm depth and was 0.16%. Maximum depth of travel was the same in both simulations--126 cm at 120 h.

B. Stochastic Simulations

Because they poorly reflect the natural, in situ, soil environment, deterministic simulations have limited application. Deterministic simulations are useful for indicating the relative importance of various physical, chemical and biological parameters. Their use in making "real world" predictions of system performance is limited. Stochastic simulations, based on sampling from probability distributions, are more useful as predictive tools because results are expressed as probabilities. One accounts for the natural variability expected in the system being analyzed by sampling from probability distributions and by expressing results as probability distributions.

One of the stated objectives of this study was to determine whether 1.2 m of soil depth was adequate for removing fecal coliform bacteria during extreme rainfall events. The results of stochastic simulations that follow are the product of that effort. The results take two forms--cumulative frequency distributions of the maximum depth of soil penetrated by fecal coliform bacteria, and cumulative frequency distributions of the fecal coliform concentrations at 120 cm soil depth.

It is suggested that when using the graphs dealing with maximum depth of bacterial transport, one should disregard the information supplied for those depths greater than the one stated in the objective--120 cm. This suggestion and

the use of the cumultive frequency distribution graphs are explained in Appendix F.

Because of cost constraints, computer simulations were not run for a period greater than 168 h (7 days). In several cases the length of time was only 96 h or 120 h.

1. Maximum Depth of Bacterial Transport

As indicated earlier, when the initial bacterial cell concentration is 4210 cells/cm^3 soil, transport is limited. Therefore, simulations were performed with initial bacterial concentrations obtained from a probability distribution with a mean bacterial concentration of 50000 cells/cm^3 soil. These results were compared with the results from simulations using the same probability distribution, but with an artificial lower bound of 4210 cells/cm^3 soil placed on the randomly generated concentrations. The results are shown in Figure V.21, and summary data on this and other simulations are provided in Appendix G.

As indicated in Figure V.21, the initial bacterial cell concentration is important to maximum depth of transport. Of the 73 simulations associated with the dashed curve, 45 initial concentrations were less than 4210 cells/cm^3 soil. Of the 53 simulations associated with the solid curve, all initial concentrations were greater than 4400 cells/cm^3 soil. Based on the concentrations at 96 h, only 15% of the 73 simulations had initial bacterial cell concentrations such that one might expect bacteria to reach

120 cm soil depth in 120 h. Of the 53 simulations, 42% were expected to have bacteria at 120 cm in 120 h.

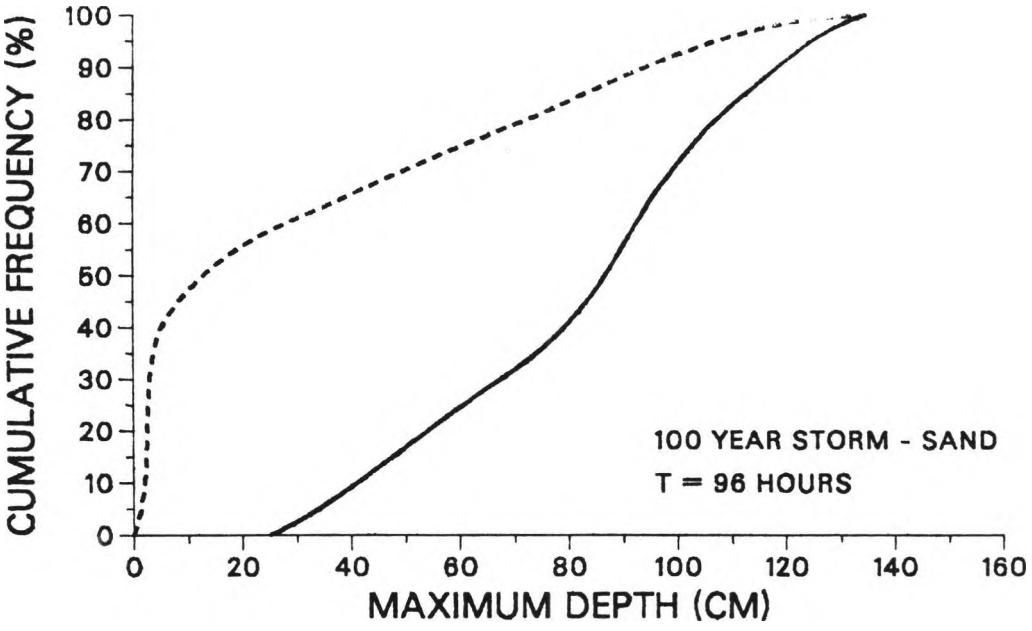

Figure V.21. Cumulative frequency distributions showing maximum depth of bacterial transport. All parameters are randomly generated. Initial bacterial cell concentration of 50000 cells per cubic centimeter soil (dashed curve), initial concentration 50000 (>4210) cells per cubic centimeter soil (solid curve).

With the simulations using higher initial bacterial cell concentrations, bacteria were transported beyond 25 cm depth in all cases, whereas the probability of the bacteria being retained within 25 cm depth was 0.58 in the simulations using the lower initial bacterial concentration.

Figure V.22 shows the relative concentration curves at 24, 96, and 168 h. In most simulations, bacteria had reached 30 to 50 cm depth in 24 h. At 48 h, bacteria had

reached their maximum depth of transport in 21% of the simulations, and that soil depth was 60 cm or less. At 96 h, bacteria had reached their maximum depth of transport in 49% of the simulations, and that depth was 108 cm or less. The probability of bacteria being transported to or beyond the 120 cm depth in 168 h was approximately 0.35.

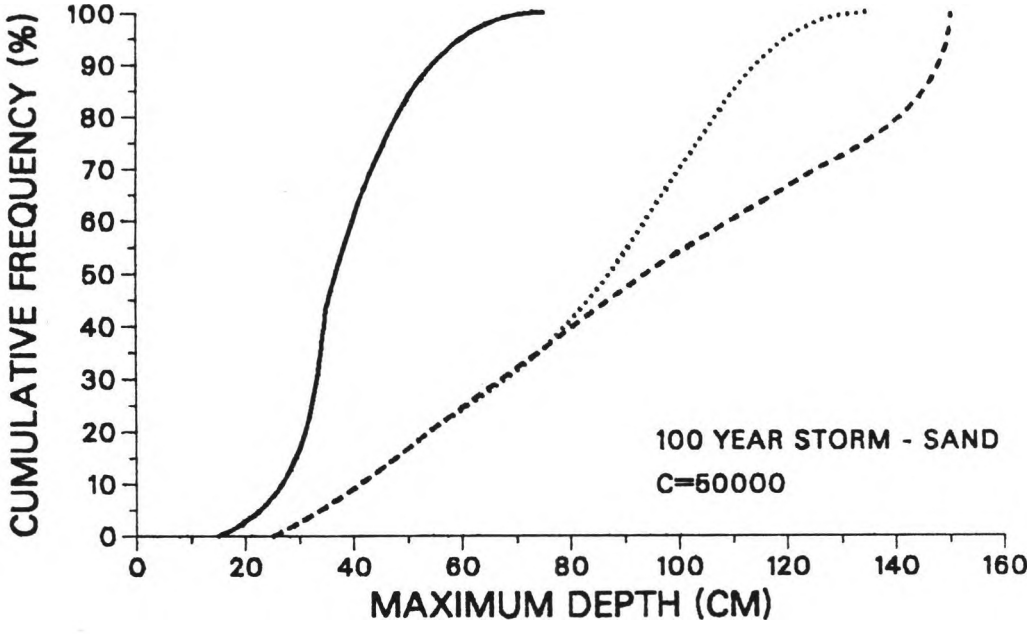

Figure V.22. Cumulative frequency distributions showing maximum depth of bacterial transport. All parameters are randomly generated. Initial bacterial concentration is 50000 (>4210) cells per cubic centimeter soil. 24 h (solid curve), 96 h (dotted curve), and 168 h (dashed curve).

The initial bacterial cell concentrations are the same as those associated with the solid curve in Figure V.21. All concentrations were greater than 4400 cells/cm^3 soil.

An analysis of the results of individual simulations indicated that an initial bacterial concentration of 20000 to 25000 cells/cm^3 soil was normally sufficient to cause contamination at 120 cm depth if parameter values were close to the mean. Two examples are shown for comparison. In the first example, the initial bacterial concentration was 19354 cells/cm^3 soil, the distribution coefficient was 0.128 cm^3/g (high), the die-off coefficient was 0.009/h (low), and the saturated hydraulic conductivity was 49.2 cm/h (high). The maximum depth of bacterial transport was 126 cm, in 144 h. In the second example, the initial bacterial concentration was 22977 cells/cm^3 soil, the distribution coefficient was 0.120 cm^3/g (high), the die-off coefficient was 0.026/h (high), and the saturated hydraulic conductivity was 176.2 cm/h (high). The maximum depth of bacterial transport was 99 cm, in 120 h.

Comparisons were made between two soils--sand and loamy sand--subjected to the 10 year storm (6.4 cm of rain over a 3 h period). The results are shown in Figures V.23(a) and V.23(b).

One would expect bacterial transport to be greater in sand than in loamy sand, and such is the case. Using the 40 cm soil depth at 24 h and the 120 cm depth at 168 h for comparison, one finds that the probability of bacterial transport beyond each depth to be 0.36 for 40 cm at 24 h and 0.48 for 120 cm at 168 h in sand. In loamy sand the probability of transport beyond 40 cm depth in 24 h was

0.15, and for 120 cm depth at 168 h, the probability was 0.36. Note the high probability of reaching 120 cm in each case.

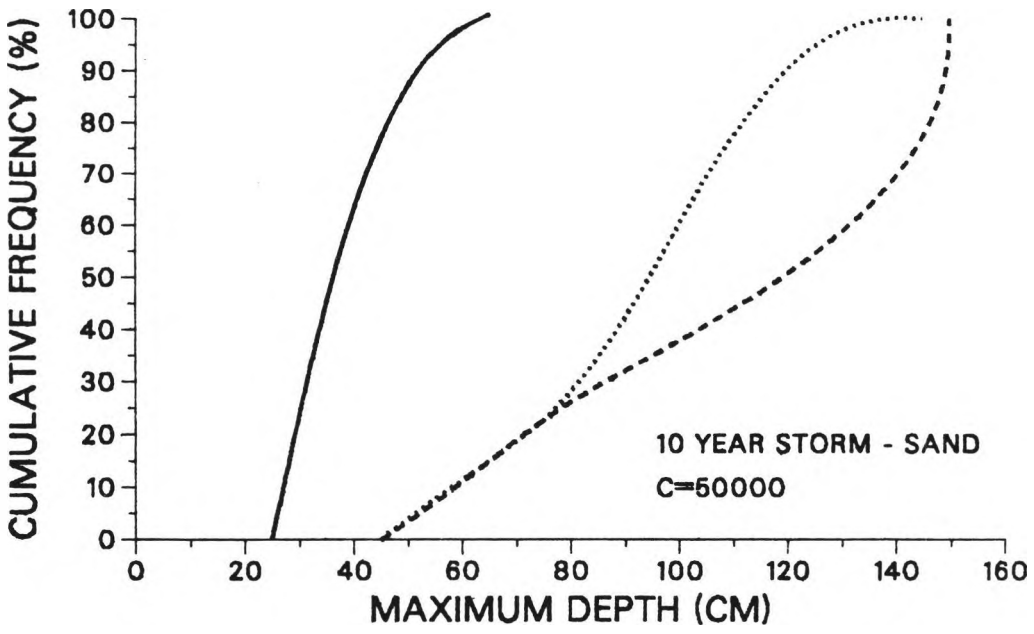

Figure V.23(a). Cumulative frequency distributions showing maximum depth of bacteria transport. All parameters randomly generated. Initial bacterial concentration 50000 (>4210) cells per cubic centimeter soil, 24 h (solid curve), 96 h (dotted curve), and (168 h (dashed curve) - sand.

Simulations were performed to indicate the relative importance of the distribution and die-off coefficients on maximum depth of bacterial transport. The same random number generator seed was used for each set of simulations, so that the random parameters were generally similar in each set.

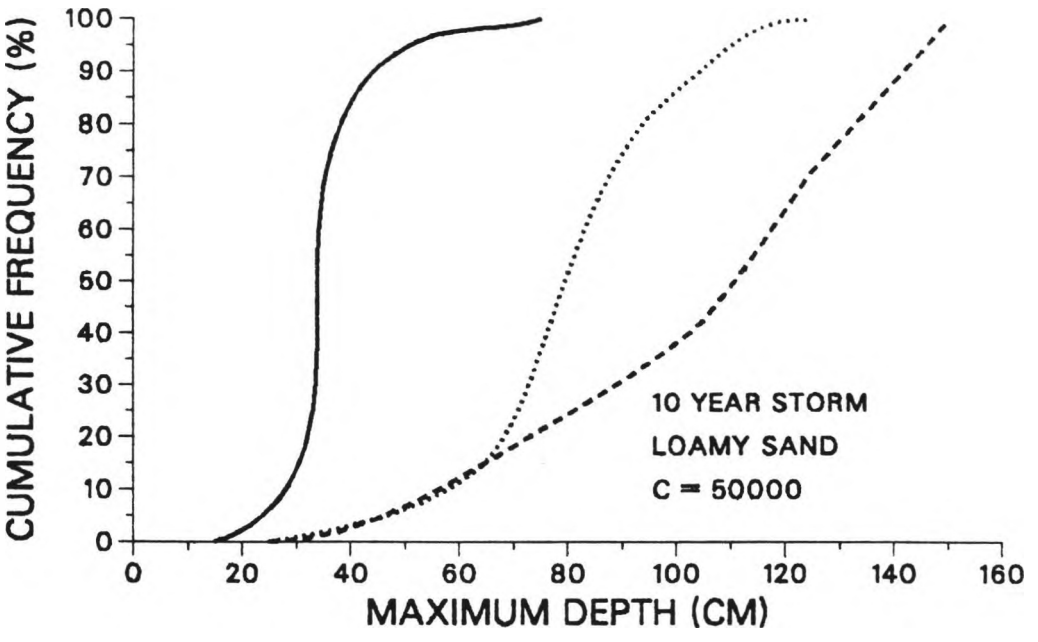

Figure V.23(b). Cumulative frequency distributions showing maximum depth of bacteria transport. All parameters randomly generated. Initial bacterial concentration 50000 (>4210) cells per cubic centimeter soil, 24 h (solid curve), 96 h (dotted curve), and (168 h (dashed curve) - loamy sand.

The results are shown in Figures V.24(a) and V.24(b). Disregard those regions of the graph where curves are vertical.

Note that the dotted curve crosses the dashed curve in Figure V.24(b). In those simulations in which the die-off coefficient is zero, bacteria had either stopped progressing in the soil, or the maximum depth reached at 96 h was generally in the range of 110 to 130 cm in depth. Because of the plug flow nature of the concentration profile when die-off is not a factor (Figure V.18) the curves have a different pattern at 168 h.

Analysis of the results showing maximum depth of bacterial transport after 168 h indicates that in some instances bacteria stopped progressing to depths beyond 110 cm. In most instances bacteria reached 150 cm. In 4 simulations (7%) the maximum depth of transport was between 105 and 145 cm, whereas in 35 simulations (57%) bacteria had been transported to the end of the soil column--150 cm. Thus, in Figures V.24(a) and V.24(b) the dotted curves are similar until about 100 cm depth. The curves are dissimilar

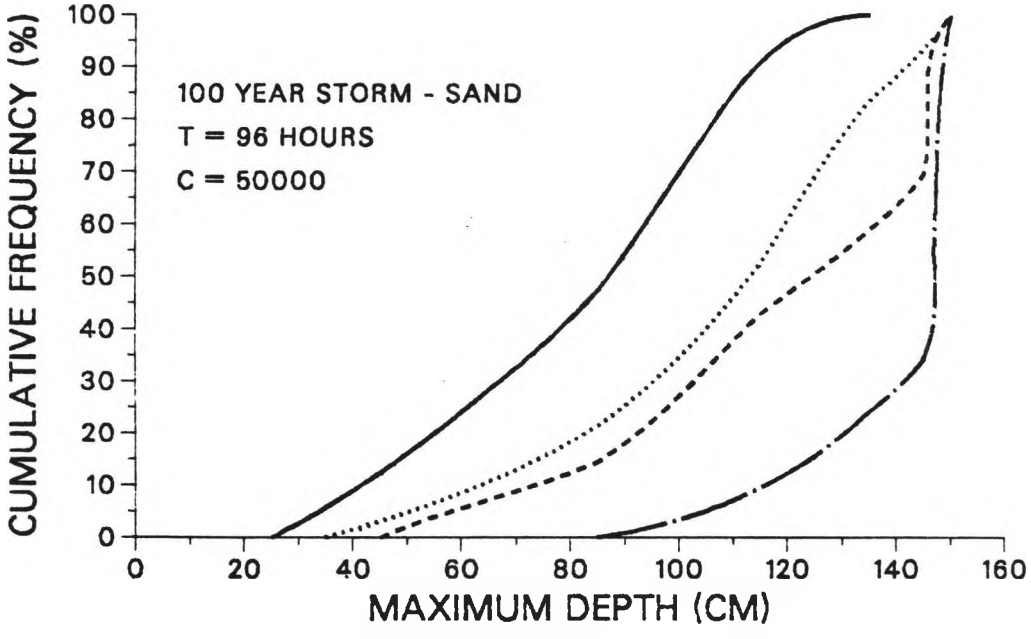

Figure V.24(a). Cumulative frequency distributions showing maximum depth of bacterial transport when parameter values are randomly generated (solid curve); when the die-off coefficient =0 (dotted curve); when the distribution coefficient=0 (dashed curve); and when both die-off and distribution values=0 (chain-dot curve) - 96 h.

from that point on. The dotted curve in Figure V.24(b) is flat until 145 cm--the result of the few cases where bacteria stopped between 105 and 145 cm.

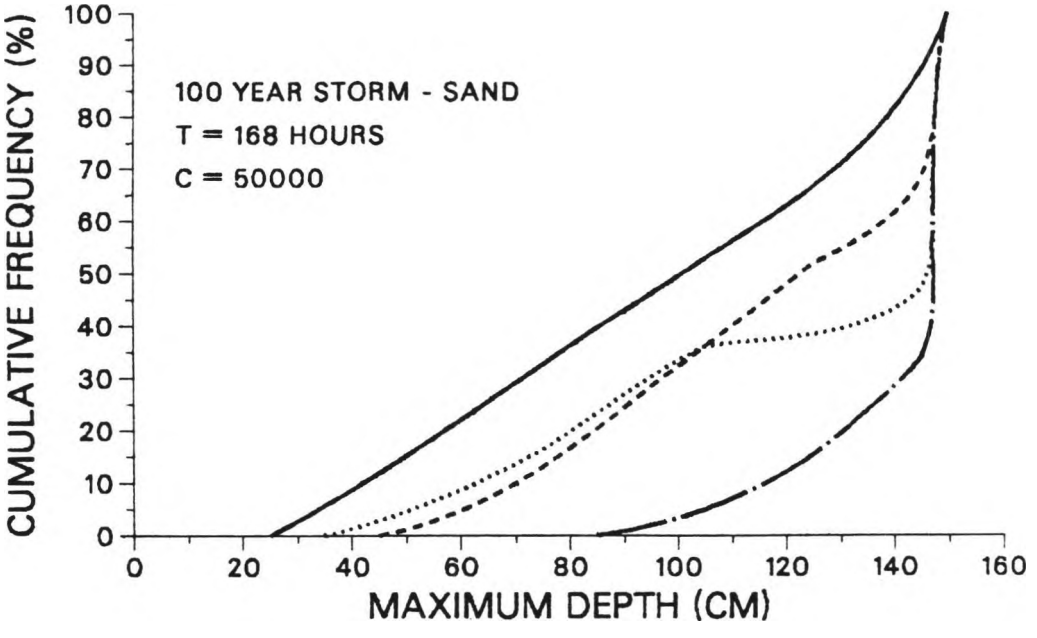

Figure V.24(b). Cumulative frequency distributions showing maximum depth of bacterial transport when parameter values are randomly generated (solid curve); when the die-off coefficient =0 (dotted curve); when the distribution coefficient=0 (dashed curve); and when both die-off and distribution values=0 (chain-dot curve) - 168 h.

The curves in Figures V.24(a) and V.24(b) show the importance of time. When die-off is not a factor, bacterial transport is retarded, but the bacteria do not die. Given adequate time and a sufficient initial concentration, bacteria will eventually reach 120 cm.

The results summarized in Figures V.24(a) and V.24(b) show the importance of both the die-off and distribution

coefficient to bacterial transport. The probability of bacteria reaching 120 cm in 168 h when all parameters are randomly generated is 0.35 (solid curve). If a soil were primarily coarse material with little clay, then adsorption and straining would be limited. In this case, the distribution coefficient would be very small, or zero. The probability of bacteria reaching 120 cm in 168 h in this case is 0.52 (dashed line). If the soil water temperature were low and predation limited, then the die-off coefficient would be very small, or zero. The probability of reaching 120 cm in this situation would be 0.64. If adsorption, straining, temperature, and predators were not factors, then the probability of reaching 120 cm is 0.88.

These results indicate that bacteria are at least twice as likely to reach 120 cm when the die-off and distribution coefficient are not included in the transport equation. Whether or not these results are valid depends on what limiting factors are or are not accounted for in the two coefficients.

2. Bacterial Concentration at 120 cm Soil Depth

Cumulative frequency distributions for the log (base 10) bacterial concentrations were produced using the same simulations described in Section 1.

Bacterial concentrations were determined at the 120 cm soil depth for sand and loamy sands subjected to the 10 year storm. All parameters were randomly generated. A

comparison of cumulative frequency distribution curves is shown in Figure V.25.

In 27 simulations (48% of the total) for sandy soil the bacterial cell concentration at 120 cm was effectively zero (10 cells/cm^3 soil or less). In 33 simulations (50%) for loamy sand the bacterial cell concentration was also 10 cells/cm^3 soil or less.

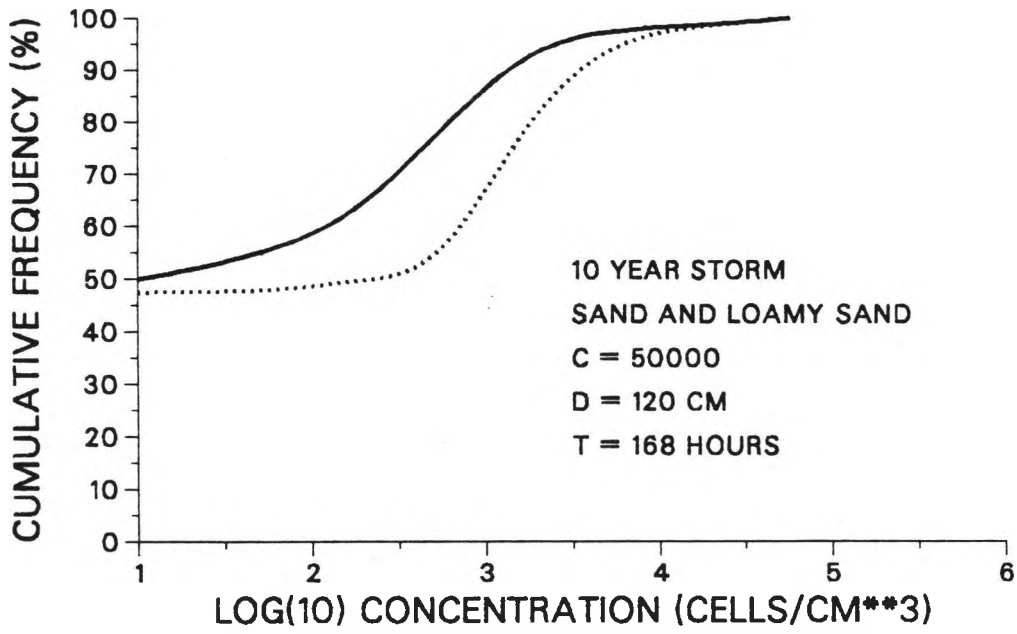

Figure V.25. Cumulative frequency distributions showing bacterial concentrations at 120 cm soil depth. All parameters randomly generated. Initial bacterial concentration 50000 (>4210) cells per cubic centimeter soil. Loamy sand (solid curve); sand (dotted curve).

An analysis of the frequency distribution of bacterial concentrations indicated that the highest frequency of concentrations, discounting those mentioned in the previous

paragraph, occurred in the range of log 2.5 to log 3.5 cells/cm^3 soil for loamy sand soil and in the range of log 3.0 to log 4.0 cells/cm^3 soil for the sandy soil.

These results were not surprising since bacterial transport in sandy soils would be greater than in loamy sand soils. The probability of a bacterial concentration of 1000 cells/cm^3 soil or more at 120 cm depth and 168 h was 0.31 for the sandy soil and 0.13 for the loamy sand soil.

Simulation results were analyzed to determine the relative importance of the distribution and die-off coefficients on bacterial concentration at 120 cm soil depth. The results came from the the same data set used to produce Figures V.24(a) and V.24(b), although bacterial concentration, not depth of transport, was the topic of interest.

When the die-off coefficient is equal to zero, the plug flow nature of the concentration profiles again affects the form of the dotted curves in Figures V.26(a) and V.26(b). At 48 h, no bacteria reached 120 cm depth when die-off equaled zero. At 96 h, 32 simulations (52%) indicated bacterial concentrations of less than 10 cells/cm^3 soil. Concentrations greater than log 3 cells/cm^3 soil occurred in 20 (33%) of the simulations. At 168 h, 22 simulations (36%) indicated bacterial concentrations of less than 10 cells/cm^3 soil. Concentrations greater than log 3 cells/cm^3 soil occurred in 39 (64%) of the simulations. At 168 h, 49% of the simulations had concentrations in the range of log 3.5

to log 4.5 cells/cm^3 soil. The large number of simulations in which the bacterial concentration at 120 cm was between log 3.5 cells/cm^3 soil and log 4.5 cells/cm^3 soil caused the rapid rise in the cumulative frequency from around 0.40 to 0.82.

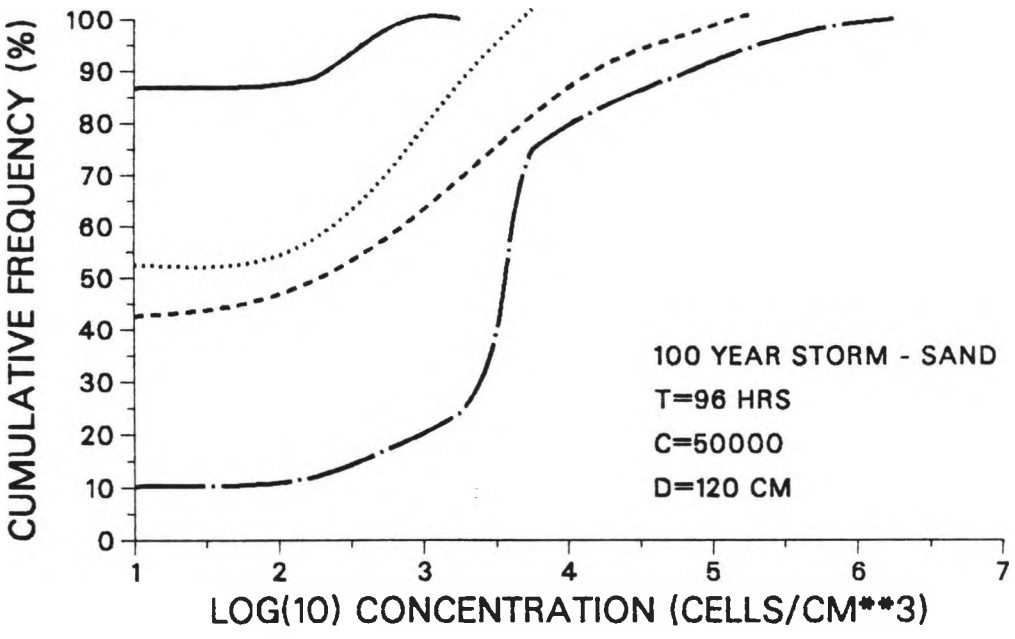

Figure V.26(a). Cumulative frequency distributions showing bacterial concentration at 120 cm depth when all parameter values are randomly generated (solid curve); when the die-off coefficient=0 (dotted curve); when the distribution coefficient=0 (dashed curve); and when both die-off and distribution values=0 - 96 h.

Analysis of Figure V.26(b) indicates results that are fully expected. When retardation is not a factor, bacteria would rapidly move through the soil column, leading to high concentrations at depth. The probability that the bacterial concentration is 4000 cells/cm^3 soil or greater is 0.18 when

the distribution coefficient is not included in the transport equation. Similarly, the probability for similar concentrations when die-off is not a factor is 0.13. When all the parameters are randomly generated, the probability of 4000 cells/cm^3 soil or more is 0.07. If both die-off and distribution are not factors, then the probability is 0.46.

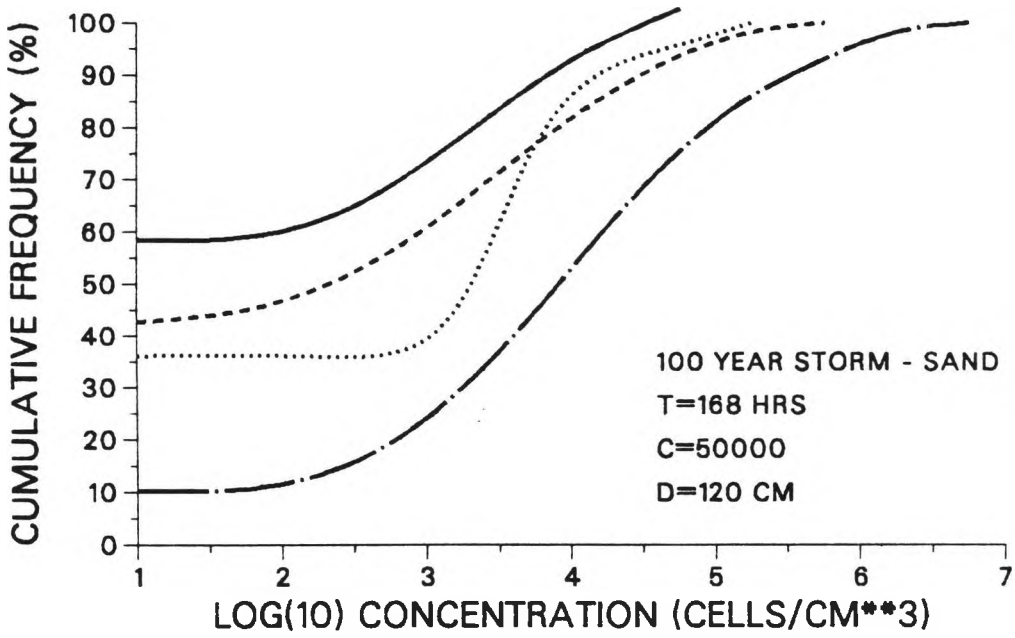

Figure V.26(b). Cumulative frequency distributions showing bacterial concentration at 120 cm depth when all parameter values are randomly generated (solid curve); when the die-off coefficient=0 (dotted curve); when the distribution coefficient=0 (dashed curve); and when both die-off and distribution values=0 - 168 h.

VI. SUGGESTED REGULATORY REVISION

The results of this investigation suggest that fecal coliform bacteria will eventually be transported beyond the arbitrary 1.2 m of suitable soil depth in coarse-grained soils typically found in the mountains along the Front Range of Colorado. With these results in mind, it is suggested that existing regulations may need to be revised to account for bacterial transport in these coarse, mountainous soils. Given the time and cost constraints under which government regulatory officials must work, any suggested revision must be easy to complete and inexpensive.

The common practice in wastewater engineering when bacterial retention cannot be obtained within the allotted soil depth is to increase that depth. Historically, this has been an arbitrary practice with little scientific justification.

The results of this research suggest that an increase in soil depth can have an important impact on bacterial retention. For comparative purposes only, one might analyze the solid curve in Figure V.24(b) on page 98. If one were to increase the soil depth from 120 to 140 cm (a 17% increase in depth), note that computer simulation results indicate that the probability of bacterial retention increases from 0.64 to 0.84 (an increase of 31%). Soil depth is an

important factor, but one must be careful when arbirarily applying the results of this research to field situations. Much additional research, under field conditions, is required before a direct, quantifiable correlation between depth of soil and bacterial retention is justified. The format of the results and the methodology of this investigation preclude the presentation of an easy method for determining an adequate depth for bacterial retention.

Analysis of the literature and the results of the computer simulations presented in this thesis indicate that the percentage of fines (silt and clay particles able to pass the U.S. Standard Sieve No. 200, with openings of 0.075 mm) is very likely the major factor leading to bacterial retention, whether by straining (clogging) or adsorption.

Stotzky (1986) is more specific. He says, "the major inorganic particulates that affect microbial events in soil are within the clay-sized fraction and consist primarily of clay minerals and polymeric hydrous oxides of mainly Fe(3+), Al(3+), and Mn(4+)." Stotzky (1986) is careful regarding what he calls "unwarranted and unsupportable inductive leaps." He goes on to say, "Although some studies with intact soil have shown the retention of bacteria and that this retention usually increases with increasing concentrations of clay, the mechanisms responsible for this retention (i.e. whether adhesion or mechanisms not involving surface interactions) have not been clarified."

Loamy sands have a higher percentage of fines than do sands. The results of the computer simulations, presented earlier, suggest that the percentage of fines are important. Comparing the 168 h curves (dashed curves) in Figures V.23(a) and V.23(b) on pages 95 and 96, one will note that the probability of bacterial retention within 120 cm soil depth is 0.64 for loamy sand and 0.52 for sand. This is an increase in retention probability of 23% when a soil with additional fines is used. As in the case with soil depth, the results of this research cannot be transferred directly to field conditions. Additional research is needed. Until new quantitative procedures are available, temporary modifications or revisions of existing regulations may be necessary.

The commonly used percolation test should be replaced by or amended with a particle size analysis. As an added factor, one might determine the quantity of organic matter present in the soil. Because organic matter may be assumed more transient than soil particles, its use may be limited. Clay-sized particles, clay minerals, and organic matter retain bacteria.

A suggested starting point in developing a procedure for estimating the bacterial retention capability of a soil using a method based on soil particle size analysis is the Busch and Luckner (1974) equation (referenced in Matthess and Pekdeger, 1985). Busch and Luckner (1974) define a geometrical suffusion security value, GSS, which can be

used for the determination of mechanical filtering criteria. The equation is basically a ratio of the diameter of the microorganism of interest to the diameter of the soil particle size with 10% finer--e.g. 10% of the particles are smaller than this specific diameter. This equation is analogous to the coefficient of uniformity used in geotechnical engineering. The Busch-Luckner equation with parameters defined is

$$GSS = \left| dm \,/\, (Fs*dk) \right| \geqq 1.5 \qquad \text{(VI.1)}$$

where

dm = diameter of microorganism (L)

Fs = empirical transit factor - numerically 6 is used; this is a factor for the heterogeneity of a porous media

dk = hydraulic equivalent diameter of pore canals, equals 0.2 d(10) (grain size with 10% finer (L)

Using the Busch-Luckner equation and the values provided in Table VI.1., one will note that a 0.0001 mm diameter bacteria would not be retained by any of the soils listed. The limiting pore diameter for coarse silt would be 0.0072 mm. This equation is based on uniform grain size distribution. Because natural sediments are not uniform one must assume that a certain percentage of the soils listed in Table VI.1. will retain bacteria. A comparison of grain size, pore size, and microbe size is provided in Figure VI.1.

Table VI.1. Relationship between grain size and critical pore size (After Matthes and Pekdeger, 1985).

Soil	Grain Size (mm)	Fs*dk (µm)
Fine silt	0.002-0.006	0.72
Medium silt	0.006-0.020	2.4
Coarse silt	0.02-0.06	7.2
Fine sand	0.06-0.20	24.
Medium sand	0.2-0.6	72.
Coarse sand	0.6-2.0	240.
Fine gravel	2.0-6.3	720.
Medium gravel	6.3-20.	2400.
Coarse gravel	20.-63.	7200.

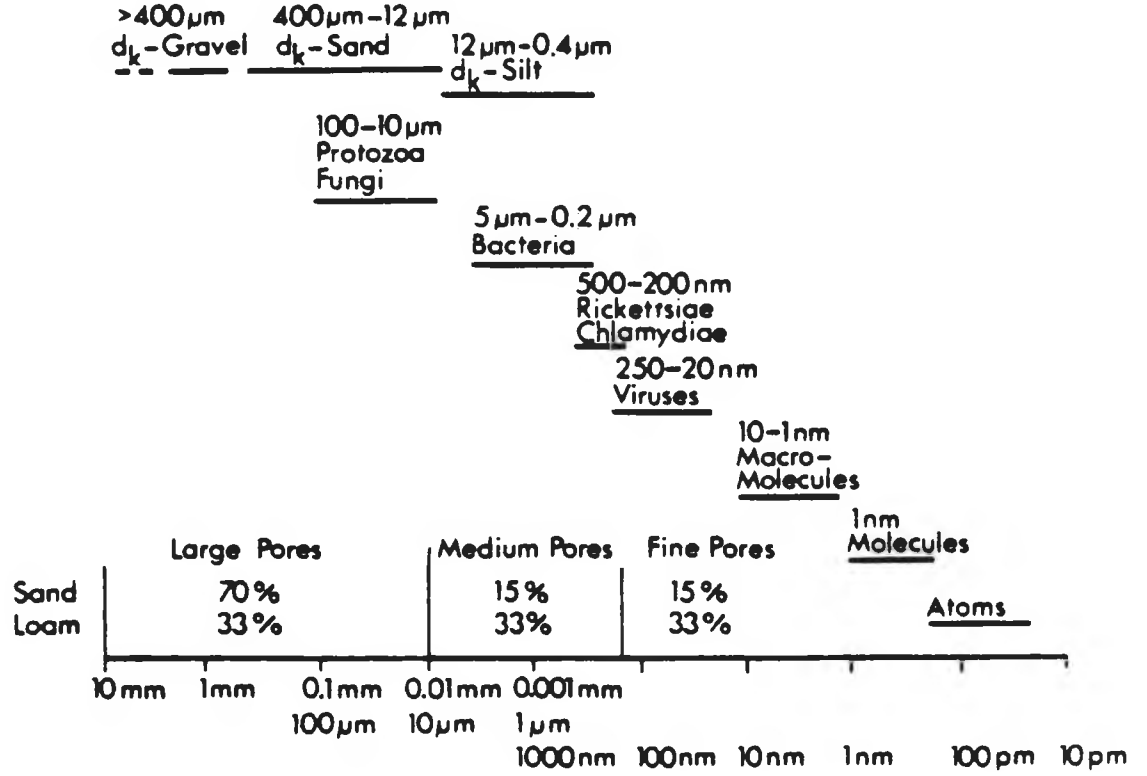

Figure VI.1. Comparison of grain size, pore size, and microbial size (After Matthes and Pekdeger, 1985).

Utilization of the Busch-Luckner equation or some form of the same would first require testing. This procedure may provide a estimation of the removal by mechanical filtration and provide a subjective feeling for the potential for adsorption--if that is a factor. An additional step would be an analysis of the clay fraction. This additional analysis may not be cost-effective.

Another empirical approach, requiring more extensive initial research, would be the development of a soil partition or distribution coefficient similar to that used in this modeling exercise. Equation IV.7 could be rearranged to leave

$$R = v_w / v_b = 1 + (\rho / \theta) k_a \qquad \text{(VI.2)}$$

Knowing that the retardation factor is the ratio of the soil water velocity to that of the contaminant of interest (Anderson, 1979), one accepts that a high value of retardation indicates a strong tendency for adsorption or low mobility.

It is known that when hydrophobic solutes are introduced to soils, the amount of solute that disappears from solution often correlates with the amount of organic matter in the soil material (Dzombak and Luthy, 1984). It is also understood that the partition coefficient for organic solutes is a function of the soil-water partition coefficient and the fractional mass of organic carbon (Karickhoff et al., 1979; Roy and Griffin, 1985).

Using reasoning similar to that above, one could develop a soil distribution (partition) coefficient which is a function of soil particle size and organic matter content. With procedures similar to that presented in Hendricks et al. (1979) or possibly with data existing in the literature, one could develop partition coefficients for silt- and clay-sized particles and organic matter. Then one would estimate the relative contribution of each to the soil distribution coefficient by soil particle and organic matter content analysis. The contributions of each could be summed in the following form

$$k = \Sigma_i k_a^i f_i \qquad \text{(VI.3)}$$

where

k_a = soil distribution coefficient

i = size or organic matter fraction

f_i = fraction of the total mass represented by component i.

This procedure considers adsorption only; straining is not included.

To account for straining, one might add some form of a multiplicative factor to the distribution coefficient in equations VI.2 or VI.3. As indicated earlier, straining of bacteria is a function of the percentage of fine-sized particles. Straining is also a function of the size distribution. One may assume that large-sized particles mixed with small-sized particles could be an effective retentive material.

The partition coefficient multiplicative factor could be based on two factors or a combination of both. The percentage fines would increase the value of retardation when multiplied times the distribution factor. One would expect a retardation in bacterial movement as the percentage of fine-sized particles increased. One might also utilize a form of the uniformity coefficient (Holtz and Kovacs, 1981):

$$C_u = d(60) / d(10) \qquad \text{(VI.4)}$$

where

d(60) = grain diameter (in mm) corresponding to 60% passing by weight

d(10) = grain diameter (in mm) corresponding to 10% passing by weight.

d(10) means that 10% of the particles are smaller than the diameter d(10). A uniform, poorly graded soil would have a very low value--1 to 3, while a very well graded soil may have a value of 15 or above (Holtz and Kovacs, 1981).

Research would indicate whether the percentage fines would have equal weight with the uniformity coefficient. Most likely the percentage of fines is more important, because it is possible to have a well-graded coarse soil with few clay-sized particles.

Equation VI.2 becomes:

$$v_w / v_b = 1 + (\rho / \theta) k_a (a * \%fines)(b * C_u) \qquad \text{(VI.5)}$$

where

C_u = uniformity coefficient

a = fine-grain weighting factor

b = uniformity weighting factor.

An example of its use is given with the following hypothetical situation. The soil has a bulk density of 1.55 and the saturated water content is 0.34. The soil distribution coefficient is arbitrarily chosen as 1.0. The percentage of fines is 40% and the coefficient of uniformity is 10--both arbitrarily chosen. The fine-grain weighting factor is given an arbitrary value of 1, and the uniformity weighting factor is arbitrarily chosen as 0.2. For these parameters the retardation factor is 369, implying that the soil water velocity would be 369 times that of the bacteria. If the soil was thought to be dryer, such as 0.15, then the velocity ratios would be 825. One could use these values to determine whether the particular soil is adequate to retain bacteria long enough for them to die-off. The assumption in this case is that they are adequately retained.

If particle size and organic matter analysis indicated limited retardation, then two additional procedures may be considered. One may remove and "homogeneously mix" a larger volume of soil to provided a greater depth for bacterial retention and die-off. One may also consider adding fines to the soil mixture to accomplish the same task. Either activity should be considered a short-term recommendation until further research can provide definitive answers.

As stated at the beginning of this chapter, these results suggest that the 1.2 m of coarse-grained,

mountainous soil is unlikely to be adequate for bacterial retention. Fecal coliform pollution at homesites located in these coarse-grained soils is well documented (Allen and Morrison, 1973). Transport of bacteria in soil involves numerous complex processes. This complexity is reflected in the difficulty of directly transferring the results of this research into quantitative management and regulatory guidelines regarding an increase in soil depth to account for the predicted bacterial movement.

VII. SUMMARY AND CONCLUSIONS

A. Summary

On-site wastewater treatment systems placed in coarse-grained, oligotrophic soils such as those typically found in the mountainous regions of the West are designed and installed with the assumption that most pathogenic microorganisms will not pass unaltered through an unsaturated zone located in the soil below each system.

Studies have shown that 0.6 to 1.2 m of unsaturated soil below an on-site system drainfield is sufficient to remove most bacteria and viruses in most environments.

Little is known of the transport of pathogenic, copiotrophic bacteria in coarse-grained soils below on-site drainfields placed in mountainous soil environments thought to be oligotrophic.

A stochastic bacterial transport model was developed to analyze bacterial translocation in coarse-grained, mountainous soils beneath a hypothetical on-site drainfield/soil interface. Specific model parameters were randomly generated using a procedure known to produce either a normal or log-normal distribution of random numbers. Numerous computer simulation runs were completed, and the

resulting output was used to generate cumulative frequency distributions.

Results from these simulations indicate that copiotrophic, enteric bacteria have the potential to travel great distances in oligotrophic, coarse-grained soils. The copiotrophic bacteria are likely to travel beyond the arbitrary 1.2 m of soil under conditions typically occurring in mountainous regions.

B. Conclusions

Results of the bacterial transport model simulations suggest the following conclusions.

1. There was minimal difference in bacterial transport between the 10 year storm of 6.4 cm of water and the 100 year storm of 9.0 cm of water.
2. Bacteria reached 1.2 cm soil depth under normal wastewater loading.
3. The initial concentration of bacteria at the soil/pipe interface is a major factor influencing the probability of bacteria being transported 120 cm in the soil.
4. The presence or absence of adsorption and the degree of straining by soil particles have a major impact on the distance of bacterial transport and the time required for transport through a specified column of soil.
5. Cold soil and soil water temperatures, as suggested by minimal values in the die-off coefficient, facilitate bacterial transport.

6. Inclusion of bacterial motility in the bacterial transport equation had minimal impact on the results.
7. Sandy soils are more permeable to bacterial transport than finer grained soils such as loamy sand.

C. Recommendations

The management recommendations, at this stage of research, are limited. The research recommendations are unlimited because the unknowns on in-situ soil bacterial activity exceed the knowns. With regard to these conditions, the following recommendations are narrow in focus.

1. In spite of its limitations, the percolation test will continue as the primary site sampling procedure in most states. It is suggested that a soil particle size analysis procedure be developed and adopted for those locations where coarse-grained soils are commonly found.
2. Research on temporal changes of coarse-grained, macrocrystalline rocks, and the effect on soil permeability to water and microorganisms should be encouraged. Coarse, mountain soils are young soils. One may assume that the physical and chemical weathering will alter the soil structure. Large soil particles will become smaller, and the organic matter in the soil should increase over time. The result would be a soil less permeable to bacterial transport. Altered soil

permeability of the infiltration surface could lead to channeling of the wastewater in less permeable locations (Stenstrom, 1984).

3. There is a need for a biological assay of septic tank effluent, specifically at three locations--effluent within the drainpipe, effluent within the biological clogging layer, and effluent within the soil matrix below the leachfield trench or bed. In addition, the biological assay should include microorganisms associated with the solid matrix. Most bacterial concentrations provided in the literature are given for septic tank effluent measured at the effluent port and determined using the most probable number procedure --an approximation at best. The bacterial population between the effluent port of the septic tank and the soil/pipe interface has not been determined.
4. Septic tank effluent should be tested at various locations throughout the system to determine nutrient limitations--specifically available carbon. Hartel and Alexander (1987) determined that the major factor limiting proliferation of soil bacterial cells was the absence of carbon or nitrogen. A postulate of this thesis is that the soil below a drainfield is carbon-limited to enteric bacteria, even when cryptic growth (Chapman and Gray, 1986) is accounted for. These assumptions need to be tested.

5. Investigations are suggested to determine the impact of sporadic house use and the use of alternating beds on bacterial transport through potentially dried, coarse-grained material at the soil/pipe interface. A system subject to irregular usage may dry. When usage continues at a later date, the effluent may flow directly into the soil without filtration through the clogging layer.
6. Study on successional changes in the soil community prior to leachfield system installation and after one year of continuous use is suggested. Successional changes in the biological population may alter predator-prey relationships, organism viability, and competitive relationships. New niches may be occupied by genetically altered organisms. These topics have not been studied in an on-site wastewater system.
7. The research described in this thesis is based on the equilibrium assumption, where the reaction between the soil solution and soil solid phases are rapid and constant relative to the rate of convective transport. This would satisfy the local equilibrium assumption, the use of the distribution coefficient is valid (Travis and Etnier, 1981; Bahr and Rubin, 1987) and algebraic formulae (e.g. the Freundlich and Langmuir isotherms) may be used (Valocchi, 1985). This assumption requires further investigation. The Langmuir, Freundlich, and other specialized isotherms

have been applied to adsorption of microorganisms (Daniels, 1980), but the equilibrium assumption is commonly used more often than the kinetic assumption because the mathematics are easier (Klute, 1983).

9. Additional investigations in cell size reduction are required. In-situ bacterial cell reduction has not been confirmed, although "dwarf" cells have been noted using direct microscopic observation (Bakken and Olsen, 1987). Shehata and Marr (1971) found a direct correlation between growth rate and mean cell volume with Escherichia coli cells. Matin (1979) found that growth and size were directly correlated with Pseudomonas, but both were laboratory studies using continuous cultures. Bakken and Olsen (1987) suggest that the majority of the small cells found in soil samples are not small forms of ordinary-sized bacteria. They found that the "dwarf" cells were species unable to form colonies on agar, or that they did not swell to normal dimensions when growing.
10. The influence of low temperatures on bacterial activity should be investigated. In mountainous locations temperatures may be a limiting factor during the winter months. Bacterial activity is reduced at low temperatures. Viraraghavan (1985) found waste-water temperatures of 3.3 C inside drainage tile and 2.2 C in soil at 0.76 m depth near the tile during the months on December and January in Ottawa, Canada.

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IX. APPENDICES

Appendix A. Definition of Bacterial Groups based on Ecological Niche and Habitat

A.1 Definition of oligotrophic and copiotrophic bacteria

A coarse soil ecosystem harbors a variety of diverse microorganisms. Grouping and naming bacteria based on their ecological niche is largely by personal preference. A consensus would probably accept three groups--autochthonous, zymogenous, and allochthonous.

The autochthonous bacteria are indigenous soil microbes with relatively stable populations regardless of environmental fluctuations. In a soil with limited nutrients, arthrobacters, a group of gram-positive bacteria, would be dominant in number. Zymogenous bacteria are transient, and their population fluctuates with the availability of nutrients. This group is typified by the pseudomonads, a group of gram-negative bacteria (Ensign, 1970). The allochthonous bacteria are non-indigenous. They may enter the soil during precipitation events or are carried in by other, larger organisms. The coliform group consists of gram-negative, allochthonous bacteria.

There is a divergence of opinion in the semantics of soil microbial ecology. Autochthonous and zymogenous are said to mean the same operationally as the aquatic

oligotroph and copiotroph terms, respectively (Andrews and Harris, 1986), with no allochthonous group defined. Because soil bacteria require an aquatic environment to function in a normal manner, autochthonous bacteria are referred to here as soil oligotrophs; zymogenous and allochthonous bacteria are referred to as soil copiotrophs.

Oligotrophs are those bacteria that can be isolated on culture media containing 1 to 15 mg organic C/l. They are generally small spheres or slender rods (less than .001 mm in length). Oligotrophs have high substrate affinity and low substrate specificity (Poindexter, 1981).

Copiotrophs (also called eutrophs) are those bacteria that require abundant nutrients, and this abundance is an important factor in their competitiveness (Poindexter, 1981). Klein (1984) suggests that copiotrophs can be isolated on media containing 1000 to 10,000 mg organic C/l.

Arthrobacter sp. are typical soil oligotrophs. The physiological properties of copiotrophs are typified by those of Escherichia coli, a common intestinal bacterium in humans (Fletcher and Marshall, 1982).

A.2 Example of Oligotrophic Soil Environment

The example of an oligotrophic soil environment is provided by Wilson et al. (1983) and Balkwill and Ghiorse (1985). Their site in Oklahoma differs from a coarse-grained mountain soil environment, but there are similarities--sandy soils, a shallow water table, and carbon-limited soils.

This site was predominantly sandy soils, with a water table located at 3.6 m. The total organic content of the sediment was 0.1% in the unsaturated zone and 0.04% in the interface and saturated zones (Wilson et al., 1983). A nutrient-limited oligotrophic environment was defined by Balkwill and Ghiorse (1985) as one with less than 0.04% organic matter in the sediment and less than 10 mg dissolved organic C/l in the groundwater.

Soil samples were studied at three depths--1.2, 3.0, and 5.0 m. The predominant forms (85-90%) of bacteria in all subsurface samples, regardless of depth or collection date, were gram-positive, coccoid rods that ranged from 0.0004 to 0.0009 mm in diameter (Balkwill and Ghiorse, 1985). Numbers of bacteria were generally constant with depth (3 to 9 x 10^6 /g dry material). No protozoa, yeasts, or other fungi were found in the samples (Wilson et al., 1983).

Appendix B. Explanation of Constraints Stated in Scope, Chapter I, Part C.

B.1 Fecal coliform defined

Fecal coliform bacteria are commonly used as indicators of recent fecal pollution and of the possible presence of pathogenic organisms. These bacteria are normally present, in large numbers, in the human intestine (Ziebell et al., 1975). The fecal coliform bacteria are easily isolated and enumerated, whereas most techniques for culturing, isolating, and quantifying pathogens are inaccurate and difficult for routine work (Ibiebele et al., 1985).

The fecal coliform group "comprises all aerobic and facultative anaerobic, gram-negative, non-spore forming, rod-shaped bacteria that ferment lactose with gas formation within 48 hrs" at 44.5° C, or those which produce a blue colony within 24 hr at 44.5° C on an M-FC medium (Standard Methods for the Examination of Water and Wastewater, 15th Ed.). The incubation temperature for fecal coliform is 44.5 C because at this temperature intestinal organisms can reproduce while non-intestinal organisms are less likely to grow.

The coliform group includes Salmonella, Shigella, Aerobacter and Eschericia coli (Mitchell, 1974). The medium and the incubation temperature are designed to eliminate all species except Eschericia coli.

B.2 Inherent Error in Sample Concentrations and Procedures

The true population of septic tank/leachfield effluent microorganisms is not known. Sublethal injury (McFeters et al., 1982) resulting from several environmental factors which impact sampling and sample transport (McFeters et al., 1974 and Bissonnette et al., 1975), and competition from heterotrophic plate count bacteria (LeChevallier and McFeters, 1985) during culturing limit the accuracy of most sample results. Alexander (1977) suggests that the total number of bacteria in soil is always higher than determined in plate count, and that cultural counting techniques approximate only 1 to 10% of the total count.

Problems develop when trying to apply laboratory column results to field situations. Organisms with the same genotype may show different phenotypes in the field. Bacteria typically do not develop extracellular polysaccharides in laboratory cultures (Costerton et al., 1978), although their presence is common and important in a natural environment. Much experimental work has been carried out with chemostat cultures under steady state conditions. Field conditions are not steady state; they are transient. On a pore scale, batch cultures may be more realistic. In spite of these difficulties, most microbial population studies utilize the Monod equation. The Monod equation is not valid in non-steady state conditions because the parameters are not independent of time (Curds and Bazin, 1977). It is impossible to specify any microbe in precise

terms of its structure and function without specifying the environmental conditions common at that time and point in space. Therefore, the problem of "plastic physiology" vs. growth in natural conditions becomes unavoidable (Tempest et al., 1983). Unfortunately, the laboratory vs. field problem cannot be solved at this time. In-situ experimental work is difficult, if not impossible in some cases, and many of the results are suspect. One is forced to utilize the experimental results available--most of which were generated in the laboratory.

B.3 Impact of Biological Clogging Layer

Research has not clearly defined or quantified the impact of the clogging layer on microbial population dynamics. Numerous studies have reported the bacterial population changes between the influent and effluent port of a septic tank for a few commonly studied bacteria (Ziebell et al., 1975; Otis et al., 1975; Tyler et al., 1978; and Stenstrom, 1984). The literature is limited with repect to what happens to a microbial population as it is carried from the septic tank through the drainpipe to the pipe/soil interface.

A biological mat or clogging layer does develop in the pipe and the pipe/soil interface. Mitchell and Nevo (1964) and Avnimelech and Nevo (1964) found a significant correlation between clogging rate and polysaccharide production. Mitchell and Nevo (1964) suggested that polysaccharides, not the bacterial cells, would have the

most impact on water flow through sands. Avnimelech and Nevo (1964) suggested that high C:N ratios induced long lasting clogging, while low C:N ratios caused clogging for only short periods. Kristiansen (1981a) found no indication of higher production of organic matter in the clogged region. He found a C:N ratio of 5.9 in the clogging layer and a C:N ratio of 5.8 in the rest of a sand filter trench. "Average" C:N in soil is 10 (Alexander, 1977). A very small amount of slimy material may contribute to clogging by cementing together small particles such as bacterial cells (Kristiansen, 1981a).

The clogging layer would reduce the hydraulic conductivity of the porous media. The infiltration rate through the clogged layer in sands is approximately 5 cm/d, which is the loading rate adopted for soil disposal systems placed in sand (Ziebell et al., 1975 and Bouma et al., 1972). The role of the clogged layer in microbial population reduction is not well defined or quantified. The usual approach is to utilize the population determined at the septic tank effluent port and "deliver" that population to the soil surface in the drainfield.

B.4 Neglect of Hysteresis

The relationship between water content and pressure head will depend on the volumetric water content when the reversal from drainage to wetting (or vice versa) occurs. No single-valued water content-pressure head relationship is correct; there are infinitely many hysteretic curves (Klute,

1969 and Hopmans and Dane, 1986). Entrapped air, dead end pores, the arrangement of pores and particles (Klute, 1973) and the type of boundary condition applied (Hopmans and Dane, 1986) all influence the water content-pressure head function. Also, one must remember that the water content-pressure head relationships are determined at hydraulic equilibrium, not under a state of water flow. As a result the water content-pressure head relationship under static conditions may not be the same as under unsteady-state condition (Klute, 1973).

Because water content profiles are very site-specific and because these profiles are more affected by hysteresis with pressure head boundary conditions than for flux boundary conditions (Hopmans and Dane, 1986), a water content-pressure head function with "average" parameters for the specific texture of soils was chosen.

For a given pressure head the water content is greater on the drainage curve than on the wetting curve on a typical soil water characteristic curve. As a result, with a higher water content assumed, the hydraulic conductivity is overestimated.

For a study of this nature, estimating a true wetting curve for coarse-grained soils would be impossible; estimating a "generic" wetting curve would be difficult. The necessity of such an action at this stage is questionable. Hysteresis is a factor, but it must be neglected in this study.

B.5 Generation of Design Storm Intensity and Duration

Two design storms, the 100 yr-6 h storm and the 10 yr-6 h storm, were chosen because they provided the greatest amount of precipitation during the shortest time interval for a hypothetical location in Rist Canyon, west of Fort Collins, Colorado. This location was chosen because it typifies the mountainous regions where coarse-grained soils present problems in placement of on-site systems. Storm depth and duration were determined using a precipitation frequency atlas for Colorado (Miller et al., 1973). The storm depths were 9 cm and 6.4 cm for the 100 year and 10 year storms, respectively.

The storm distribution was determined using a method presented by Huff (1967). A first quartile storm at the 10% level was chosen. With this storm, 80% of the precipitation occurs during the first 20% of the storm. This situation is frequently associated with short-duration storms, such as major rain bursts (usually thunderstorms) followed by light rain (Huff, 1967). Storms of this type are frequent along the front range of Colorado.

Using the procedure given by Huff (1967) calculations indicated that 96% of the precipitation occurred during the first three hours (75% during the first hour, 18% during the second hour, and 3% during the third). Both the 100 yr and the 10 yr storms were reduced from 6 h to 3 h storms. The 100 yr storm had a distribution of 6.8, 1.6, and 0.6 cm

during the three hours. The 10 yr storm had a distribution of 4.8, 1.1, and 0.5 cm during the three hours.

These rainfall rates were precipitation inputs to the soil water transport model.

Appendix C. Derivation of the Cui Growth Equation.

Monod (1942) proposed that growth rate of bacteria might be related to substrate concentration in a manner similar to enzyme kinetics (Bader, 1982). Because of this relationship, the Monod equation is often related to the Michaelis-Menten equation, although the latter is an enzyme kinetic equation (Bader, 1982).

The Monod equation is

$$\frac{dC}{dt} = C \left[\frac{\mu_m \, s}{K_s + s} \right] \qquad (C1)$$

where

μ_m = maximum growth rate at high nutrient concentration (/T)

K_s = saturation constant (concentration which allows the organism to grow at half the maximum rate (M/L^3)

s = substrate concentration (M/L^3)

Under batch conditions, parameters can be defined to describe nutrient transfer from the culture medium to the bacterial population. Let S' be the nutrient per volume that has been absorbed by the bacteria, and s be the nutrient per volume that remains in the solution and not yet utilized by the bacterial population. Then the total amount of nutrient in the batch culture is S_m, a constant, and

$$S_m = S' + s \qquad (C2)$$

Using a transfer coefficient, a, with units of mass, to translate the nutrient term to a population density, results in

$$s = aC \qquad \text{and} \qquad S_m = aC' \tag{C3}$$

One can then suggest that s grams of nutrients has resulted in C of bacterial population, and S_m grams of nutrient has become C' of bacterial population. C' is the maximum population allowed in the batch culture.

Thus, the Cui equation is derived from the Monod equation (C1) in the following manner:

$$\frac{dC}{Cdt} = \frac{\mu_m s}{K_s + s} = \frac{\mu_m (S_m - S')}{K_s + S_m - S'} = \frac{\mu_m (C'-C)}{C''-C} = \frac{\mu_g (1-C/C')}{(1-C/C'')} \tag{C4}$$

where

$$C' = S_m / a \tag{C5}$$

$$C'' = (K_s + S_m)/a \tag{C6}$$

$$\mu_g = \mu_m C'/C'' \tag{C7}$$

Because

$$C'/C'' = S_m/(K_s + S_m) = 1/(1 + K_s/S_m) \tag{C8}$$

the ratio K_s/S_m controls the value of C'/C". When K_s/S_m is small, then C'/C" = 1, and the growth curve is exponential. When K_s/S_m is large, then C" >> C', and the population is nutrient-limited. The growth form is then logistic (Cui and Lawson, 1982).

Knowing the initial bacterial population, the maximum bacterial population, and C(i) and t(i) at i=1,2,...n, in the batch culture, C" and μ_g can be determined by the least squares method (Cui and Lawson, 1982).

For continuous cultures in a chemostat system, the Cui equation would take the form

$$\frac{dC}{dt} = \mu_g C \frac{1 - C/C'}{1 - C/C''} - D C \qquad (C9)$$

where

D = output rate (dilution rate of medium) (/T)

and

$$D = F/V \qquad (C10)$$

F is the flow rate, and V is the chemostat volume.

Under steady state conditions, dC/dt = 0, and the output rate equals the growth rate (Cui et al., 1984).

Appendix D. Explanation of Particle Surface Conditioning and Bacterial Hydrophobicity and Adsorption

D.1 Conditioning of Porous Media Surfaces

Interfaces in aqueous surroundings are rapidly coated with a "conditioning" layer of adsorbed macromolecules and lipids (Fletcher, 1976). This diverse array of macromolecules, including proteins, glycoproteins, proteoglycans, and polysaccharides, are present in low concentrations in natural environments. These macromolecules may be excretory products from living organisms or be decompositional products from dead plants, prokaryotes, or eukaryotes (Fletcher and Marshall, 1982). These surface materials can serve as nutrients (carbon, energy, and nitrogen sources) for bacteria (Kjelleberg and Hermansson, 1984). The adsorption of these materials on particle surfaces changes the energy characteristics of the surfaces (Fletcher and Marshall, 1982).

D.2 Bacterial Hydrophobicity and Adsorption to Surfaces

Essentially all soil surfaces are eventually colonized by bacteria (Fletcher and Marshall, 1982). Most of these bacteria bear a net negative surface charge (Harden and Harris, 1953), while most mineral surfaces are negatively charged. The result is a repulsive force between bacteria and mineral surfaces (Fletcher and Marshall, 1982).

The surface charge of soil is typically associated with the presence of clay-sized particles and soil organic

matter. The charged surface is usually the result of isomorphic substitution and ionization of functional groups (Bohn et al., 1979).

Isomorphic substitution of ions with greater or lower charge than the ion for which it substitutes, will develop a positive or negative particle surface. Negative charge development is more common. The total charge of soil particles may vary with pH. Through the gain or loss of hydrogen ions, soil particle charge may vary. Highly weathered soils dominated by allophane and hydrous oxides may actually have a net positive charge at low pH (Bohn et al., 1979).

Repulsive forces between bacteria and particle surfaces depend on several factors--the net charge of the two surfaces, the distance between the surfaces, the electrolyte concentration, and the radii of curvature of the surfaces (Fletcher and Marshall, 1982). These repulsive forces can be overcome by hydrophobic bacteria, resulting in an increased probability of surface adsorption.

Bacterial hydrophobicity "has no unequivocal definition, nor a definitive scale of values" (Rosenberg and Kjelleberg, 1986). Generally, hydrophobic bacteria are "rejected" from the aqueous phase and attracted toward any non-aqueous phase (including soil particles) (Marshall, 1976). Bacteria that are hydrophilic all over, with the exception of a hydrophobic tip may be hydrophobic in one

analysis and hydrophilic in another (Marshall and Cruickshank, 1973).

An increase in electrolytes will suppress electrostatic interactions and result in an increase in hydrophobicity (Rosenberg and Kjelleberg,1986) and enhance adsorption potential. The strongest adsorption of bacterial cells generally occurs at pH of 3-6. Addition of multivalent cations to a solution can increase adsorption, while the addition of inorganic salts to a suspension can promote desorption (Daniels, 1980). It is thought that humic or fulvic acids--organic compounds naturally present in water and soil--also cause desorption (Sobsey, 1981).

A reduction in the size of bacteria (Fletcher and Marshall, 1982), or the extrusion of narrow-diameter probes which can come within close enough range of a particle surface to form hydrogen or ionic bonds, can increase hydrophobicity (Rogers, 1979) and facilitate adsorption.

No one factor is thought to cause cell-surface hydrophobicity. Several have been suggested--fimbriae, proteins, core oligosaccharides, outer membrane lipids, etc. These bacterial cell components vary as a function of growth conditions, including such factors as aeration, temperature, growth medium, and cell age, and they vary from species to species and strain to strain (Rosenberg and Kjelleberg, 1986).

Bacteria appear to adsorb by means of extracellular surface polymers (Costerton et al., 1978). Three main types

of surface polymers appear to be involved in the adsorption interaction, (1) lipopolysaccharides, in gram-negative bacteria, (2) peptidoglycan, in gram-positive bacteria, and (3) extracellular polymers and capsules which occur on both types of cells (Fletcher and Marshall, 1982). Lipopolysaccharides extend a considerable distance from the end of the outer membrane of many fecal coliform organisms. (Rogers, 1979). Some proteins actually inhibit attachment of bacteria to a variety of surfaces (Fletcher, 1976).

Intermittent water flow over soil particle surfaces may provide sufficient time for the polymer/surface adsorption to develop, and once adsorbed they are not readily affected by liquid shear (Powell and Slater, 1982). Some investigators (Wimpenny et al., 1983) believe the polymer bonds are irreversible.

In situ surface characteristics of bacteria and porous media are difficult to estimate, making it difficult to extrapolate from laboratory experiments to in situ adsorption (Rosenberg and Kjelleberg, 1986).

Surface adsorption and cell hydrophobicity may be influenced by the type and amount of clay particles present in the soil. In aqueous suspension, colloidal clays form an envelope around bacterial cells as a result of the electrostatic attraction of clay to charged bacterial surfaces (Marshall, 1975). Results published by Roper and Marshall (1978) indicate that clay particles provide an

effective barrier from predation and parasitism for some bacteria--fecal coliform bacteria included.

Relatively little is known about direct surface interactions between clays and bacteria in soil in situ (Stotzky, 1986), but it is reasonable to assume that the presence of clay particles on bacterial surfaces would influence the soil particle surface-bacterium interaction. "Clay minerals apparently exert their primary influence on microbial events by modifying the physicochemical characteristics of microbial habitats" (Stotzky, 1986).

Appendix E. Numerical Solution of Finite Difference Approximations of Soil Water and Bacterial Transport Equations.

The method of solution is an explicit-implicit finite difference approximation (Selim and Iskandar, 1980). This method was used successfully by Selim (1978) for transient water and solute movement in soil.

In finite difference form the pressure head variable, h, is expressed as

$$h_i^j = h(z,t) = h(i\Delta z, j\Delta t) \qquad (E1)$$

When the soil water flow equation (III.6) is written, it is necessary to write the space derivatives to match the time derivatives. This is accomplished by taking 1/2 time step at the explicit level h(j=t) and 1/2 time step at the implicit level h(j=t+Δt).

The equations are non-linear because both the K and the CAP terms of equation (III.6) are a function of h at j+1/2, but depend on values of h at j+1, for which solutions are sought (Selim and Iskandar, 1980). An iteration method used by Remson et al. (1971, p.98) is used to predict h at j+1/2 using h at j (Selim and Iskandar, 1980). Selim and Kirkham (1973) showed that the solution of the water flow equation can be approximated using h at j when small values of Δt are used. This simplification makes the system of equations linear (Selim and Iskandar, 1980).

By rearranging terms of the soil water equation in finite difference form and incorporating the initial and

boundary conditions, the water transport equation can be written in matrix-vector notation as

$$W \vec{h}^{\,j+1} = \vec{u} \qquad \text{(E2)}$$

where W is a tridiagonal matrix and $\vec{h}$ and $\vec{u}$ are the associated column vectors.

The tridiagonal system of equations is solved by an adaptation of the Gaussian algorithm as described by Henrici (1962, p. 352)(Selim and Iskandar, 1980). The bacterial tranport equation (III.22) is solved with the same procedure.

Appendix F. Explanation on Use of Cumulative Relative Frequency Distributions.

Empirical cumulative relative frequency distributions were constructed using the results of the stochastic simulations. A hypothetical example is used to explain their construction. Assume 50 simulations were conducted, and a distribution was to be constructed based on the results at 120 h. The maximum depth of bacterial penetration at 120 h in each of the simulations was determined and grouped in class intervals. The number in each class interval is a percentage of the total number--the relative frequency histogram. From this a cumulative relative frequency distribution was constructed by summing the relative frequency of each class interval with the relative frequency of each previous interval. The sum of all relative frequencies is equal to one, or 100% if expressed in percentages.

To read the cumulative frequency distribution, find the intersection of the particular curve with the depth of interest. If the depth of interest is 120 cm and the lines of intersection coincide with a cumulative frequency of 10%, then one may suggest that the probability of bacteria being transported beyond 120 cm is 0.90, and the converse, that the probability of bacteria being retained in the first 120 cm is 0.10.

It is important that one not use the cumulative frequency graphs for depths greater than 140 cm because the

interpretation could be incorrect. This problem is the result of the special constraints of this study. The soil column length is defined as 150 cm. When bacteria reach the 150 cm depth, no further consideration is given to those bacteria. Therefore, the last class interval is 150+ cm. As a result, the curves in the cumulative frequency distribution converge to 100% near 150 cm depth. In some situations the cumulative frequency curves approach the vertical giving distorted, impossible results. As an example--assume that in 50 simulations, bacteria reached 150 cm depth in 47 simulations. The cumulative frequency curve would go from 6% to 100% between 145 and 150 cm. Any attempts at interpretation in this region would provide faulty information. It is suggested that when using the graphs dealing with maximum depth of bacterial transport, use only those depths up to and including the one stated in the objectives--120 cm.

Appendix G. Summary Data on Parameters Used in Simulations.

The values listed below are the means of N simulations. The range of values is in parentheses. The distribution coefficient is expressed in cm^3 /g. The coliform concentration is expressed in cells/cm^3 soil. The die-off coefficient is expressed in /h. The saturated hydraulic conductivity is expressed in cm/h.

A. 100 Year Storm - Sand
Initial Bacterial Concentration = 50000

N=73
Distribution Coefficient = 0.181 (.061 - .341)
Coliform Concentration = 29360 (10 - 480989)
Die-off Coefficient = .018 (0 - .040)
S. Hydraulic Conductivity = 139 (5.4 - 975.9)

B. 100 Year Storm - Sand
Initial Bacterial Concentration = 50000 -- >4210

(1) All Parameters Randomly Generated
N=53
Distribution Coefficient = 0.175 (.009 - .319)
Coliform Concentration = 60668 (4409 - 848943)
Die-off Coefficient = 0.018 (.002 - .036)
S. Hydraulic Conductivity = 283.1 (5.4 - 3148.0)

(2) Decay Coefficient = 0
N=61
Distribution Coefficient = 0.178 (.084 - .333)
Coliform Concentration = 136572 (4396 - 2942878)
S. Hydraulic Conductivity = 143.0 (6.4 - 1184.8)

(3) Distribution Coefficient = 0
N=56
Coliform Concentration = 142427 (4396 - 2942878)
Die-off Coefficient = 0.017 (.004 - .038)
S. Hydraulic Conductivity = 152.5 (6.4 - 1184.8)

(4) Decay and Distribution Coefficient = 0
N=58
Coliform Concentration = 290710 (4458 - 3903524)
S. Hydraulic Conductivity = 76.3 (5.0 - 524.2)

C. 10 Year Storm - Sand
Initial Bacterial Concentration = 50000 -- >4210

N=57
Distribution Coefficient = 0.177 (.043 - .293)
Coliform Concentration = 257296 (4222 - 12332385)
Die-off Coefficient = .015 (0 - .028)
S. Hydraulic Conductivity = 70.6 (5.1 - 745.7)

D. 10 Year Storm - Loamy Sand
Initial Bacterial Concentration = 50000 -- >4210

N=66
Distribution Coefficient = 0.216 (.006 - .329)
Coliform Concentration = 291917 (4855 - 6400118)
Die-off Coefficient = 0.016 (.001 - .036)
S. Hydraulic Conductivity = 87.4 (5.0 - 1978.2)

NOTE: The same random number generator "seed" was used for simulations summarized in section B above. To compare the results when various parameters are eliminated, the range of the other parameter values should be similar. They are not exactly the same because N simulations are not exactly the same.

Appendix H. Computer Program Documentation and Listing.

The computer program is written in FORTRAN 77 and consists of a main (BACMOV) program, eight SUBROUTINE programs, and six FUNCTION programs. Normal and uniform random number generators were obtained from the IMSL (International Mathematical and Statistical Library) library of subroutines available through the CSU Computing Center.

Documentation is included at necessary points throughout the program. A description of the main and each sub-program is provided below, followed by an explanation of the input data, and the sequence of steps during a typical simulation.

BACMOV reads input and prints output and controls the flow of the program.

SUBROUTINE ROUTE adjusts soil properties based on input, and controls the timing of the solution to the water and bacterial transport equations.

SUBROUTINE IDIST2 interpolates values at various depths based on the initial distribution.

SUBROUTINE WATER provides the solution to water flow equation.

SUBROUTINE TRIDM provides the solution to the tridiagonal matrix-vector equation.

SUBROUTINE BACNUM determines bacterial concentration when diluted by rain.

SUBROUTINE MICROC provides the solution to the bacterial transport equation.

SUBROUTINE WPROP2 provides soil water properties for each grid.

SUBROUTINE OUTPUT prints results at specified time.

FUNCTION DISPER generates dispersion coefficients based on water content and flux.

FUNCTION SATK generates a random value for saturated hydraulic conductivity.

FUNCTION DECAYC generates a random value for the bacterial die-off coefficient.

FUNCTION XCOLI generates a random value for the initial bacterial concentration.

FUNCTION RKC generates a random value for the bacterial distribution coefficient.

FUNCTION RTD generates a value for the retardation factor based on the distribution coefficient and water content.

The input data records are as follows:

1. NCYC = the number of rain cycles during a storm
2. KNOB = the type of output, 0.1 and 1 h intervals
   or 4, 12, 24 h intervals
3. DTT = initial time interval
   DZZ = initial grid length
4. CL = soil depth
5. DHEAD = displacement pressure head
   XLAM = lambda
   THS = water content at saturation
   THR = residual water content

6. DALPHA = dispersivity
7. TCYC = hours of output printed after rainfall ends
   TWRITE = interval of printing during cycle
   (usually equal to one hour)
   WTINF = duration of loading
8. NIN = number of data points for initial pressure head
9. XXX = soil depths for which pressure head is known
10. C1 = initial pressure head at each depth
11. RAIN = rate of rainfall
12. TINF = duration of rainfall

The sequential steps in a typical bacterial transport simulation are as follows:

(1.) Input data read, 1 - 7, as above.

(2.) Generation of random values for input bacterial concentration, die-off coefficient, saturated hydraulic conductivity, and distribution coefficient.

(3.) Input of soil depths and respective pressure head

(4.) Determination of initial water content, hydraulic conductivity, and water capacity for each grid.

(5.) Initial conditions printed at t=0.

(6.) Input of rain rate and duration.

(7.) Determination of bacterial concentration in top grid based on dilution from rain.

(8.) Solution of water and bacterial transport equations at each time step during rainfall.

(9.) Solution of equations during period of waste-water loading only.

(10.) All loading stopped. Ouput printed each time period requested. Time is relaxed (DT=2*DT) each DO loop cycle.

(11.) Return to (6.) if another rain event occurs. Program ends when requested.

```
      C*******************************************************C
      C                                                       C
      C      A  SIMPLIFIED    MODEL   FOR    PREDICTION      C
      C                                                       C
      C      OF   BACTERIAL    MOVEMENT    IN    SOIL        C
      C                                                       C
      C                                                       C
      C*******************************************************C
      C
00001       PROGRAM BACMOV (OUTPUT,TAPE5,TAPE6=OUTPUT)
      C
00002       COMMON/L1/   AA(155),BB(155),CC(155),R(155)
00003       COMMON/L2/   N,NM1,NM2,NP1,NP2
00004       COMMON/L3/   ALPHA,BETA,DT,DZ
00005       COMMON/L4/   NX,NX1,NRMAX,CON1
00006       COMMON/L5/   SFLUX
00007       COMMON/L6/   XXX(155),C1(155),C2(155),NIN
00008       COMMON/L7/   TIME,TINF,TCYC
00009       COMMON/L8/   H(155),CON(155),CAP(155),TH(155)
00010       COMMON/L9/   CL
00011       COMMON/L10/  DHEAD,XLAM,XEPS,CSAT
00012       COMMON/L11/  C(155),CO(155),CBREAK
00013       COMMON/L12/  CSCOLI,RRD,RKDC,RKAC
00014       COMMON/L13/  THS,THR,DSEED
00015       COMMON/L14/  DTT,DZZ,TWRITE
00016       COMMON/L15/  KNOB,NCYC,INFCT,WTINF
00017       COMMON/L16/  XTINF,COLI,RAIN
      C
00018       DOUBLE PRECISION DSEED
00019       DSEED=5446322.D+00
      C
00020    45 FORMAT(5X,'KNOB (OUTPUT FORMAT)              = ',I5)
00021    55 FORMAT(5X,'NUMBER OF STAGES IN STORM CYCLE   = ',I5)
00022   100 FORMAT(8F10.3)
00023   101 FORMAT(5X,'INITIAL DT, HR  =',F10.3/,5X,
           *'INITIAL DZ , CM =',F10.3//)
00024   110 FORMAT(5X,'TOTAL LENGTH OF SOIL PROFILE, CM =',F10.3/)
00025   115 FORMAT(5X,'SOIL WATER PARAMETERS : '//,
           *9X,'DISPLACEMENT PRESSURE HEAD =',F10.3/,
           *9X,'                    LAMBDA =',F10.3/,
           *9X,'   SATURATED WATER CONTENT =',F10.3/,
           *9X,'    RESIDUAL WATER CONTENT =',F10.3//)
00026   120 FORMAT(5X,'DISPERSIVITY = ',F10.3//)
00027   130 FORMAT(5X,'DURATION OF WASTEWATER LOADING AFTER',1X,
           *'END OF RAINFALL = ',F10.3)
00028   145 FORMAT(5X,'HOURS OF OUTPUT PRINTED AFTER RAIN STOPS',
           *13X,'= ',F10.3/)
00029   150 FORMAT(//,5X,'RATE OF RAIN  APPLICATION , CM/HR =',2X,
           *F10.3/,5X,'INFILTRATION TIME, I.E. DURATION OF RAINFALL',
           *', HOURS = ',F10.3/)
00030   160 FORMAT(T25,'I N P U T   D A T A',///)
00031   165 FORMAT('1')
00032   200 FORMAT(5X,'WASTEWATER FLUX IS CONSTANT AT 5 CM/DAY',1X,
           *'OR 0.208 CM/HR',//)
00033   210 FORMAT(5X,'DISTRIBUTION COEFFICIENT, K(AC),(CM**3/G)',
           *4X,' = ',F10.3)
00034   215 FORMAT(5X,'INPUT FECAL COLIFORM CONCENTRATION (#/CM**3)',
           *3X,' = ',F10.0)
00035   225 FORMAT(5X,'FECAL COLIFORM DECAY COEFFICIENT (PER HOUR)',1X,
           *' = ',F10.3)
```

```
00036     235  FORMAT(5X,'SATURATED H. CONDUCTIVITY (CM/HR)',10X,
                *'  = ',F10.3)
00037     300  FORMAT(I4)
00038     400  FORMAT(20X,'COLIFORM BREAKTHROUGH AT 120 CM, HR = ',F6.0//)
          C
          C      ******   DICTIONARY   ******
          C
          C---NSIMS    = NUMBER OF SIMULATION RUNS
          C---NCYC     = NUMBER OF RAIN CYCLES DURING A STORM
          C---KNOB     = 0, OUTPUT PRINTED AT 0.1 AND 1 HR INTERVALS
          C---           2, OUTPUT AT 4,8,12,16,20,24 HOURS
          C---DTT      = INITIAL APPROXIMATION OF DELTA T (HR)
          C---DZZ      = INITIAL APPROXIMATION OF DELTA Z (CM)
          C---CL       = TOTAL LENGTH (CM) OF SOIL PROFILE
          C---DHEAD    = DISPLACEMENT HEAD (CM) (AIR ENTRY PRESSURE)
          C---XLAM     = SOIL WATER PARAMETER LAMBDA
          C---THS      = SATURATED WATER CONTENT
          C---THR      = RESIDUAL WATER CONTENT
          C
00039           NSIMS=1
          C
00040           DO 9999 K=1,NSIMS
00041           REWIND 5
          C
00042           WRITE(6,165)
00043           WRITE(6,160)
00044           READ(5,300)  NCYC
00045           WRITE(6,55)  NCYC
00046           READ(5,300)  KNOB
00047           WRITE(6,45)  KNOB
00048           READ(5,100)  DTT,DZZ
00049           WRITE(6,101) DTT,DZZ
00050           READ(5,100)  CL
00051           WRITE(6,110) CL
00052           READ(5,100)  DHEAD,XLAM,THS,THR
00053           WRITE(6,115) DHEAD,XLAM,THS,THR
00054           READ(5,100)  DALPHA
00055           WRITE(6,120) DALPHA
          C
          C     *****   DICTIONARY   *****
          C
          C---WTINF    = INFILTRATION TIME (DURATION OF LOADING)(HR)
          C---TCYC     = HOURS OF OUTPUT PRINTED AFTER TINF ENDS
          C---TWRITE   = INTERVAL AT WHICH OUTPUT IS PRINTED DURING
          C              TCYC (HR).  USUALLY SET EQUAL TO ONE HOUR.
          C
          C
00056           READ(5,100) TCYC,TWRITE,WTINF
00057           WRITE(6,130) WTINF
00058           WRITE(6,145) TCYC
00059           WRITE(6,200)
          C
00060           RAIN=0.0
00061           INFCT=1
00062           CBREAK=0.0
          C
00063           COLI=50000.
00064           RKAC=0.113
00065           CSAT=16.79
00066           RKDC=0.016
```

```
      C
      C---IF SPECIFIC PARAMETER VALUES ARE NOT PROVIDED,
      C---THEY ARE RANDOMLY GENERATED.
      C
      C     RKAC=RKC(DSEED,THS)
      C     COLI=XCOLI(DSEED)
      C     COLI=ANINT(COLI)
      C     CSAT=SATK(DSEED)
      C     RKDC=DECAYC(DSEED)
      C
00067       WRITE(6,210) RKAC
00068       WRITE(6,215) COLI
00069       WRITE(6,225) RKDC
00070       WRITE(6,235) CSAT

      C
      C
00071     5 DT=DTT
00072       DZ=DZZ
      C
      C---THE COLUMN LENGTH IS DIVIDED INTO GRIDS
      C
00073       N=CL/DZ+0.10
00074       NM1=N-1
00075       NM2=N-2
00076       NP1=N+1
00077       NP2=N+2
      C
      C---READ NUMBER OF DATA POINTS FOR PRESSURE HEADS
      C
00078       READ(5,300) NIN
      C
      C---READ SOIL DEPTH (LOCATIONS) FOR PRESSURE HEADS
      C
00079       READ(5,100)  (XXX(I),I=1,NIN)
      C
      C---READ PRESSURE HEAD FOR CORRESPONDING DEPTHS
      C
00080       READ(5,100)  (C1(I),I=1,NIN)
      C
      C---SUBROUTINE IDIST2 WILL GENERATE THE APPROPRIATE
      C---NUMBER OF DEPTHS (LOCATIONS) GIVEN THE INPUT DEPTHS.
      C---FOR EXAMPLE, IF INPUT VALUES ARE PROVIDED AT EVERY
      C---10 CM DEPTH,  IDIST2 WILL INTERPOLATE VALUES EVERY
      C---5 CM, 2 CM, OR 1 CM, ETC.
      C
00081       CALL IDIST2
      C
00082       DO  11  I=1,NP1
00083    11 H(I)=R(I)
00084       DO 12 I=1,NP1
00085       C(I)=0.0
00086       CO(I)=0.0
00087       CON(I)=0.0
00088       CAP(I)=0.0
00089    12 TH(I)=0.0
      C
00090       TIME=0.0
      C
      C---DETERMINE INITIAL VALUES FOR WATER CONTENT,
```

```
      C---CONDUCTIVITY, AND WATER CAPACITY FOR EACH GRID.
      C
00091       CALL WPROP2
      C
      C    *****   DICTIONARY   *****
      C
      C---RAIN     = RATE OF RAINFALL (CM/HR)
      C---SFLUX    = RATE OF WATER + WASTEWATER APPLICATION (CM/HR)
      C---TINF     = INFILTRATION TIME (DURATION OF RAINFALL) (HR)
      C---NCYC     = NUMBER OF RAIN CYCLES
      C
      C
      C---PRINTS INITIAL CONDITIONS AT T=0
      C
00092       CALL OUTPUT
      C
00093    20 DO 999 L=1,NCYC
      C
00094       READ(5,100) RAIN,TINF
00095       WRITE(6,150) RAIN,TINF
      C
      C---COUNTER FOR SHUTTING OFF SOLUTIONS WHEN RAIN ENDS
      C
00096       INFCT=INFCT+1
      C
      C---WASTEWATER FLUX IS CONSTANT 5 CM/DAY OR 0.208 CM/HR
      C
00097       SFLUX=RAIN+0.208
      C
      C---BACNUM IS CALLED TO DETERMINE THE CONCENTRATION
      C---OF BACTERIA GOING INTO THE SOIL, GIVEN THE INITIAL
      C---CONCENTRATION WHICH IS IN NUMBER PER CUBIC
      C---CENTIMETER, AND THE DILUTING EFFECT OF THE RAIN.
      C
00098       CALL BACNUM(COLI,RAIN,BUGC)
00099       CSCOLI=BUGC
      C
      C
00100    30 XTINF=TINF
00101       TINF=TIME+XTINF
00102       DT=DTT
00103       DZ=DZZ
      C
00104       CALL ROUTE
      C
      C
00105   999 CONTINUE
      C
00106       WRITE(6,400)  CBREAK
      C
00107  9999 CONTINUE
00108       STOP
00109       END
```

```
00001          SUBROUTINE ROUTE
               C
00002          COMMON/L1/    AA(155),BB(155),CC(155),R(155)
00003          COMMON/L2/    N,NM1,NM2,NP1,NP2
00004          COMMON/L3/    ALPHA,BETA,DT,DZ
00005          COMMON/L4/    NX,NX1,NRMAX,CON1
00006          COMMON/L5/    SFLUX
00007          COMMON/L6/    XXX(155),C1(155),C2(155),NIN
00008          COMMON/L7/    TIME,TINF,TCYC
00009          COMMON/L8/    H(155),CON(155),CAP(155),TH(155)
00010          COMMON/L9/    CL
00011          COMMON/L10/   DHEAD,XLAM,XEPS,CSAT
00012          COMMON/L11/   C(155),CO(155),CBREAK
00013          COMMON/L12/   CSCOLI,RRD,RKDC,RKAC
00014          COMMON/L13/   THS,THR,DSEED
00015          COMMON/L14/   DTT,DZZ,TWRITE
00016          COMMON/L15/   KNOB,NCYC,INFCT,WTINF
00017          COMMON/L16/   XTINF,COLI,RAIN
               C
00018          NX=N
00019          NX1=NX-1
               C
               C---IF SFLUX IS VERY LOW, THEN DT REMAINS AS DEFINED, IF
               C---SFLUX IS HIGH, THEN DT IS MADE SMALLER THAN INPUT DT.
               C
00020          IF(SFLUX.LE.0.0) GO TO 56
00021          TTT=4.0/(SFLUX*1000.0)
00022          IF(DT.LE.TTT) GO TO 5
00023          NT=DT/TTT+0.10
00024          DT=DT/NT
00025        5 CONTINUE
00026          IF (INFCT .GT. 2) GO TO 15
               C
               C---THE CODE TO (15 CONTINUE) IS DONE ONLY ON FIRST PASS
               C
00027          ALPHA=DT/(2.0*DZ*DZ)
00028          BETA=DT/DZ
               C
00029          CALL WPROP2
               C
               C---IF THE SURFACE CONDUCTIVITY IS GREATER THAN ONE HALF
               C---THE FLUX RATE, BASED ON THE INITIAL WATER CONTENT,
               C---SKIP THE SURFACE WETTING SECTION IN THE NEXT LINES.
               C
00030          IF(CON1.GE.(SFLUX/2)) GO TO 15
               C
               C---THIS SECTION MAKES H(1) WETTER UNTIL CON1 .GE. SFLUX/2
               C
               C
00031        6 H(1)=H(1)+20
00032          CALL WPROP2
               C
               C---THE FOLLOWING LINES ARE TO MAKE SOIL SURFACE LESS
               C---"WATER REPELLENT".  PROGRAM BOMBS IF CON1 REMAINS .LT.
               C---SFLUX/2. SURFACE IS WETTED UNTIL SURFACE CONDUCTIVITY IS
               C---AT LEAST 1/2 FLUX RATE.  THEN SURFACE H(1) IS
               C---ASSUMED, AND SOIL PROFILE IS WETTER.
               C
00033          IF(CON1.LT.(SFLUX/2)) GO TO 6
00034          IF(H(1).GT.0.0) H(1)=0.0
```

```
C---VALUE, -150, IS NOT CONSTANT.  IT IS THE INITIAL
C---VALUE OF H(1).  IF INITIAL CONTITIONS CHANGED,
C---THE VALUE  -150  AND ILZ=75  MUST BE CHANGED.
C
00035     10  H(1)=H(1)-150.
C
00036         DELH=2.0
00037         ILZ=75
C
C---THIS DO LOOP SOLVES THE WATER EQUATION FOR
C---INITIAL H(1) TO H(1)=0.  CALCULATIONS DONE
C---ILZ TIMES IN H INCREMENTS OF 2.  THE EQUATIONS
C---ARE SOLVED DURING EARLY TIME (DT*ILZ).
C
00038         DO  13  IK=1,ILZ
00039         CALL WATER
00040         CALL MICROC
00041         H(1)=H(1)+DELH
00042     13  CONTINUE
C
00043     14  TIME=TIME+DT*ILZ
C
00044     15  CONTINUE
C
C---AT THIS POINT A SMALL AMOUNT OF INFILTRATION
C---TIME WAS USED TO WET THE SOIL.
C
C---START HERE IF SURFACE CONDUCTIVITY IS
C---"ADEQUATE" FOR RAIN.
C
00045         DT=DT*2.0
00046         ALPHA=DT/(2.0*DZ*DZ)
00047         BETA=DT/DZ
C
C---DIVIDE INFILTRATION TIME INTO TENTHS.
C
C---XT = TIME REMAINING FOR FLUX AT SURFACE
C
00048         XT=TINF-TIME
C
C---DIVIDE RAINFALL INTO 1/10 HOUR INCREMENTS
C
00049         TENTHS=XTINF*10.
00050         ITEN=INT(TENTHS)
C
C---THE REMAINING INFILTRATION TIME IS DIVIDED
C---INTO TENTHS.  "IL" REPRESENTS THE NUMBER
C---OF TIMES THE EQUATIONS ARE SOLVED DURING
C---EACH 1/10 HOUR PERIOD--BASED ON "DT".
C---NOTE, IL*DT*TENTHS=XTINF
C
00051         XT=XT/TENTHS
00052         IL=XT/DT+0.100
C
C---SOLVING THE WATER EQUATION AND MICROB EQUATION
C---DURING INFILTRATION.  "ADJ" ADJUSTS PRESSURE
C---HEAD IN SURFACE GRID BASED ON SFLUX RATE AND
C---SURFACE CONDUCTIVITY AT SPECIFIC POINT IN
C---TIME.  HIGH FLUX AND LOW CONDUCTIVITY MEANS
```

```
      C---H(1) GETS WETTER IN BIGGER INCREMENTS.
      C
00053       DO  30  IZFT=1,ITEN
00054       DO  25 II=1,IL
00055       ADJ=DZ*(1.0-SFLUX/CON1)
00056       H(1)=H(2)-ADJ
00057       CALL WATER
00058       CALL MICROC
00059       IF(C(120).EQ.1.0.AND.C(121).NE.1.0)CBREAK=TIME
00060    25 CONTINUE
00061       TIME=TIME+IL*DT
00062       IF(KNOB .EQ. 2) GO TO 29
      C
      C---OUTPUT IS PRINTED AT EACH 0.1 HOUR DURING RAINFALL.
      C
00063       CALL OUTPUT
      C
00064       GO TO 30
      C
00065    29 CONTINUE
00066       IF(TIME.GT.23.96 .AND. TIME.LT.24.04) CALL OUTPUT
00067       IF(TIME.GT.47.96 .AND. TIME.LT.48.04) CALL OUTPUT
00068       IF(TIME.GT.71.96 .AND. TIME.LT.72.04) CALL OUTPUT
00069       IF(TIME.GT.95.96 .AND. TIME.LT.96.04) CALL OUTPUT
00070       IF(TIME.GT.119.96.AND. TIME.LT.120.04) CALL OUTPUT
00071    30 CONTINUE
      C
      C---IF RAINFALL NOT ENDED, RETURN FOR NEXT RAINFALL
      C
00072       IF (INFCT .NE. NCYC+1) RETURN
      C
      C---THIS SECTION ADDED FOR PERIOD RAIN HAS STOPPED,
      C---BUT WASTEWATER LOADING CONTINUES.
      C
      C---SAME PROCEDURE DURING RAIN AS DURING PERIOD
      C---WHEN WASTEWATER CONTINUES TO BE LOADED.
      C
00073       IF(WTINF .EQ. 0.0) GO TO 40
00074       RAIN=0.0
00075       SFLUX=0.208
00076       WXT=WTINF
00077       WTEN=WTINF*10.
00078       IWTEN=INT(WTEN)
00079       WXT=WXT/WTEN
00080       IWL=WXT/DT+0.100
      C
      C---BACTERIA NUMBERS RECOMPUTED. DILUTION FROM
      C---RAIN HAS ENDED.
      C
00081       CALL BACNUM(COLI,RAIN,BUGC)
00082       CSCOLI=BUGC
      C
      C---SOLVING WATER, MICROB EQUATIONS DURING PERIOD
      C---OF WASTEWATER LOADING ONLY.
      C
00083       DO  35 IZFT=1,IWTEN
00084       DO  32 II=1,IWL
00085       ADJ=DZ*(1.0-SFLUX/CON1)
00086       H(1)=H(2)-ADJ
00087       CALL WATER
```

```
00088          CALL MICROC
00089          IF(C(120).EQ.1.0.AND.C(121).NE.1.0)CBREAK=TIME
00090       32 CONTINUE
00091          TIME=TIME+IWL*DT
00092          IF(KNOB .EQ. 2) GO TO 34
               C
               C---OUTPUT PRINTED EACH 0.1 HOUR DURING LOADING.
               C
00093          CALL OUTPUT
               C
00094          GO TO 35
               C
00095       34 CONTINUE
00096          IF(TIME.GT.23.96 .AND. TIME.LT.24.04) CALL OUTPUT
00097          IF(TIME.GT.47.96 .AND. TIME.LT.48.04) CALL OUTPUT
00098          IF(TIME.GT.71.96 .AND. TIME.LT.72.04) CALL OUTPUT
00099          IF(TIME.GT.95.96 .AND. TIME.LT.96.04) CALL OUTPUT
00100          IF(TIME.GT.119.96.AND. TIME.LT.120.04) CALL OUTPUT
00101       35 CONTINUE
               C
               C---FOR THE PERIOD AFTER INFILTRATION HAS ENDED.
               C
00102       40 SFLUX=0.0
               C
00103          IF(TCYC .EQ. 0.0) RETURN
               C
               C---INCREMENTS ARE FOR ONE HOUR
               C
00104       50 IL=1.00/DT+0.100
00105          DT=1.00/IL
               C
               C---SOLVES EQUATIONS AT 'IL' INCREMENTS FOR ONE TIME
               C---PERIOD, THEN OUTPUT IS PRINTED
               C
00106          DO  52  II=1,IL
               C
               C---SFLUX = 0.0, THEREFORE ADJ = DZ
               C
00107          ADJ=DZ*(1.0-SFLUX/CON1)
00108          H(1)=H(2)-ADJ
00109          CALL WATER
00110          CALL MICROC
00111          IF(C(120).EQ.1.0.AND.C(121).NE.1.0)CBREAK=TIME
00112       52 CONTINUE
00113          TIME=TIME+IL*DT
00114          IF(KNOB .EQ. 2) GO TO 55
               C
00115          CALL OUTPUT
               C
00116          GO TO 56
               C
00117       55 CONTINUE
00118          IF(TIME.GT.23.96 .AND. TIME.LT.24.04) CALL OUTPUT
00119          IF(TIME.GT.47.96 .AND. TIME.LT.48.04) CALL OUTPUT
00120          IF(TIME.GT.71.96 .AND. TIME.LT.72.04) CALL OUTPUT
00121          IF(TIME.GT.95.96 .AND. TIME.LT.96.04) CALL OUTPUT
00122          IF(TIME.GT.119.96.AND. TIME.LT.120.04) CALL OUTPUT
00123       56 CONTINUE
               C
               C---TIME IS RELAXED,EQUATIONS SOLVED FOR ANOTHER TIME
```

```
      C---INCREMENT, THEN OUTPUT IS PRINTED.
      C
00124         DT=DT*2
00125         IF(DT.GT.0.050.AND.DT.LT.0.10)  DT=0.10
00126         ALPHA=DT/(2.0*DZ*DZ)
00127         BETA=DT/DZ
00128         IL=1.00/DT+0.100
00129         DT=1.0/IL
      C
00130         DO  58 II=1,IL
00131         ADJ=DZ*(1.0-SFLUX/CON1)
00132         H(1)=H(2)-ADJ
00133         CALL WATER
00134         CALL MICROC
00135         IF(C(120).EQ.1.0.AND.C(121).NE.1.0)CBREAK=TIME
00136      58 CONTINUE
00137         TIME=TIME+IL*DT
00138         IF(KNOB .EQ. 2) GO TO 63
      C
00139         CALL OUTPUT
      C
00140         GO TO 64
      C
00141      63 CONTINUE
00142         IF(TIME.GT.23.96 .AND. TIME.LT.24.04) CALL OUTPUT
00143         IF(TIME.GT.47.96 .AND. TIME.LT.48.04) CALL OUTPUT
00144         IF(TIME.GT.71.96 .AND. TIME.LT.72.04) CALL OUTPUT
00145         IF(TIME.GT.95.96 .AND. TIME.LT.96.04) CALL OUTPUT
00146         IF(TIME.GT.119.96.AND. TIME.LT.120.04) CALL OUTPUT
      C---TIME IS RELAXED
      C
00147      64 DT=2*DT
00148         IF(DT.GT.0.050.AND.DT.LT.0.10)  DT=0.10
00149         IF(DT.GT.0.190.AND.DT.LT.0.40)  DT=0.250
      C
00150         ALPHA=DT/(2.0*DZ*DZ)
00151         BETA=DT/DZ
      C
00152         IZEFT=(TCYC-TIME)/1.0
00153         DO  90  IZZ=1,IZEFT
00154         IL=1.00/DT+0.100
00155         IF(IL.LT.1) IL=1
00156         DT=1.0/IL
00157         DO  65 II=1,IL
00158         ADJ=DZ*(1.0-SFLUX/CON1)
00159         H(1)=H(2)-ADJ
00160         CALL WATER
00161         CALL MICROC
00162         IF(C(120).EQ.1.0.AND.C(121).NE.1.0)CBREAK=TIME
00163      65 CONTINUE
00164         TIME=TIME+IL*DT
00165         IF(KNOB .EQ. 2) GO TO 70
      C
00166         CALL OUTPUT
      C
00167         GO TO 80
      C
00168      70 CONTINUE
00169         IF(TIME.GT.23.96 .AND. TIME.LT.24.04) CALL OUTPUT
00170         IF(TIME.GT.47.96 .AND. TIME.LT.48.04) CALL OUTPUT
```

```
00171          IF(TIME.GT.71.96 .AND. TIME.LT.72.04) CALL OUTPUT
00172          IF(TIME.GT.95.96 .AND. TIME.LT.96.04) CALL OUTPUT
00173          IF(TIME.GT.119.96.AND. TIME.LT.120.04) CALL OUTPUT
       C---TIME IS RELAXED DURING EACH CYCLE UNTIL END
       C
00174       80 DT=2*DT
00175          IF(DT.GT.2.0) DT=2.0
00176          ALPHA=DT/(2*DZ*DZ)
00177          BETA=DT/DZ
00178       90 CONTINUE
00179          RETURN
00180          END
```

```
00001          SUBROUTINE IDIST2
       C
00002          COMMON/L1/    AA(155),BB(155),CC(155),R(155)
00003          COMMON/L2/    N,NM1,NM2,NP1,NP2
00004          COMMON/L3/    ALPHA,BETA,DT,DZ
00005          COMMON/L6/    XXX(155),C1(155),C2(155),NIN
00006          I=1
00007          DO  20  K=1,NP1
00008          A=DZ*(K-1)
00009        5 IF(A.LE.XXX(I+1)) GO TO 10
00010          I=I+1
00011          GO TO 5
00012       10 R(K)=C1(I)+(A-XXX(I))*((C1(I+1)-C1(I))/(XXX(I+1)-XXX(I)))
00013       20 CONTINUE
00014          RETURN
00015          END
```

```
00001          SUBROUTINE WPROP2
               C
               C---CALCULATES SOIL WATER CHARACTERISTIC FUNCTION
               C---AND HYDRAULIC CONDUCTIVITY FUNCTION.
               C
               C
00002          COMMON/L1/    AA(155),BB(155),CC(155),R(155)
00003          COMMON/L2/    N,NM1,NM2,NP1,NP2
00004          COMMON/L4/    NX,NX1,NRMAX,CON1
00005          COMMON/L8/    H(155),CON(155),CAP(155),TH(155)
00006          COMMON/L10/   DHEAD,XLAM,XEPS,CSAT
00007          COMMON/L13/   THS,THR,DSEED
00008          COMMON/L15/   KNOB,NCYC,INFCT,WTINF
               C
               C---CALCULATE FUNCTION PARAMETERS.
               C
00009          THETA=THS-THR
00010          XEPS=(2.+3*XLAM)/XLAM
00011          XX=XLAM/DHEAD
00012          ZZ=XLAM+1.0
               C
               C---DETERMINE WATER CONTENT AND WATER CAPACITY
               C---VALUES FOR EACH GRID.
               C
00013          DO  90  I=1,NP1
00014          R(I)=H(I)
00015          IF(R(I).GE.DHEAD)  R(I)=DHEAD
00016          CAP(I)=-XX*THETA*((DHEAD/R(I))**ZZ)
00017          TH(I)=THETA*((DHEAD/R(I))**XLAM)+THR
00018       90 CONTINUE
               C
               C---DETERMINE CONDUCTIVITY FOR EACH GRID.
               C
00019          DO 92 I=1,N
00020          THAVE=((TH(I))+(TH(I+1)))/2.0
00021          CON(I)=CSAT*((THAVE-THR)/THETA)**XEPS
00022       92 CONTINUE
               C
               C---DETERMINE CONDUCTIVITY AT BASE.
               C
00023          I=NP1
00024          R(I)=H(I)
00025          IF(R(I).GE.DHEAD)  R(I)=DHEAD
00026          CON(NP1)=CSAT*((TH(NP1)-THR)/(THETA))**XEPS
               C
               C---DETERMINE SURFACE HYDRAULIC CONDUCTIVITY
               C
00027          CON1=CSAT*((TH(1)-THR)/THETA)**XEPS
00028          RETURN
00029          END
```

```
00001          SUBROUTINE WATER
      C
00002          COMMON/L1/    AA(155),BB(155),CC(155),R(155)
00003          COMMON/L2/    N,NM1,NM2,NP1,NP2
00004          COMMON/L3/    ALPHA,BETA,DT,DZ
00005          COMMON/L4/    NX,NX1,NRMAX,CON1
00006          COMMON/L8/    H(155),CON(155),CAP(155),TH(155)
00007          CALL WPROP2
      C
00008          DO  1  I=1,NM1
00009          AA(I)=CAP(I+1)+ALPHA*(CON(I+1)+CON(I))
00010          BB(I)=-ALPHA*CON(I+1)
00011          CC(I)=-ALPHA*CON(I+1)
00012        1 CONTINUE
00013          DO 2 I=1,NM1
00014          X1=CAP(I+1)*H(I+1)
00015          X2=ALPHA*CON(I)*H(I)-ALPHA*H(I+1)*(CON(I+1)+CON(I))
00016          X3=ALPHA*CON(I+1)*H(I+2)
00017          X4=-BETA*(CON(I+1)-CON(I))
00018          R(I)=X1+X2+X3+X4
00019        2 CONTINUE
00020          R(1)=R(1)+ALPHA*CON(1)*H(1)
00021          R(NM1)=R(NM1)-BB(NM1)*H(NP1)
00022          CALL TRIDM(AA,BB,CC,R,NM1)
00023          DO 3 K=2,N
00024        3 H(K)=R(K-1)
00025          RETURN
00026          END
```

```
00001          SUBROUTINE TRIDM(A,B,C,D,N)
      C
00002          DIMENSION A(1),B(1),C(1),D(1)
00003          DO  1  I=2,N
00004          C(I-1)=C(I-1)/A(I-1)
00005          A(I)=A(I)-(C(I-1)*B(I-1))
00006        1 CONTINUE
00007          DO  2  I=2,N
00008          D(I)=D(I)-(C(I-1)*D(I-1))
00009        2 CONTINUE
00010          D(N)=D(N)/A(N)
00011          DO  3  I=2,N
00012          D(N+1-I)=(D(N+1-I)-(B(N+1-I)*D(N+2-I)))/A(N+1-I)
00013        3 CONTINUE
00014          RETURN
00015          END
```

```
00001           SUBROUTINE MICROC
                C
00002           COMMON/L1/    AA(155),BB(155),CC(155),R(155)
00003           COMMON/L2/    N,NM1,NM2,NP1,NP2
00004           COMMON/L3/    ALPHA,BETA,DT,DZ
00005           COMMON/L5/    SFLUX
00006           COMMON/L8/    H(155),CON(155),CAP(155),TH(155)
00007           COMMON/L11/   C(155),CO(155),CBREAK
00008           COMMON/L12/   CSCOLI,RRD,RKDC,RKAC
00009           COMMON/L13/   THS,THR,DSEED
00010           COMMON/L15/   KNOB,NCYC,INFCT,WTINF
                C
                C
00011           M=1
00012           WFLUX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
00013           IF(SFLUX.LE.0.0)GO TO 8
00014           DISP=DISPER(WFLUX,TH(M))
00015           C(1)=CSCOLI
00016           M=2
00017           WFLUX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
                C
00018           DO 5 I=1,NM1
                C
                C---RETARDATION FACTOR BASED ON PRESENT WATER CONTENT.
                C---DISPERSION BASED ON WATER CONTENT AND FLUX.
                C
00019           RRD=RTD(M,RKAC,TH(M))
00020           DISP=DISPER(WFLUX,TH(M))
00021           AA(I)=RRD+2.0*ALPHA*DISP-BETA*WFLUX/TH(M)
00022           BB(I)=BETA*WFLUX/TH(M)-ALPHA*DISP
00023           R(I)=RRD*C(M)+ALPHA*DISP*(C(M+1)-2.0*C(M)+C(M-1))
00024         2 R(I)=R(I)-DT*RKDC*C(M)
00025           M=I+2
00026           WFLUX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
00027           DISP=DISPER(WFLUX,TH(M))
00028           CC(I)=-ALPHA*DISP
00029         5 CONTINUE
                C
                C---VALUES DETERMINED GIVEN UPPER AND LOWER B.C.
                C
00030           M=N
00031           RRD=RTD(M,RKAC,TH(M))
00032           DISP=DISPER(WFLUX,TH(M))
00033           AA(NM1)=RRD+ALPHA*DISP
00034           WFLUX=-CON(1)*(H(2)-H(1))/DZ+CON(1)
00035           DISP=DISPER(WFLUX,TH(1))
00036           R(1)=R(1)+ALPHA*DISP*C(1)
00037           GO TO 14
                C
                C---MAKES C(2)=C(1) BECAUSE NO NEW INPUT HAS
                C---OCCURRED IN C(1).
                C
00038         8 C(1)=C(2)
00039           M=2
00040           WFLUX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
00041           DO 11 I=1,NM1
00042           RRD=RTD(M,RKAC,TH(M))
00043           DISP=DISPER(WFLUX,TH(M))
00044           AA(I)=RRD+2.0*ALPHA*DISP-BETA*WFLUX/TH(M)
00045           BB(I)=BETA*WFLUX/TH(M)-ALPHA*DISP
```

```
00046          R(I)=RRD*C(M)+ALPHA*DISP*(C(M+1)-2.0*C(M)+C(M-1))
00047       10 R(I)=R(I)-DT*RKDC*C(M)
00048          M=I+2
00049          WFLUX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
00050          DISP=DISPER(WFLUX,TH(M))
00051          CC(I)=-ALPHA*DISP
00052       11 CONTINUE
           C
           C---VALUE DETERMINED AT LOWER BOUNDARY.
           C
00053          M=N
00054          RRD=RTD(M,RKAC,TH(M))
00055          DISP=DISPER(WFLUX,TH(M))
00056          AA(NM1)=RRD+ALPHA*DISP
00057          M=2
00058          WFLUX=-CON(M)*(H(M+1)-H(M))/DZ+CON(M)
00059          RRD=RTD(M,RKAC,TH(M))
00060          DISP=DISPER(WFLUX,TH(M))
00061          AA(1)=RRD+ALPHA*DISP-BETA*WFLUX/TH(M)
00062       14 CALL TRIDM(AA,BB,CC,R,NM1)
00063          DO 15 I=2,N
00064       15 C(I)=ANINT(R(I-1))
00065          C(NP1)=ANINT(C(N))
00066          RETURN
00067          END
```

```
00001          SUBROUTINE BACNUM(BUG,PRECIP,BACTER)
           C
           C---DETERMINES CONCENTRATION OF BACTERIA ENTERING
           C---SOIL, GIVEN INITIAL CONCENTRATION, AND DILUTING
           C---EFFECT OF THE RAIN.
           C
00002          BACTER=0.208*BUG/(PRECIP+0.208)
00003          RETURN
00004          END
```

```
00001          FUNCTION DISPER(WFLUX,WC)
               C
               C---DISPERSION DETERMINED EACH GRID EACH TIME STEP
               C---IN ORDER TO SATISFY THE STABILITY CRITERIA.
               C---DALPHA = VALUE OF DISPERSIVITY = DELTA Z/2
               C
00002          DALPHA=0.5
00003          DISPER=(WFLUX/WC)*DALPHA
00004          IF(DISPER .LT. 1.0) DISPER=1.0
00005          RETURN
00006          END


00001          FUNCTION SATK(DSEED)
               C
00002          COMMON/L5/   SFLUX
               C
               C---GENERATE RANDOM NORMAL NUMBER, U.
               C
               C---NECESSARY TO INPUT LN K(S) VALUES OF MU AND SIGMA
               C
00003          XMU=2.82
00004          SIGMA=1.83
               C
00005       10 U=GGNQF(DSEED)
00006          SATK=EXP(XMU+SIGMA*U)
00007          IF (SATK .LT. 5.0) GO TO 10
00008          RETURN
00009          END


00001          FUNCTION DECAYC(DSEED)
00002          COMMON/TERMS/  R(12)
               C
               C---MUST MODIFY MEAN AND DEVIATION IF NECESSARY
               C
00003          AVECOL=0.016
00004          DEVCOL=0.008
00005          NR=12
00006        1 SUM=0.0
00007          CALL GGUBS(DSEED,NR,R)
00008          DO 5 I=1,NR
00009          SUM=SUM+R(I)
00010        5 CONTINUE
00011          DECAYC=DEVCOL*(SUM-6.0)+AVECOL
00012          IF(DECAYC.GT.(3.*DEVCOL+AVECOL).OR.
              *DECAYC.LT.(-3. *DEVCOL+AVECOL))GO TO 1
00013          IF(DECAYC.LE.0.0)GO TO 1
00014          RETURN
00015          END
```

```
00001          FUNCTION XCOLI(DSEED)
               C
               C---MUST MODIFY MEAN AND DEVIATION IF NECESSARY
               C
00002          XXCOLI=6.068
00003          SCOLI=2.134
00004          U=GGNQF(DSEED)
00005          XCOLI=EXP(XXCOLI+SCOLI*U)
00006          RETURN
00007          END
```

```
00001          FUNCTION RKC(DSEED,WC)
00002          COMMON/TERMS/  R(12)
               C
               C---FUNCTION WILL GENERATE  K(AC) BASED ON A
               C---RANDOM VALUE OF RETARDATION (1 TO 2).  VALUE
               C---GENERATED IS BASED ON SATURATED WATER CONTENT.
               C
               C---THE MEAN AND DEVIATION PROVIDED WILL PROVIDE VALUES OF RD BETWEEN
               C---1 AND 2.
               C
00003          AVE=1.5
00004          SD=0.167
00005          NR=12
00006        1 SUM=0.0
00007          CALL GGUBS(DSEED,NR,R)
00008          DO 5 I=1,NR
00009          SUM=SUM+R(I)
00010        5 CONTINUE
00011          RD=SD*(SUM-6.0)+AVE
00012          IF(RD.GT.(2.0).OR.RD.LE.(1.0)) GO TO 1
               ROU=1.55
00013          RKC=(RD-1.0)*(WC/ROU)
00014          IF(RKC.LE.0.0) GO TO 1
00015          RETURN
00016          END
```

```
00001          FUNCTION RTD(M,RKAC,WC)
               C
               C---FUNCTION GENERATES RETARDATION VALUE BETWEEN
               C---1 AND 2 USING K(AC) VALUE GENERATED AT START
               C---OF PROGRAM.  VALUE VARIES WITH WATER CONTENT.
               C
               C---ENTER BULK DENSITY OF SOIL
               ROU=1.55
00002          RTD=1.0+(RKAC*ROU)/WC
00003          RETURN
00004          END
```

```
00001           SUBROUTINE OUTPUT
      C
00002           COMMON/L2/    N,NM1,NM2,NP1,NP2
00003           COMMON/L3/    ALPHA,BETA,DT,DZ
00004           COMMON/L4/    NX,NX1,NRMAX,CON1
00005           COMMON/L7/    TIME,TINF,TCYC
00006           COMMON/L8/    H(155),CON(155),CAP(155),TH(155)
00007           COMMON/L9/    CL
00008           COMMON/L11/   C(155),CO(155),CBREAK
00009           COMMON/L13/   THS,THR,DSEED
00010       100 FORMAT('1')
00011       200 FORMAT(24X,'TOTAL ELAPSED TIME  =',F10.1,'  HOURS'/)
00012       299 FORMAT(T5,'SOIL DEPTH',
               *T18,'PRESSURE HEAD',
               *T34,'SOIL-WATER CONTENT',
               *T55,'FC BACTERIA',
               *T72,'C/C(0)')
00013       301 FORMAT(T9,'CM',T24,'CM',T37,'CM**3/CM**3',T54,
               *'CONCENTRATION')
00014       302 FORMAT(T59,'#/CM**3')
00015       499 FORMAT(T5,F8.2,T17,F10.2,T36,F8.2,T56,F8.0,T72,F5.2)
      C
00016           WRITE(6,100)
00017           WRITE(6,200) TIME
00018           WRITE(6,299)
00019           WRITE(6,301)
00020           WRITE(6,302)
      C
      C---CONCENTRATIONS CHANGED TO INTEGER. BACTERIA NOT
      C---FRACTIONAL PARTS.
      C
00021           IC1=NINT(C(1))
00022           DO 10 I=1,NP1,1
00023           IF(C(I).EQ.0.0) GO TO 10
00024           ICI=NINT(C(I))
00025           IF(IC1.LT.1) IC1=1
00026           CO(I)=FLOAT(ICI)/FLOAT(IC1)
00027        10 CONTINUE
00028           DO  20  I=1,NP1,3
00029           ZZ=(I-1)*DZ
00030           WRITE(6,499) ZZ,H(I),TH(I),C(I),CO(I)
00031        20 CONTINUE
00032           WRITE(6,101)
00033       101 FORMAT('0')
00034           RETURN
00035           END
      C
```

Example of Computer Output

I N P U T D A T A

NUMBER OF STAGES IN STORM CYCLE = 3
KNOB (OUTPUT FORMAT) = 2
INITIAL DT, HR = 0.010
INITIAL DZ , CM = 1.000

TOTAL LENGTH OF SOIL PROFILE, CM = 150.000

SOIL WATER PARAMETERS :

DISPLACEMENT PRESSURE HEAD = -15.780
LAMBDA = 0.533
SATURATED WATER CONTENT = 0.345
RESIDUAL WATER CONTENT = 0.016

DISPERSIVITY = 0.500

DURATION OF WASTEWATER LOADING AFTER END OF RAINFALL = 122.000
HOURS OF OUTPUT PRINTED AFTER RAIN STOPS = 120.000

WASTEWATER FLUX IS CONSTANT AT 5 CM/DAY OR 0.208 CM/HR

DISTRIBUTION COEFFICIENT, K(AC),(CM**3/G) = 0.113
INPUT FECAL COLIFORM CONCENTRATION (#/CM**3) = 50000.
FECAL COLIFORM DECAY COEFFICIENT (PER HOUR) = 0.016
SATURATED H. CONDUCTIVITY (CM/HR) = 16.790

RATE OF RAIN APPLICATION , CM/HR = 6.800
INFILTRATION TIME, I.E. DURATION OF RAINFALL, HOURS = 1.000

RATE OF RAIN APPLICATION , CM/HR = 1.600
INFILTRATION TIME, I.E. DURATION OF RAINFALL, HOURS = 1.000

RATE OF RAIN APPLICATION , CM/HR = 0.600
INFILTRATION TIME, I.E. DURATION OF RAINFALL, HOURS = 1.000

TOTAL ELAPSED TIME = 0.0 HOURS

SOIL DEPTH CM	PRESSURE HEAD CM	SOIL-WATER CONTENT CM**3/CM**3	FC BACTERIA CONCENTRATION #/CM**3	C/C(0)
0.00	-150.00	0.12	0.	0.00
3.00	-147.00	0.12	0.	0.00
6.00	-144.00	0.12	0.	0.00
9.00	-141.00	0.12	0.	0.00
12.00	-138.00	0.12	0.	0.00
15.00	-135.00	0.12	0.	0.00
18.00	-132.00	0.12	0.	0.00
21.00	-129.00	0.12	0.	0.00
24.00	-126.00	0.12	0.	0.00
27.00	-123.00	0.13	0.	0.00
30.00	-120.00	0.13	0.	0.00
33.00	-117.00	0.13	0.	0.00
36.00	-114.00	0.13	0.	0.00
39.00	-111.00	0.13	0.	0.00
42.00	-108.00	0.13	0.	0.00
45.00	-105.00	0.14	0.	0.00
48.00	-102.00	0.14	0.	0.00
51.00	-99.00	0.14	0.	0.00
54.00	-96.00	0.14	0.	0.00
57.00	-93.00	0.14	0.	0.00
60.00	-90.00	0.15	0.	0.00
63.00	-87.00	0.15	0.	0.00
66.00	-84.00	0.15	0.	0.00
69.00	-81.00	0.15	0.	0.00
72.00	-78.00	0.16	0.	0.00
75.00	-75.00	0.16	0.	0.00
78.00	-72.00	0.16	0.	0.00
81.00	-69.00	0.17	0.	0.00
84.00	-66.00	0.17	0.	0.00
87.00	-63.00	0.17	0.	0.00
90.00	-60.00	0.18	0.	0.00
93.00	-57.00	0.18	0.	0.00
96.00	-54.00	0.19	0.	0.00
99.00	-51.00	0.19	0.	0.00
102.00	-48.00	0.20	0.	0.00
105.00	-45.00	0.20	0.	0.00
108.00	-42.00	0.21	0.	0.00
111.00	-39.00	0.22	0.	0.00
114.00	-36.00	0.23	0.	0.00
117.00	-33.00	0.24	0.	0.00
120.00	-30.00	0.25	0.	0.00
123.00	-27.00	0.26	0.	0.00
126.00	-24.00	0.28	0.	0.00
129.00	-21.00	0.30	0.	0.00
132.00	-18.00	0.32	0.	0.00
135.00	-15.00	0.34	0.	0.00
138.00	-12.00	0.34	0.	0.00
141.00	-9.00	0.34	0.	0.00
144.00	-6.00	0.34	0.	0.00
147.00	-3.00	0.34	0.	0.00
150.00	0.00	0.34	0.	0.00

TOTAL ELAPSED TIME = 120.0 HOURS

SOIL DEPTH CM	PRESSURE HEAD CM	SOIL-WATER CONTENT CM**3/CM**3	FC BACTERIA CONCENTRATION #/CM**3	C/C(0)
0.00	-53.44	0.19	50000.	1.00
3.00	-53.43	0.19	47774.	0.96
6.00	-53.43	0.19	45592.	0.91
9.00	-53.42	0.19	43491.	0.87
12.00	-53.42	0.19	41471.	0.83
15.00	-53.41	0.19	39532.	0.79
18.00	-53.40	0.19	37671.	0.75
21.00	-53.39	0.19	35886.	0.72
24.00	-53.38	0.19	34173.	0.68
27.00	-53.36	0.19	32531.	0.65
30.00	-53.34	0.19	30957.	0.62
33.00	-53.31	0.19	29448.	0.59
36.00	-53.28	0.19	28000.	0.56
39.00	-53.24	0.19	26611.	0.53
42.00	-53.19	0.19	25280.	0.51
45.00	-53.14	0.19	24005.	0.48
48.00	-53.07	0.19	22782.	0.46
51.00	-52.98	0.19	21610.	0.43
54.00	-52.88	0.19	20486.	0.41
57.00	-52.75	0.19	19409.	0.39
60.00	-52.60	0.19	17868.	0.36
63.00	-52.41	0.19	15279.	0.31
66.00	-52.19	0.19	12389.	0.25
69.00	-51.91	0.19	9618.	0.19
72.00	-51.58	0.19	7264.	0.15
75.00	-51.19	0.19	5227.	0.10
78.00	-50.71	0.19	4344.	0.09
81.00	-50.15	0.19	3897.	0.08
84.00	-49.47	0.19	3468.	0.07
87.00	-48.68	0.20	3054.	0.06
90.00	-47.75	0.20	2656.	0.05
93.00	-46.68	0.20	2275.	0.05
96.00	-45.43	0.20	1908.	0.04
99.00	-44.01	0.21	1553.	0.03
102.00	-42.41	0.21	1211.	0.02
105.00	-40.62	0.21	881.	0.02
108.00	-38.65	0.22	564.	0.01
111.00	-36.49	0.23	257.	0.01
114.00	-34.17	0.23	0.	0.00
117.00	-31.70	0.24	0.	0.00
120.00	-29.09	0.25	0.	0.00
123.00	-26.37	0.27	0.	0.00
126.00	-23.57	0.28	0.	0.00
129.00	-20.69	0.30	0.	0.00
132.00	-17.77	0.32	0.	0.00
135.00	-14.81	0.34	0.	0.00
138.00	-11.85	0.34	0.	0.00
141.00	-8.89	0.34	0.	0.00
144.00	-5.93	0.34	0.	0.00
147.00	-2.96	0.34	0.	0.00
150.00	0.00	0.34	0.	0.00

COLIFORM BREAKTHROUGH AT 120 CM, HR = 0.