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Solid Waste

Criteria for Identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act

Appendix C

Technical Methods for Calculating Time of Travel in the Unsaturated Zone

Interim Final

GUIDANCE CRITERIA FOR IDENTIFYING AREAS OF VULNERABLE HYDROGEOLOGY

APPENDIX C

TECHNICAL GUIDANCE MANUAL FOR CALCULATING TIME OF TRAVEL (TOT) IN THE UNSATURATED ZONE

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DISCLAIMER

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EXECUTIVE SUMMARY

This appendix to the Guidance Criteria for Identifying Areas of Vulnerable Hydrogeology describes methods for calculating ground-water time of travel (TOT) in the unsaturated zone. The methods described in this appendix are intended for use by hazardous waste facility permit applicants and writers in evaluating the vulnerability of ground water to contamination.

The appendix presents a review of the general theory of ground-water flow in the unsaturated zone and describes the processes that control flow. Equations are presented which describe these processes and illustrate the relationships between important parameters.

Two general approaches are presented for calculating unsaturated zone TOT. The first approach involves the use of analytical solutions. These solutions are simplified approaches, appropriate for simple systems, and allow the analyst to directly solve for TOT. Two solutions are described, both for determination of steady state TOT. The first solution assumes a constant moisture content in the soil profile and is appropriate for conditions dominated by gravity drainage. The second solution allows for variable moisture contents and is appropriate for conditions where factors other than gravity drainage (e.g., capillary forces) are important. The use of these solutions is described and data requirements and sources of data are identified.

The second approach involves the use of unsaturated flow models. Two general classes of models are described, numerical models and water balance models. The relative complexity of each type of model is described, as are data requirements, output, and limitations. Methods are presented for determining TOT from model output for those models where TOT is not directly calculated by the model.

The approaches to calculating TOT are summarized and a decision tree is presented to aid in selection of the most appropriate approach for specific applications. Three case histories are presented using data from actual hazardous waste facilities to illustrate calculation of TOT.

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SECTION 1.0

INTRODUCTION

Subtitle C of the Resource Conservation and Recovery Act of 1976 (RCRA) addresses the management and disposal of hazardous waste. Regulations developed by the Environmental Protection Agency (EPA) from RCRA legislation (Regulations for Owners and Operators of Permitted Hazardous Waste Facilities - 40 CFR 264 and Regulations for Federally Administered Hazardous Waste Facilities - 40 CFR 270) require owners and operators of hazardous waste land treatment, storage, and disposal (TSD) facilities to provide information concerning the design, construction, operation, and maintenance of these facilities. This information is provided in the form of a RCRA Part B permit application. Permit writers in the EPA Regions and authorized states responsible for writing permits must review this information to determine if the facility will meet the environmental protection goals established in the RCRA regulations.

A major emphasis of the above environmental protection goals is the protection of ground-water resources that may be vulnerable to contamination originating at TSD facilities located in certain hydrogeologic settings. Therefore, much of the permit application and review process addresses the adequacy of facility design, construction, operation, maintenance, and location with respect to ground-water protection. A considerable amount of guidance has been developed to aid permit writers in evaluating potential threats to ground water posed by TSD facilities. This appendix presents methods available for predicting ground-water time of travel (TOT) in the unsaturated zone.

The intent of RCRA guidance and regulations is to ensure that facilities are designed, operated, and located such that there will be negligible migration of contamination beyond the barriers of the facility. Assuming no release, the velocity of contaminant migration to the ground water beneath the site is of little or no importance. The regulations, however, also recognize the possiblity of contaminant release due to failure of facility barriers. The contaminant time of travel to the ground water and the thickness of the unsaturated zone then become important issues in assessing the potential consequences of site failure.

Consideration of unsaturated TOT may be important for several reasons. With the exception of certain hydrogeologic settings, all components of a facility permitted by RCRA will be located above the water table. Therefore, any release from a facility will migrate through the unsaturated zone before reaching the water table. The TOT through the unsatuated zone is important in determining how rapidly, and to what extent, ground-water resources will be impacted by contaminant release. Consideration of unsaturated TOT may be necessary to determine appropriate monitoring strategies for detecting failures as well as for developing appropriate corrective actions.

In some locations, particularly those characterized by arid climates and deep unsaturated zones, flow through the unsaturated zone may be minimal. In such cases, the unsaturated zone may effectively form a buffer zone to delay contaminants when migrating to the water table. Recognition of such conditions is important in assessing the adequacy of a facility design.

Calculation of TOT in the unsaturated zone is not a trivial task. Simple graphical methods useful for estimating TOT in the saturated zone (e.g., construction of flow nets) are not applicable due to nonlinearities associated with unsaturated flow. Solution of unsaturated TOT must instead rely on analytical and numerical methods. Available techniques vary significantly with respect to mathematical complexity and data requirements. Selection of an appropriate technique must consider the objectives of the application and the availability of time, resources, and data.

The purpose of this appendix is to acquaint permit writers and applicants with the techniques available for determination of TOT in the unsaturated zone. The appendix is divided into six sections. This section provides an introduction to the need for determination of TOT. Section 2.0 presents technical background material regarding unsaturated flow. A general discussion of the two technical approaches for TOT determination, analytical methods, and unsaturated flow models is provided in Section 3.0.

Sections 4.0 and 5.0 discuss these approaches in more detail, and example determinations of TOT are presented in Section 6.0.

SECTION 2

TECHNICAL BACKGROUND ON UNSATURATED FLOW

The unsaturated zone is the transition region between the atmosphere and the saturated ground-water system. Passage of water through this zone is very dynamic and depends on detailed variations in the hydraulic properties of the water in the soil.

Rainfall, irrigation, and ponded water are the primary sources of water to the unsaturated zone. Redistribution or downward movement of this water through the soil occurs under the influence of gravity as long as there is a sufficient quantity present to overcome the restraining forces of capillary hydraulic potential.

Water is removed from the surface of the unsaturated zone by the processes of evaporation and/or transpiration. The rates of both processes depend directly on available solar energy and surface winds. Water also moves out the bottom of the unsaturated zone as drainage if the soil-water holding capacity is exceeded. Drained water may possibly enter the water table depending on its depth.

Water can also move within and be stored in the unsaturated zone. Water storage is characterized by a water content distribution. Water moves through and within a soil via two physical mechanisms: capillary Darcian flow (liquid phase) and vapor diffusion. Darcian flow is described by hydraulic conductivity and matric potential gradients, both of which are highly dependent on moisture content. Vapor diffusion controls actual surface evaporation and results from thermal gradients.

A soil is saturated when all void space (space not occupied by solid particles) is filled with water. An unsaturated soil contains air-filled void space as well as water. A measure of the quantity of water contained by a soil is called the water content which can be defined either on a volumetric basis (volume of water/total volume of soil, water, and voids) or a mass basis (mass of water/mass of soil solids).

Movement of water in the unsaturated zone is always directed from areas of higher to those of lower potential energy (assuming isothermal conditions). Total soil water potential (ψ) is expressed as (Feedes et al., 1978):

$$\psi = \psi_p + \psi_s + \psi_m + \psi_g$$

where

ψ_p = the pneumatic potential arising from changes in external pressure

ψ_s = osmotic potential arising from the attraction forces of water to a higher solute concentration

ψ_m = the matric potential arising from capillary and adsorptive forces of the soil matrix

ψ_g = the gravitational potential expressing the potential energy of changes in relative elevation changes.

The negative of the gradient of total potential is the force causing water movement in a soil.

The gravitation potential is an important component of the driving force of water downward through the unsaturated zone below a TSD facility. The gravitational potential of soil water at each point is determined by the elevation of the point relative to some arbitrary reference level. The matric (or capillary) potential is a negative pressure potential resulting from the adsorptive forces of the soil matrix. The matric potential can be an important factor, particularly in dry soils. The influence of the pneumatic and osmotic potential is almost always quite small and, therefore, they can be disregarded.

The relation between matric potential and soil wetness (water content) is not generally a unique one due to a phenomena known as hysteresis. Hysteresis is the phenomenon where the water content of a soil with a given matric potential can be different depending on whether the soil is wetting (sorption) or drying (desorption). The equilibrium water content at a given suction is greater in desorption than in sorption. The hysteresis effect can be attributed to several causes which include: 1) the geometric nonuniformity of individual pores; 2) entrapped air; and 3) swelling or shrinking phenomena. Typically, the hysteresis effect is small and is, therefore, disregarded in the determination of TOT (Hillel, 1971).

Movement of water through a porous medium is proportional to both the hydraulic conductivity of the medium and the hydraulic potential gradient across the medium. The hydraulic conductivity, K, represents the ability of a soil to transmit water from locations of high hydraulic potential to locations of low hydraulic potential. In cases of unsaturated flows, hydraulic conductivity is a function of moisture content (θ), such that K can be represented as $K(\theta)$. The functional relationship of $K(\theta)$ will vary from soil to soil. Typically, $K(\theta)$ will decrease rapidly by several orders of magnitude from its maximum saturated value as water content decreases.

As stated above, the moisture content can vary within the unsaturated flow system. As the moisture content changes, the matric potential (suction head or negative pressure head) and the hydraulic conductivity also change. In order to simulate water movement in the unsaturated zone, these relationships between moisture content and matric potential, and moisture content (or matric potential) and hydraulic conductivity (soil characteristic curves) must be known. The only exception to this is for cases where the moisture content, and therefore the matric head and hydraulic conductivity, remain constant throughout the unsaturated soil profile (unit gradient case). Example graphs of these two relationships are shown in Figures 2.0-1 and 2.0-2.

Most often the moisture content, matric potential, and hydraulic conductivity relationships are not available for the soils of interest at a particular site. If these data are not available, the best means of obtaining site-specific values is through laboratory measurements. Field measurements can be made, but unlike those for saturated soils, they are typically not as accurate and reliable as laboratory tests.

The moisture content versus pressure head relationship can be measured relatively easily, whereas methods for direct determination of hydraulic conductivity (K) as a function of moisture content (θ) or matric potential (ψ_m) over the unsaturated range of interest are experimentally difficult. As a result, the K versus θ or ψ_m relationship is often calculated using analytical methods such as those presented by Mualem (1976a), Burdine (1953),

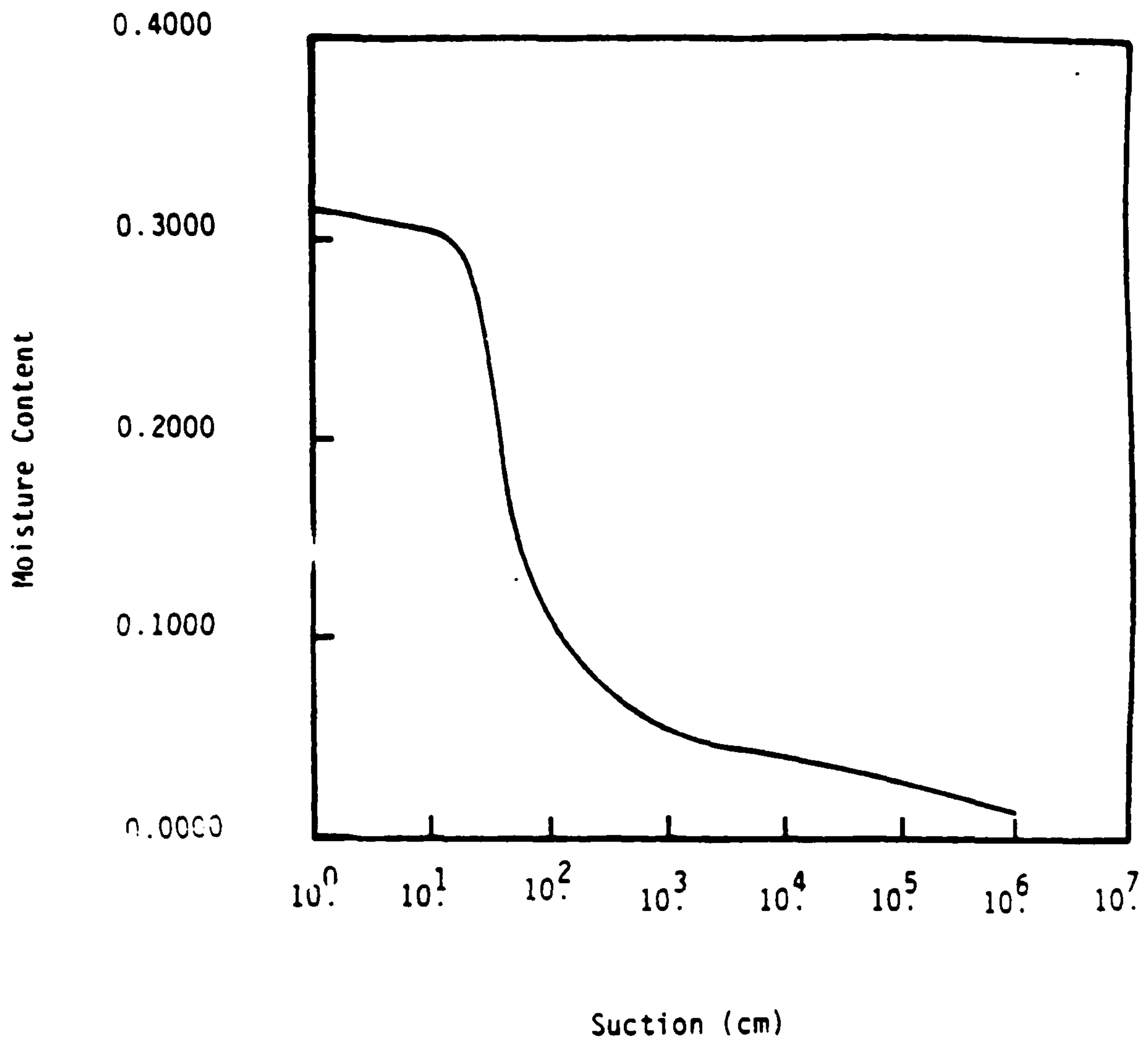


Figure 2.0-1. Graph of Moisture Content Versus Suction Head

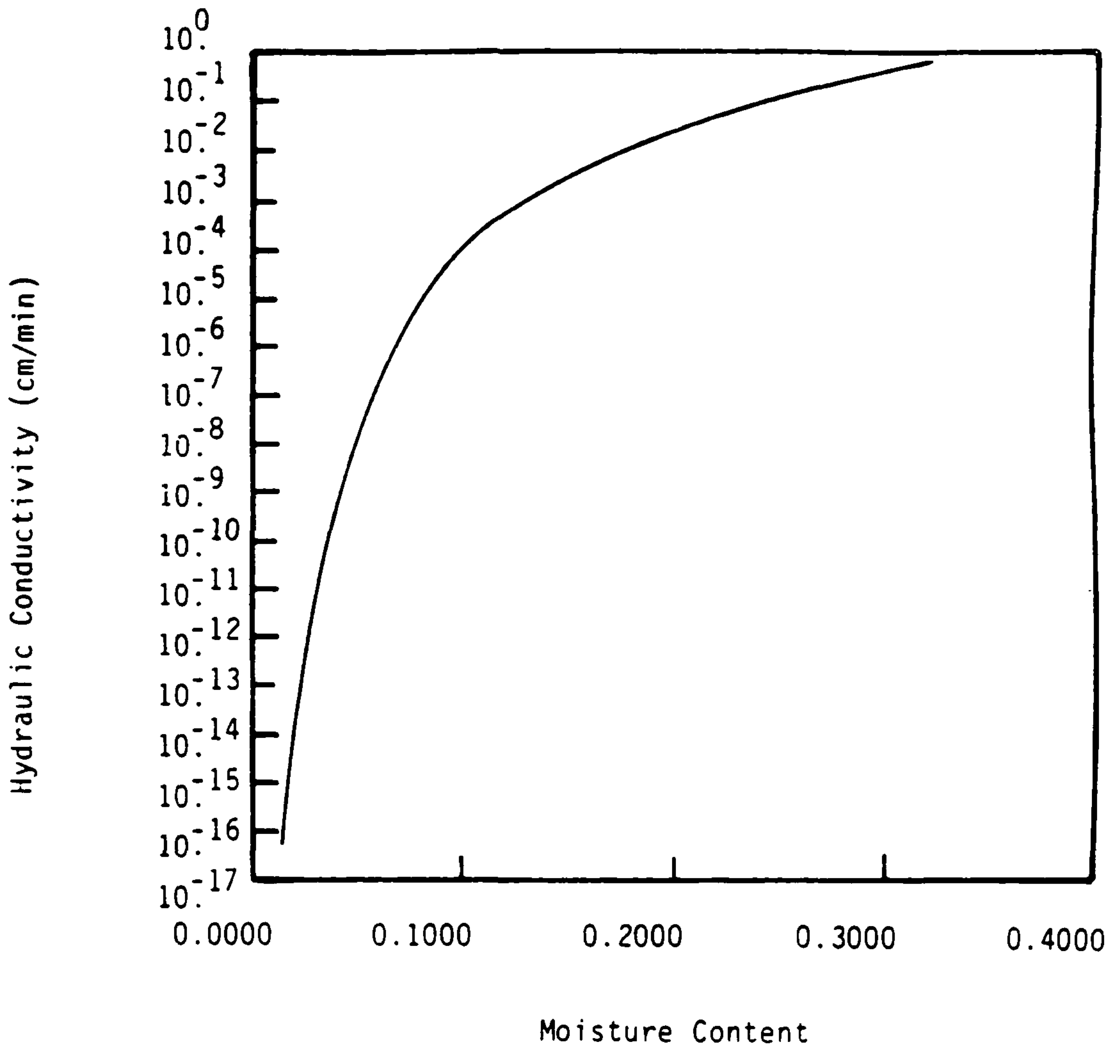


Figure 2.0-2. Graph of Hydraulic Conductivity Versus Moisture Content

and Millington and Quirk (1961). The details of these analytical methods are discussed in Mualem (1976a).

If site-specific data are not available and cannot be measured in the field or laboratory, a last resort is to obtain values for representative soils from the literature. One excellent reference is Maulem (1976b) where example soil characteristic curves for 45 soils for which actual conductivity measurements as well as moisture content as a function of matric potential were made.

SECTION 3.0

TECHNICAL APPROACHES FOR DETERMINING TOT

There are two basic technical approaches for determining TOT in the unsaturated zone, analytical solutions of TOT, and unsaturated flow modeling. Both approaches are based on the same fundamental equations, but differ in the number of simplifying assumptions made in order to solve these equations. As a result of the simplifying assumptions, the approaches differ significantly in the time necessary to obtain a solution, in computational difficulty, and in data requirements. Relative characteristics of the two approaches are summarized in Table 3.0-1.

Table 3.0-1. Relative Characteristics of Analytical Solutions and Unsaturated Flow Modeling

	Analytical Solutions	Unsaturated Flow Modeling
Computational Time	Short	Medium to Long
Data Requirements	Low to Medium	Medium to High
Complexity of Solution	Simple	Complex
Time Dependency	Steady State	Steady State or Transient

3.1. ANALYTICAL SOLUTION OF TOT

The analytical solution of unsaturated flow TOT is based upon Darcy's equation for one-dimensional flow

$$q = -K(\psi_m) \frac{\partial \psi}{\partial z}$$

where

q = flux in the vertical direction

ψ_m = matric potential (suction head or negative pressure head)

$K(\psi_m)$ = hydraulic conductivity as a function of matric potential

$\partial\psi/\partial z$ = hydraulic gradient in the vertical direction

The above relation is identical to the relation for saturated flow except that the hydraulic conductivity is not constant.

In unsaturated flow, both hydraulic conductivity and moisture content are nonlinear functions of pressure head. Pressure head, hydraulic conductivity, and moisture content need not be constant throughout the soil column. When these variables are not constant, a direct analytical solution of Darcy's equation is not possible for unsaturated flow. In order to obtain an approximate solution, simplifying assumptions must be made. Common assumptions are:

- one-dimensional flow in the vertical direction;
- water flow is steady state;
- water table conditions exist at the lower boundary;
- the upper boundary condition is constant flux;
- soil characteristics (moisture content versus matric potential and hydraulic conductivity versus matric potential) are constant with depth; and
- the hydraulic gradient is vertically down and equals unity (drainage is due strictly to gravity, or $\frac{\partial\psi_m}{\partial z} = 0$).

For nonhomogeneous soils, the constant property assumption can be approximated by dividing the soil profile into a series of layers, each layer comprised of soils having approximately the same characteristics.

The unit gradient assumption greatly simplifies the analysis. This assumption means that the matric potential and, therefore, moisture content and hydraulic conductivity are constant with depth. Using this assumption, it is possible to directly solve for moisture content in terms of the flux through the system and saturated soil properties. Knowing the moisture content and flux it is possible to calculate the pore water velocity and TOT. The unit gradient assumption is generally valid if gravitational forces dominate other forces (e.g., capillary forces).

If the unit gradient assumption is not made, the analytical solution to unsaturated flow becomes more complex. In this case, it is necessary to employ an iterative solution for pressure head and moisture content. This iterative solution is time-consuming, but can be simplified through the use of a computer.

The above solutions for TOT are one-dimensional solutions. When applying these solutions to specific sites, it is important to consider the horizontal variability of soil characteristics. If soil characteristics vary spatially, the solution should be applied to the soil profile having the highest hydraulic conductivity. The solution will then yield the highest velocity and shortest TOT (e.g., worst case) for the unsaturated flow system.

In summary, analytical solutions provide a means of quickly estimating TOT. Several assumptions are required to perform the solutions. These assumptions and, therefore, the methods themselves, are not appropriate for all applications. A detailed discussion of two analytical approaches of calculating TOT are presented in Section 4.0.

3.2 MODELING SOLUTIONS OF TOT

3.2.1 Description of Model Types

Unsaturated flow models provide another means for determining TOT in the unsaturated zone. This section discusses two general types of unsaturated flow models and how they can be applied to solve for TOT.

Two general types of unsaturated flow models are available. These are numerical models and water balance models. Numerical models solve differential equations describing water movement within the unsaturated zone. These equations are derived by combining mathematical statements for the conservation of mass and energy with equations which have been developed to relate these statements to measurable quantities such as pressure, temperature, and moisture content. Numerical models are able to account for the nonlinearities in soil properties and the variations of properties in space. Water balance models, on the other hand, simulate unsaturated flow systems such that the flow into the system is equal to the flow out of the system plus or minus storage within the system for a specific area and for a specific period of time. These models generally require the direct or indirect measurement of soil moisture and other properties which affect water movement within the unsaturated zone. Simplifying assumptions similar to those used with analytical solutions are often used with water balance models.

The two types of models represent very distinct levels of complexity in their methods of solution and their required input data. Numerical models typically require more data than water balance models. Numerical solutions use either a finite difference, finite element, or integrated finite difference technique, all of which require that the unsaturated flow system be represented as a series of nodes and elements (Figure 3.2-1). A complex system may be represented in the models with several hundred nodes, and the solution complex numerical problems may require several hours of computer time.

Water balance models, on the other hand, represent the unsaturated flow system as a series of layers of geologic materials (Figure 3.2-2). In typical applications, such models seldom have greater than ten layers, and the model input data defines the properties of each layer. Water balance models use a "book-keeping" approach to keep track of water entering and exiting the system, as well as water entering and exiting each layer within the system. Water balance models can be solved quite rapidly by computers with solution times usually on the order of minutes.

3.2.2 Determination of TOT from Model Results

The equations used to develop the solutions used in the unsaturated flow codes do not have velocity as a variable, nor is velocity a primary output of the models. Therefore, additional analysis of model results is necessary to derive TOT. The purpose of the following discussion is to present methods of determining TOT from unsaturated model results.

Four methods of determining TOT from model results are presented below. One method deals with determining the travel time for a particle along a travel path in the unsaturated zone. Another method deals with determining the time required for an instantaneous loading to migrate through the unsaturated zone to the water table. The other two methods use steady state solutions for moisture conditions or contaminant concentrations.

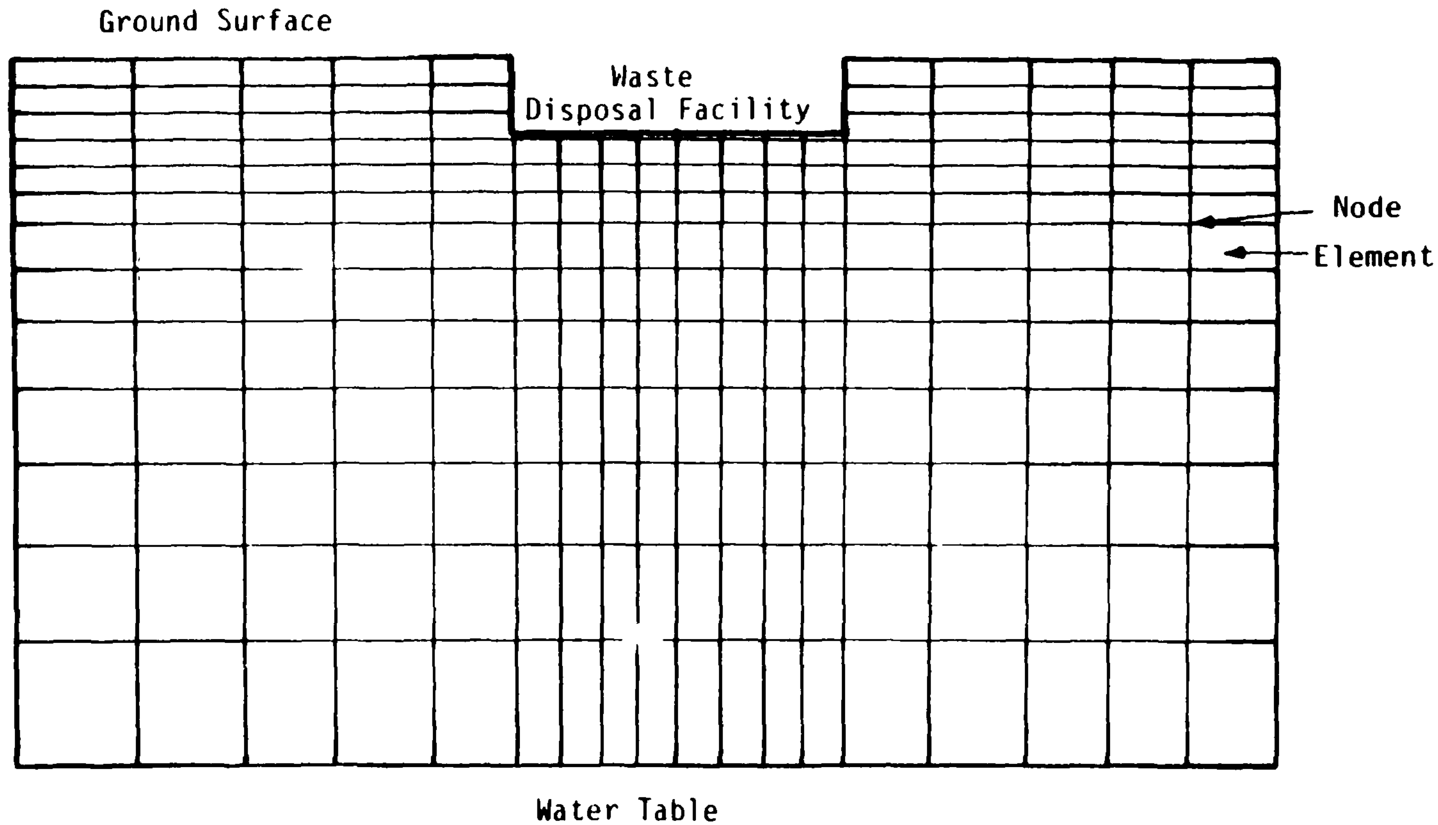


Figure 3.2-1. Cross-Section View of the Node and Element Discretization of an Unsaturated Flow System Beneath a Waste Disposal Facility

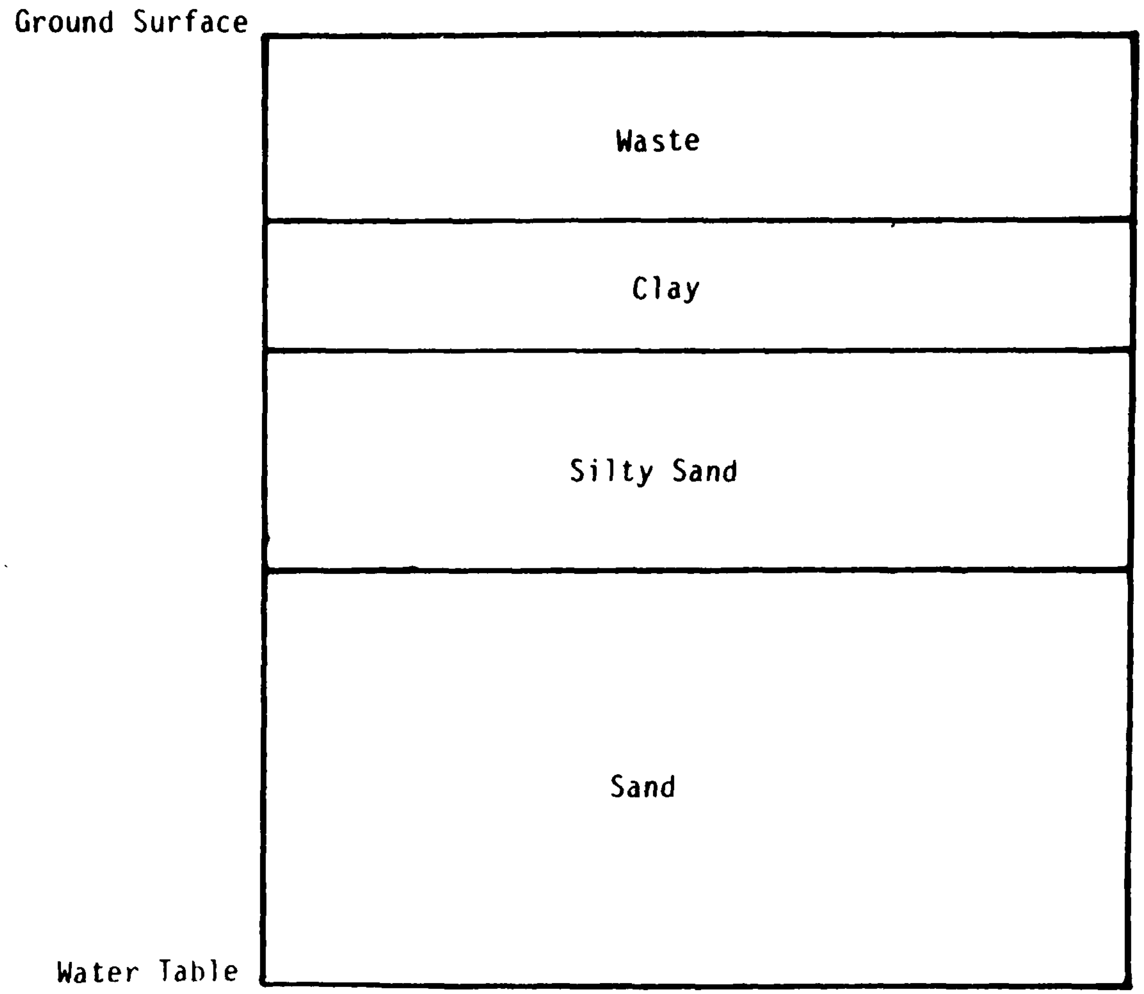


Figure 3.2-2. Cross-Section View of the Layer Representation of an Unsaturated Flow System for Use in a Typical Water Balance Model

Determination of Particle Travel Time--

This approach to TOT is appropriate for determining TOT associated with any type of loading to the system (steady state or transient). The approach is based upon Darcy's Equation for unsaturated flow (Equation 3-1) and requires that the code be capable of determining pressure head at each node or layer boundary for each time step. As described by Darcy's Equation, the velocity between two nodes (or through a layer) will be equal to the hydraulic conductivity between the two nodes times the hyraulic gradient between the two nodes. These quantities can be directly determined from matric potential. The average velocity for the element can be converted to pore water velocity for a time step, by dividing by moisture content. Knowing the pore water velocity it is possible to determine how far a particle travels during that time step.

This approach to TOT determination involves tracking the position of a particle present at the surface (or water source) at the start of the first time step. Using the average velocity of the particle's position for the first time step, the displacement of the particle for that time step is calculated. After the second time step, the velocity at the particle's new position is calculated and the particle displaced a distance for that time step. This process is repeated until the particle reaches the water table. The time required to reach the water table is the unsaturated TOT.

It should also be noted that some unsaturated flow codes have ancillary programs that will extract appropriate data and perform the above analysis. If desired, it is possible to modify any numerical code to perform the analysis.

Solution of Steady-State Travel Time--

An approach similar to the previous approach can be used to determine steady state travel times through the unsaturated zone. A model is used to solve for steady state values of hydraulic potential, moisture content, and hydrauilc conductivity at each node. These nodal values are used to determine the steady state pure water velocity between each pair of nodes (i.e., across each element in the model). Elemental velocities are then used to determine travel times for each element. The sum of all the elemental travel times along a flow path is the unsaturated TOT.

The above approach would be appropriate for determining TOT in cases where steady state conditions will be encountered (e.g., constant surface flux conditions). A limitation of the approach is that the TOT is valid only for steady state conditions and does not yield the TOT for the period leading up to steady state conditions. For example, if a column of soil at one set of steady state moisture conditions suddenly receives a new or additional constant flux of water at the surface, the above approach can be used to determine the TOT after new steady state conditions have been reached. The method will not determine the TOT associated with water which passed through the soil column during the time when new steady state conditions were being established. Therefore, the method will not identify the TOT associated with the first particle of water to reach the water table.

TOT Associated With Instantaneous Loadings--

The advantage of the above approach is the ability to determine TOT for any type of loading. The disadvantage is that the solution algorithm may not be included in the code being used. The following approach is appropriate for virtually any code, but is limited to cases involving large transient fluxes at the surface. Such fluxes represent extreme events; including natural events such as extreme precipitation, or artificial events such as sudden failure of a landfill or impoundment liner.

Introduction of a large amount of infiltration to the unsaturated zone will cause the propagation of a wetting front downward through the soil column. Transient unsaturated flow models may be used to track the progress of this wetting front through the unsaturated zone. The time required for the wetting front to reach the saturated zone may be taken as the TOT. This approach is illustrated in Figure 3.2-3. This figure shows the variation of moisture content with depth and time. The wetting front appears as an area where there is a rapid change in moisture content with depth. In the example shown in Figure 3.2-3, the time for the wetting front to reach a water table located at 40 m depth would be approximately 90 hours. If graphical model outputs are not available, the moisture content of each node (layer) should be examined at the end of each time step. A large increase in moisture content over a time step signifies the passing of the wetting front.

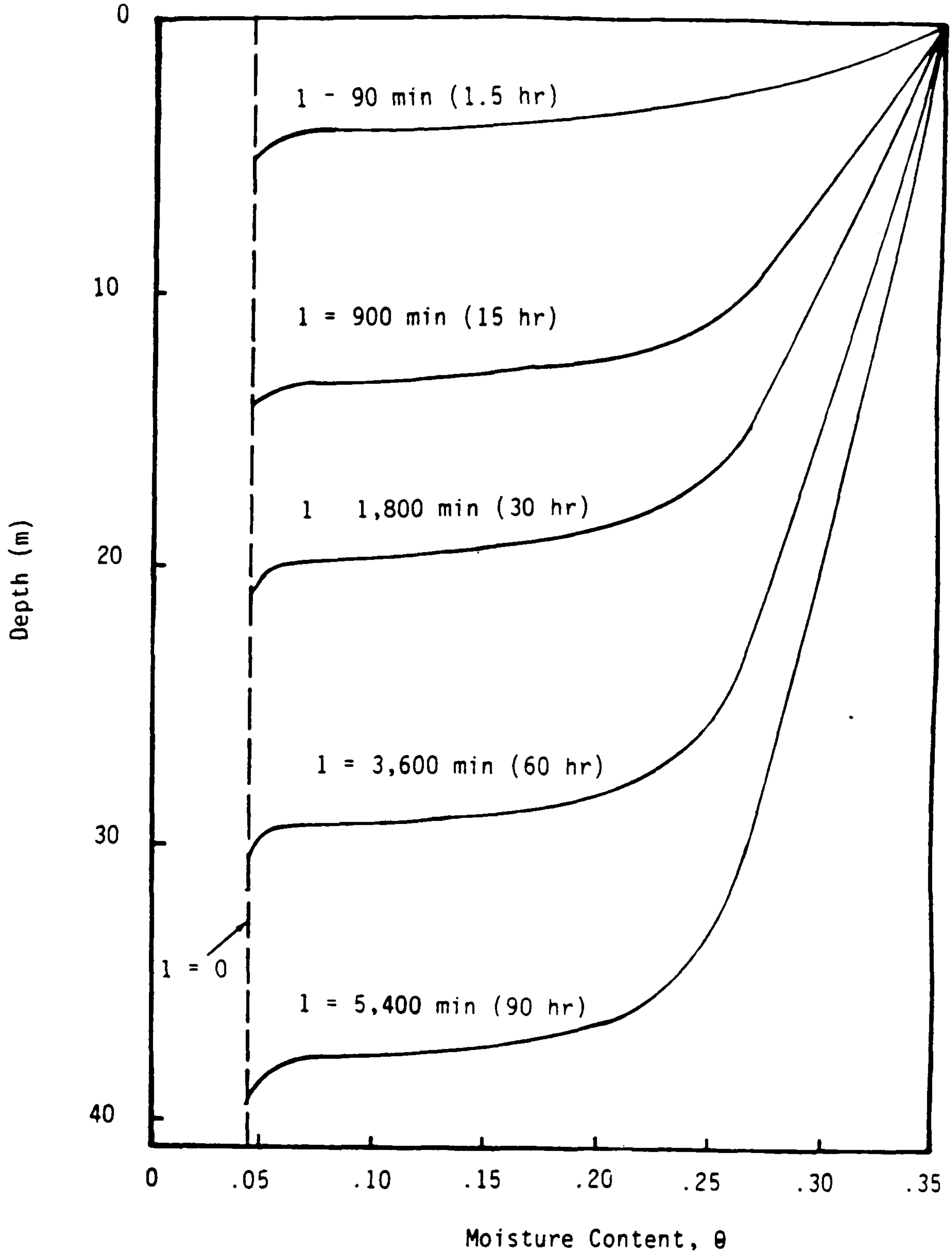


Figure 3.2-3. Example Model Results Showing Migration of Wetting Front with Time

An important consideration in the above approach is determination of the input source. The input must be large enough to cause the wetting front to migrate entirely through the soil column to the saturated zone. For example, in areas with deep unsaturated zones having low moisture contents, even very large inputs may never reach the saturated zone regardless of how long the model is run. Unfortunately, there is no general guidance for determining how large an input is required.

It is very important to note that use of this approach does not imply that variations of moisture content with time are necessary for unsaturated flow to occur. This approach is applicable only for transient flow conditions and only when the water input is large enough to cause a significant perturbation to existing conditions.

Determination of Contaminant Travel Time --

Some unsaturated codes have the capability of modeling the transport of contaminants through the unsaturated zone. A known concentration of contaminants can be input to the top of the soil column and the code used to determine the concentration of contaminants leaving the bottom of the unsaturated soil column. If the simulation is run for a long period of time, steady state conditions will be reached where the concentration of contaminants leaving the soil column is equal to the concentration entering the soil column. If there were no dispersion of contaminants (e.g., plug flow), the time required to reach steady state conditions would be equal to the time of travel for the contaminant. Because of dispersion, however, the average contaminant TOT will be somewhat less than the time to reach steady-state conditions. An average contaminant TOT can be estimated as some fraction of the time to reach steady state conditions (e.g., the time to reach output concentrations equal to one-half the steady state value). The ground-water TOT can be related to the contaminant TOT by use of a retardation factor. The retardation factor is equal to the ground-water velocity divided by the contaminant velocity. Dividing the average contaminant TOT by the retardation factor will yield the unsaturated ground-water TOT.

3.3 SELECTION OF THE APPROPRIATE METHOD TO DETERMINE TOT

A decision tree for selection of the appropriate method for determining TOT is shown in Figure 3.3-1. The decisions to be made in this figure consider both the characteristics of the site and the availability of the data. The representation of the site should be as realistic as possible depending on the availability of the data. For example, if soil properties at a site exhibit complex spatial variability but data are not available to describe this variability, the assumption of simple variability should be made. Under these circumstances, one has to realize that the assumption(s) made can significantly impact the results.

The rule of thumb for selecting the appropriate procedures is to choose the simplest one which can be applied to your specific problem. If the unsaturated flow system can be represented as a one-dimensional steady state problem with a single material type, and the flow is controlled by gravity drainage (i.e., unit gradient), the simplest analytical approach can be used to obtain a direct solution. If, however, the unit gradient assumption does not apply but the other assumptions are applicable, an analytical method using an iterative solution scheme can be applied. All transient problems, and problems in more than one dimension require the use of simulation models. Water balance models are appropriate for simple quasi-two-dimensional problems where flow is controlled by gravity drainage. Numerical models should be used for all higher dimension problems having complex geometry and boundary conditions.

The direct analytical solution technique is quick and easy to apply; however, the assumptions of the method limit its applicability. The iterative analytical solution offers more flexibility, but limitations on the dimensionality and complexity of the problem restrict its applicability. Due to the limitations of the analytical approaches, simulation modeling can be the only means of obtaining reliable results for complex problems.

Application of modeling is typically limited by the availability of data and the availability of time. The more complex a model, the greater its data requirements (both in time and space). Acquisition of these data often requires that field and laboratory programs accompany model development.

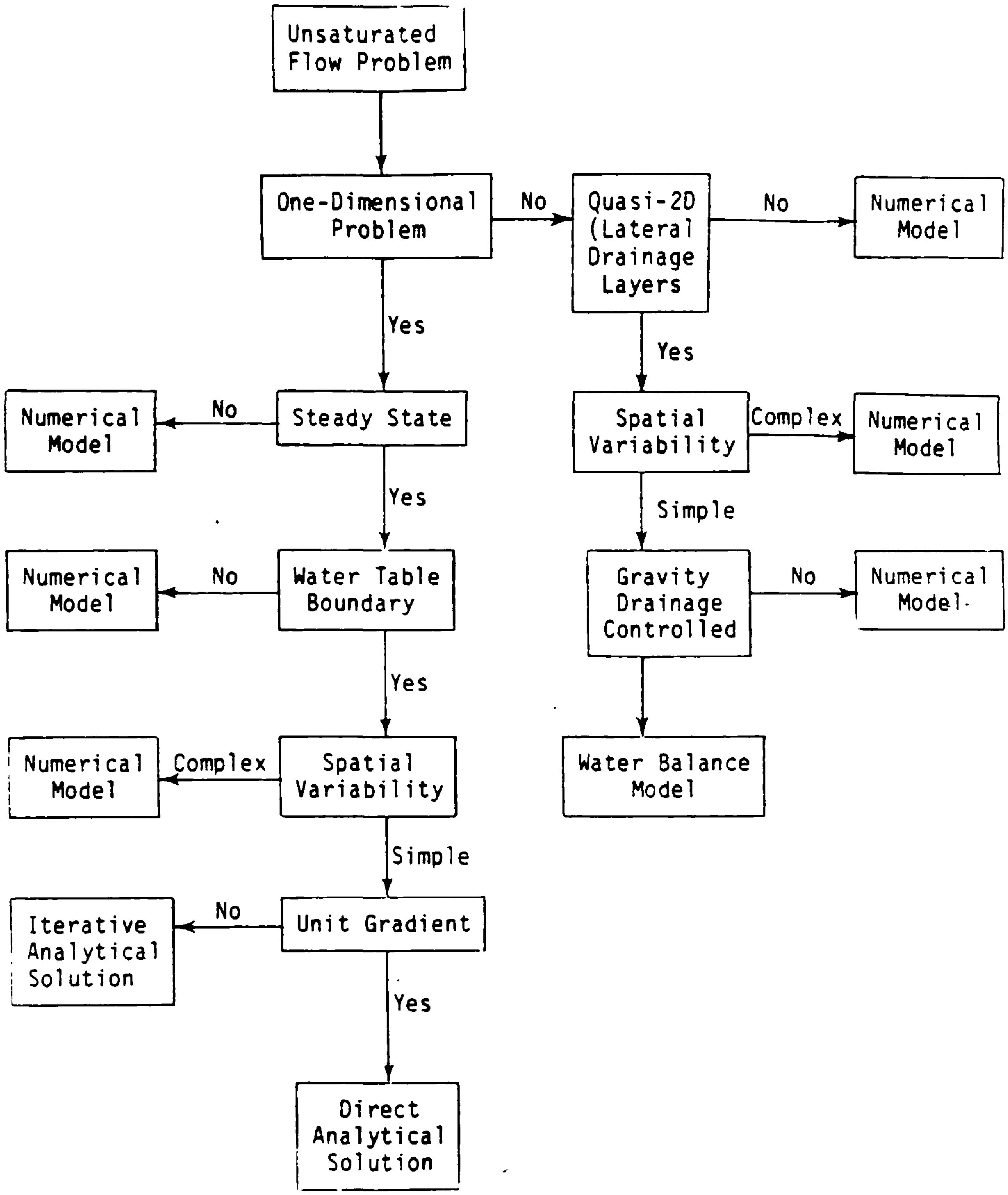


Figure 3.3-1. Summary of Selection of Approach for TOT Determination

While complex models may be set up and run with limited data using simplifying assumptions, such an approach does not take full advantage of the capabilities of these models and is, therefore, of limited value.

Development and application of models can also be very time consuming (weeks to months). Calibration and verification of models may take considerably more time. The time required is usually proportional to the complexity of the model.

The above limitations relate to modeling in general. Specific limitations related to the use of models to support permit writing activities are:

1) Time requirements, especially for development and calibration of numerical models, may exceed the time available for preparation and review of Part B applications.
2) Data supplied with Part B applications may be inadequate to develop and calibrated models, and will almost certainly be inadequate to verify models.

The above limitations do not imply that the use of unsaturated flow modeling is inappropriate to support permit writing. Rather, these limitations are presented to aid the reader in determining the suitability of modeling for Part B application.

SECTION 4.0

ANALYTICAL SOLUTIONS OF TOT

This section provides a more detailed discussion of the two analytical approaches for calculating TOT presented in Section 3.0. The data requirements and the sources of the data are presented, the methods are explained, and example calculations are provided. It will be shown that these methods provide a means of calculating TOT that is easier and less time consuming than using unsaturated flow models. However, the application of these methods is limited due to the assumptions used in their development.

4.1 DATA REQUIREMENTS AND SOURCES

The data required by the analtyical solutions for calculating TOT are listed below:

- stratigraphy of the site;
- thickness of geologic units or soils;
- soil moisture characteristics for each unit or soil; and
- steady state flux of water/moisture in the unsaturated zone.

Stratigraphic information is necessary for determining the types of soils that are present in the unsaturated zone, and to establish the layering sequence of these soils. Stratigraphy is most often determined from logs of borings drilled at the site. Subsurface investigations should be performed in preparation of Part B applications, and therefore, stratigraphic information should be available.

The thickness of the unsaturated zone, or layers within the unsaturated zone, establish the distance that water/moisture must travel before it reaches the water table. This information would most likely be obtained from borings, and should be available from the Part B application.

The soil characteristics refer to the relationship between soil moisture content (θ) and matric potential (ψ_m), and the relationship between hydraulic conductivity (K) and matric potential. These charteristics of the soil(s) are required for any determination of flow or TOT in the unsaturated zone; either analytically or through the use of models.

Ideally, these relationships should be measured in the laboratory using soil samples obtained from the site. If laboratory measurements are not possible, the following simple analytical relationships between pressure head and water content, and between conductivity and matric potential (Campbell, 1974) can be used:

$$\psi_m = \psi_e(\theta_s/\theta)^b$$

$$K = K_{sat}(\psi_e/\psi_m)^n$$

where

ψ_e = air entry matric potential;

θ_s = saturated water content;

θ = field water content;

K_{sat} = saturated hydraulic conductivity;

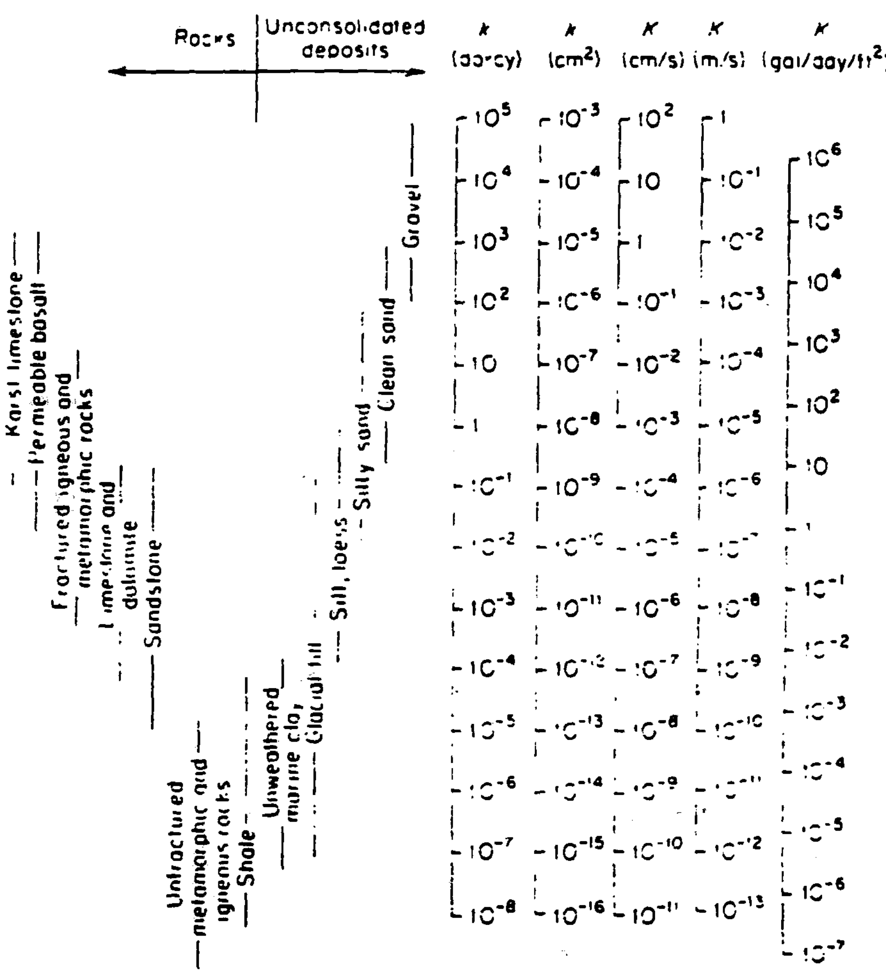
b = negative one times the slope of the log-log plot of ψ_m versus θ; and

$n = 2 + 3/b$.

Using the above relationships it is necessary to know only the slope of the log-log plot of ψ_m versus θ, the saturated hydraulic conductivity, and the saturated moisture content. The saturated hydraulic conductivity can be determined in the field or measured in the laboratory. Field methods are preferred to laboratory methods, and are detailed in Appendix A, Section 1.0. Default values, such as those listed in Table 4.1.1, should be used only as screening factors in choosing a proper field method since they may underestimate hydraulic conductivity by several orders of magnitude.

The saturated moisture content (θ_s) can also be obtained from laboratory measurements. If measurements are not possible, θ_s can be assumed to be

Table 4.1-1. Representative Values for Saturated Hydraulic Conductivity (Source: Freeze and Cherry, 1979)



equal to the total (actual) porosity. Representative values of total porosity are given in Table 4.1-2.

Table 4.1-2. Representative Values for Porosity

Material	Porosity
Coarse Gravel	28%
Medium Gravel	32%
Fine Gravel	34%
Coarse Sand	39%
Medium Sand	39%
Fine Sand	43%
Silt	46%
Clay	42%

Analytical solutions of travel time assume steady state flow of moisture through the unsaturated zone. A simple approximation of steady state flux is to assume that it is equal to the net infiltration at the site. Net infiltration is equal to the net precipitation minus actual evapotranspiration. If such information is not included in the Part B application, it should be obtainable from weather stations or agricultural research stations.

4.2 DESCRIPTION OF ANALYTICAL SOLUTIONS

Two analytical solutions to unsaturated travel time are presented below. Both solutions require the steady state assumptions described in Section 3.0. The first solution assumes that the hydraulic gradient is equal to 1. The second solution allows for variable moisture content in the soil column (i.e., hydraulic gradient may not be equal to 1).

4.2.1 Solution for Unit Hydraulic Gradient

The following solution assumes steady state flow and a unit hydraulic gradient and employs the analytical soil moisture, pressure, and conductivity relationships described earlier (Campbell, 1974). Utilizing Darcy's equation and the soil characteristic relationships described by Campbell (1974), it is possible to derive the following expression for moisture content as a function of steady state flux (Heller, Gee, and Myers, 1985)

$$\theta = \left(\frac{q}{K_{sat}}\right)^m \theta_s$$

where

q = steady state flux;

K_{sat} = saturated hydraulic conductivity;

θ_s = saturated moisture content; and

$m = 1/(2b + 3)$, where b is negative one times the slope of the log-log plot of ψm versus θ, as described earlier.

Using the above equation, it is possible to directly calculate the steady state moisture content of the soil. Pore-water velocity (the velocity of a water particle) is defined as

$$V = q/\theta$$

Therefore, travel time (T) can be caluculated as the thickness of the soil layer (L) divided by the pore-water velocity

$$T - L/V = L\theta/q$$

The above solution of travel time can be applied to single or multiple layered systems. For multiple layers, the above calculations are performed for each layer. The total travel time through the unsaturated zone is then equal to the sum of the travel times for each layer.

Example calculations are presented below to illustrate the procedure. Example 1 shows calculations for a single layered system; Example 2 shows calculations for a multi-layered system.

Example Problem 1

This first problem provides an example of the procedure for calculating TOT through an unsaturated zone consisting of a single material type. A schematic of this single layered system is shown in Figure 4.2-1.

The following parameters must be known (either measured in the field or laboratory, or obtained from the literature) in order to apply this solution. Example values of each parameter are provided.

Parameter	Example Value
Flux (q)	0.5 cm/yr
Saturated water content (θ_s) for soil profile	0.31 m^3/m^3
The slope (-b) of a log-log plot of ψ_m versus θ	-3.162
Saturated hydraulic conductivity (K_{sat}) of the soil	5.4×10^4 cm/yr
Length of unsaturated column (L)	3760 cm

Step 1: Calculate m

$$m = \frac{1}{2b + 3}$$

$$= \frac{1}{6.324 + 3}$$

$$- 0.107$$

Step 2: Calculate Steady-State Moisture Content θ

$$\theta = \left(\frac{q}{K_{sat}}\right)^m \theta_s$$

$$= \left(\frac{0.5 \text{ cm/yr}}{5.4 \times 10^4 \text{ cm/yr}}\right)^{0.107} (0.31 \text{ m}^3/\text{m}^3)$$

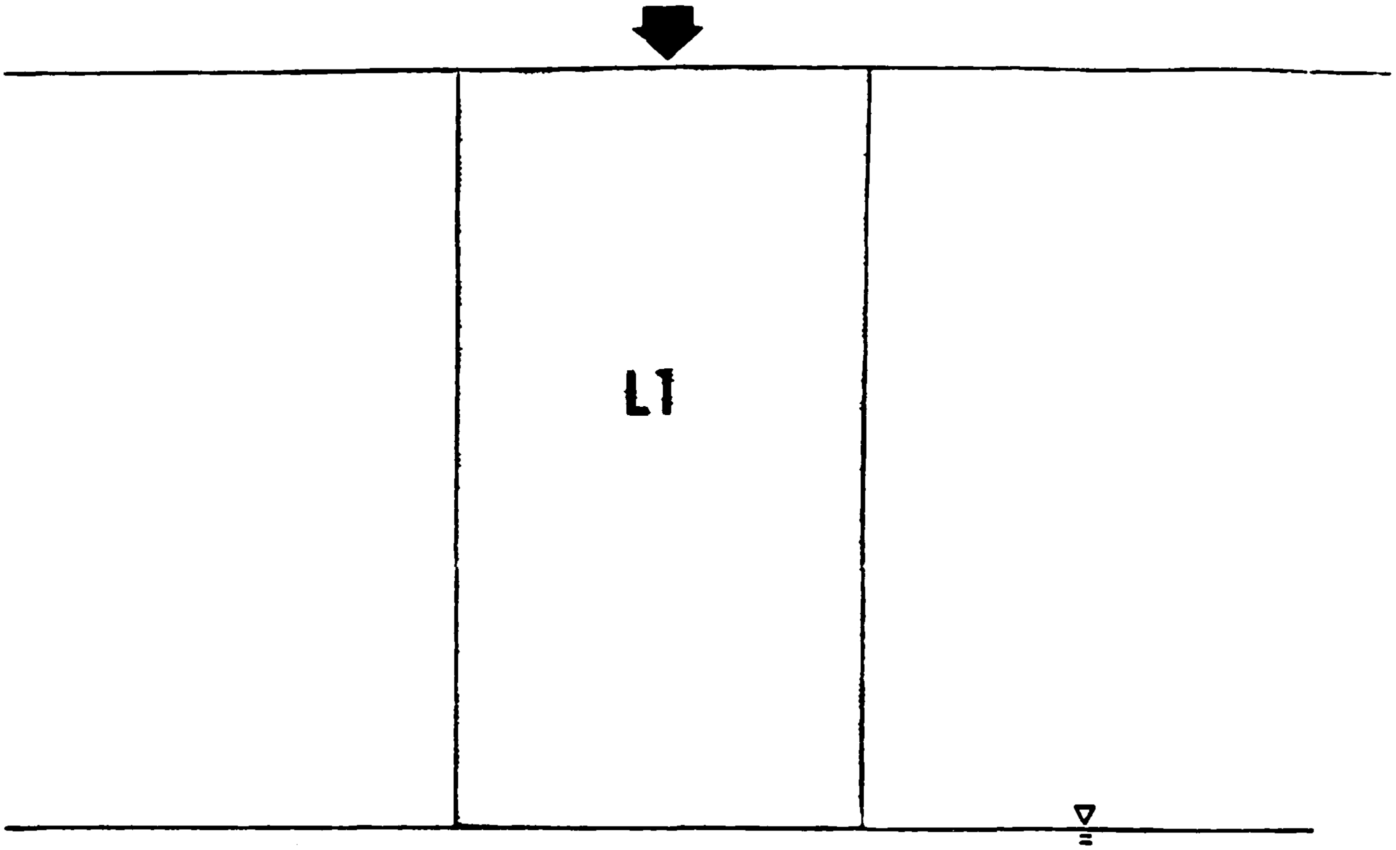


Figure 4.2-1. Schematic of Example Single-Layered System

$$= 0.09\ m^3/m^3$$

Step 3: Calculate Travel Time (T)

$$T = \frac{L\theta}{q}$$

$$= \frac{(3760\ cm)(0.09\ m^3 m^3)}{0.5\ cm/yr}$$

$$= 677\ years$$

Example Problem 2

This second problem is similar to the first except that it illustrates the procedure for calculating TOT through a multi-layered unsaturated flow system. A schematic of this multi-layered system is shown in Figure 4.2-2.

The following parameters must be known in order to apply this solution. Example values of each parameter are provided.

Parameter	Value	Notes
Flux (q)	0.5 cm/yr	Constant throughout section
Saturated Water Content		
θ_{s1}	0.31	
θ_{s2}	0.40	
θ_{s3}	0.42	
Slope of log-log plot of ψ versus θ(-b)		
b_1	-3.162	
b_2	-3.475	
b_3	-3.610	
Saturated hydraulic conductivity (K_{sat})		
K_1	5.4×10^4 cm/yr	
K_2	1.0×10^4 cm/yr	
K_3	0.5×10^4 cm/yr	
Length of unsaturated column (L)		
L_1	1,000 cm	
L_2	1,000 cm	
L_3	1,760 cm	

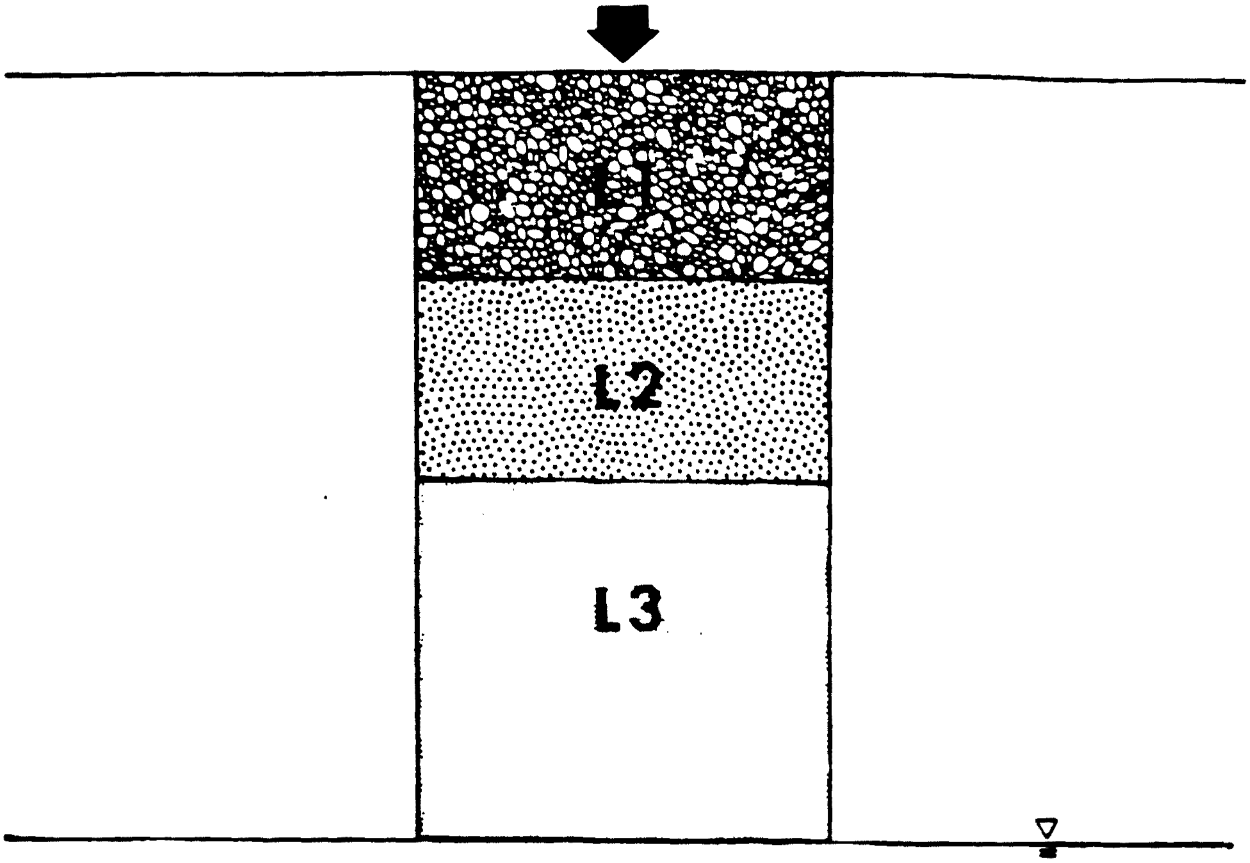


Figure 4.2-2. Schematic of Example Multi-Layered System

Step 1: Calculate m for Each Layer

$$m = \frac{1}{2b + 3}$$

m_1 0.107

$m_2 = 0.101$

$m_3 = 0.098$

Step 2: Calculate Steady-State Moisture Content for Each Layer

$$\theta = \left(\frac{q}{K_{sat}}\right)^m \theta_s$$

$\theta_1 = 0.09$

$\theta_2 = 0.15$

$\theta_3 = 0.17$

The total travel time through the section in the sum of the times through each of the layers.

Step 3: Calculate Travel Time (T)

$$T_1 = \frac{(1,000\ cm)(0.09)}{0.5\ cm/yr} = 180\ yr$$

$$T_2 = \frac{(1,000\ cm)(0.15)}{0.5\ cm/yr} = 300\ yr$$

$$T_3 = \frac{(1,760\ cm)(0.17)}{0.5\ cm/yr} = 600\ yr$$

$$T = T_1 + T_2 + T_3 = 1,080\ yr$$

4.2.2 Solution for Variable Moisture Content

Solution of the variable moisture content case is more complex and requires discretization of the soil profile into a number of node or grid points as shown in Figure 4.2.2-1. The analytical solution for the case is (Jacobson, Freshley, and Dove, 1985)

$$\psi_i = \psi_{i-1} + \Delta z_i \ (q/K^* - 1)$$

where

ψ_i = pressure head at the upper grid point;

ψ_{i-1} = pressure head at the lower grid point;

q = flux through the soil column;

Δz_i = elevation difference between grid points; and

K^* = harmonic mean hydraulic conductivity between grid points

$$K^* = \frac{\Delta z_i}{\delta z_i/K_i + \delta z_{i-1}/K_{i-1}}$$

K_i, K_{i-1} = hydraulic conductivity at the upper and lower grid points, respectively.

The solution begins with the grid point located at the lower boundary (water table), where ψ_{i-1} is known to be 0, and K_{i-1} is known from ψ_{i-1} and the soil characteristic curve. The solution proceeds iteratively by assuming a value of ψ_i, determining K^*, and then solving for ψ_i. A new value is assumed for ψ_i and the process repeated until there is convergence on a solution. The calculated value of ψ_i is then used as ψ_{i-1} for the next pair of grid points and the process is repeated.

Once the solution has determined the pressure head at every grid point, the moisture content and hydraulic conductivity at every grid point can be obtained from soil characteristic curves. Examples of soil characteristic curves, how to use them, and where to get them is provided in Section 2.0. Knowing the moisture content and hydraulic conductivity at two grid points, the travel time between the grid points is given by

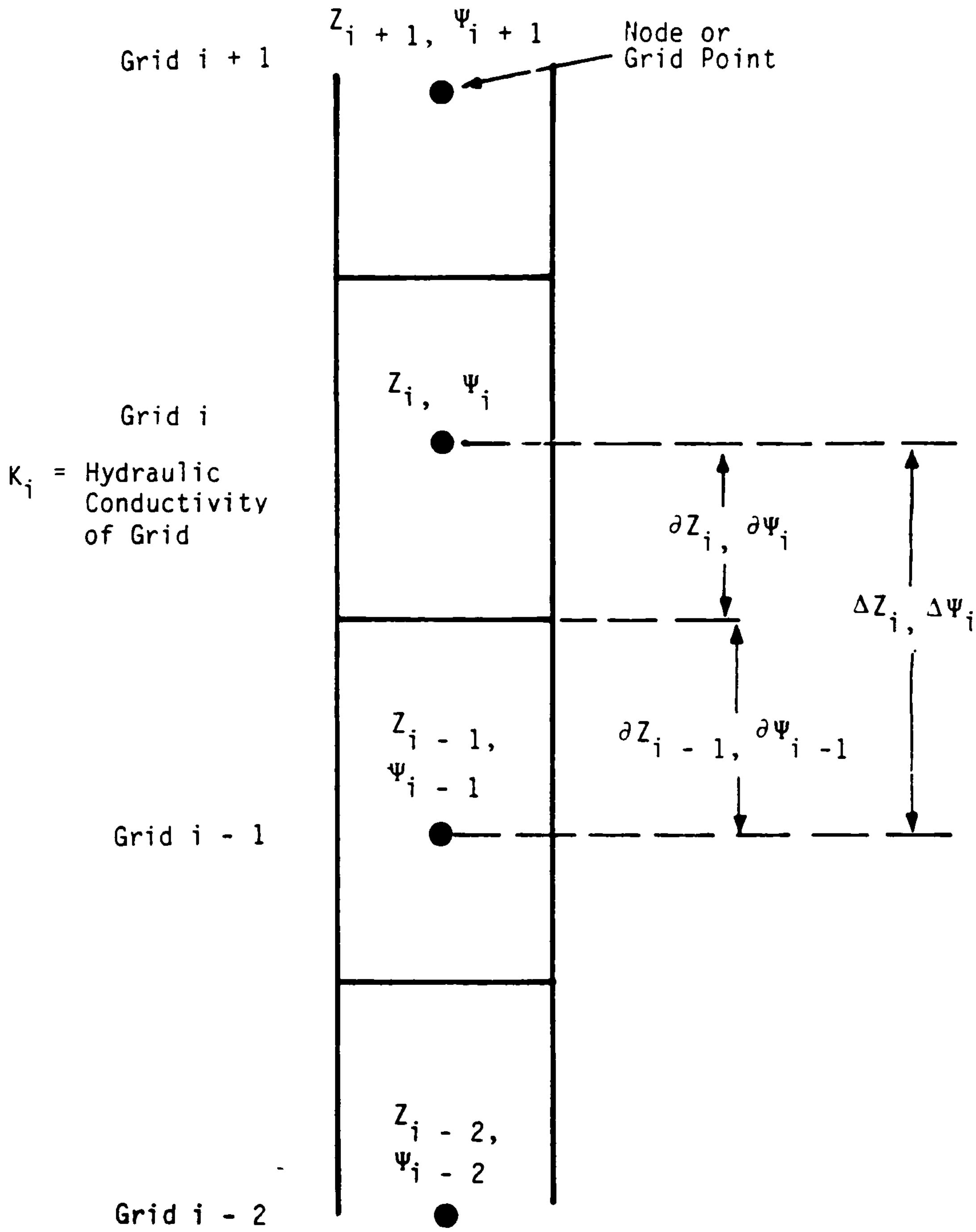


Figure 4.2.2-1. Discretization Between Grid Points

$$\Delta t_i = \frac{(\Delta z_i)^2 \, \theta^*_i}{K^*_i \, \Delta h_i}$$

The above equation is used to determine the travel time between every pair of grid points. These travel time segments are then summed to obtain the total travel time through the soil column.

It is possible to perform the above solutions manually for very simple systems. However, as with all iterative solutions, the process can be very time consuming. Therefore, the use of a computer is recommended. A computer code to perform the above solutions for pressure head and travel times has been developed by Jacobson, Freshley, and Dove (1985).

SECTION 5.0

UNSATURATED FLOW MODELS

5.1 INTRODUCTION

The two types of unsaturated flow models identified in Section 2.0 are examined in greater detail in this section. It should be noted that the intent of this appendix is not to recommend specific computer codes for use by permit writers or to provide detailed instructions in the use of any particular codes.

The purpose is to demonstrate the use of two codes which are considered to be representative of codes in these two categories.

A large number of unsaturated flow codes are presently available. General characteristics of many of these codes are presented in Table 5.1-1.

A partial list of available unsaturated flow models is also contained in EPA (1984).

Selection of a code should be made by the perspective user considering such factors as:

1) familiarity with the operation of an appropriate code;
2) availability of data required by the code;
3) applicability of the code to the specific problem (e.g., dimensionality, complexity of the system);
4) acceptability and documentation of the code; and
5) hardware availability.

Familiarity with a code is perhaps the most important consideration. If an analyst is already familiar with a particular code, that code should be used provided it meets the requirements of the application. Availability of data is the second most important consideration. The available data for an application should be compared with the data requirements of the codes being considered. Applicability of the code to the problem is perhaps equally as

Table 5.1-1. Summary of Unsaturated Zone Codes

Code Name	Code No.	Spatial Characteristics: Dimensions 1	2	3	Discretization Method FDM	IFDM	FEM	Other	Special Features	Past Applications	Principal Contact	Comments
AMOCO	37			X	X					Oil reservoir	AMOCO	Proprietary Code
ALPURS	21			X	X				Three-phase oil, water, gas		Mobil Corp.	Proprietary Code
BETA-II	40			X	X					Oil reservoir	Intercomp.	Proprietary Code
BRUTSAERT1	33		X		X					Experimental	Brutsaert	
BRUTSAERT2	39		X		X					Experimental/Laboratory	Brutsaert	
CMG	38			X	X					Oil reservoir	CMG	Proprietary Code
COOK	29		X						Two-phase oil & gas	Oil reservoir	Cook	Proprietary Code
DELAAT	48		X				X		Roots, evapotranspiration	Ground-water extraction crop production	De Laat	European Code
FEMWATER	24		X				X				Yeh	
FLUMP	5		X				X				Narasimhan	
GRANDALF	30		X		X					Underground nuclear explosions	Morrison	
GPSIM	31			X	X						Exxon	Proprietary Code
MOMOLS	52	X			X					Experimental	Rojstoczer	
PORES	49			X	X					Oil reservoir	UKAEA	European Code
REEVES-DUGUID	22		X				X		Radioactive decay		Reeves	
SHELL	42			X	X					Oil reservoir	Shell Oil Co.	Proprietary Code
SSC	41			X						Oil reservoir	SSC	Proprietary Code
STGWT/MOGWT	27	X			X						de Smedt	European Code
SUM2	46		X				X		Roots, evapotranspiration	Ground-water extraction	De Laat	European Code
SUPERMOCK	47		X		X				Roots	Ground-water extraction	Reed	
TRACR3D	55			X		X			1- or 2-phase flow with tracer in either phase (air or water) Freundlich, Langmuir sorption, radioactive decay, capillary effects	Tracer flow in unsat. conditions, Radionuclide transport, Tracer flow in fractured system	Travis	Can operate in 1, 2 or 3 dimensions
TRIPM	51		X				X		3-member decay chain	Radioactive waste disposal	Gureghian	
TRUST	4			X			X				Narasimham	
TS&E	32			X						Oil reservoir	Tech. Soft. & Eng.	Proprietary Code
UNFLOW	7		X				X			Radioactive waste disposal	Pickens	
UNSAT1	28	X					X				van Genuchten	
UNSAT1D	10	X			X				Roots, evapotranspiration	Crop studies	Bond	
UNSAT2	26		X				X		Roots	Engineering design	Neuman	
VERGE	8			X			X			Radioactive waste storage	Verge	
VS2D	45		X		X				Roots, evapotranspiration		Lappala	
WAFE	50		X			X			Coupled heat & 2-phase mass transport (air vapor & liquid) Accurate treatment of H_2O Separate velocity field phase	Confined underground radioactive waste disposal, In-situ fossil energy recovery studies, 2-phase flow and tracer studies	Travis	Can operate in 1 or 2 dimensions

KEY: FDM = finite difference method.
IFDM = integrated finite difference method.
FEM = finite element method.

Table 5.1-1. Cont'd.

Code Name	No.	Spatial Characteristics: Dimensions 1	2	3	Discretization Method FDM	IFDM	FEM	Other	Special Features	Past Applications	Principal Contact	Comments
BACHMAT	6	X			X				Surface/ground water		Backmat	Middle-east Code
DUGUID-REEVES	19		X				X		Absorption & decay		Duguid	Compatible with Code No. 22
FECTRA	17		X				X		1st-order decay, sorption		Baca	
FEMWASTE	25		X				X				Yeh	Compatible with Code No. 22
MLTRAN	54		X				X				Reisenauer	Compatible with Code No. 44
MMT-DPRW	44		X					X		Ground-water studies	Simmons	Discrete Parcel Random Walk
SCAT1D	35	X			X				Stochastic velocity field		Oster	Stochastic Code
SCAT2D	36		X		X				Stochastic velocity field		Oster	Stochastic Code
TRNMDL	2	X			X						Av-Ron	Middle-east Code

KEY: FDM = finite difference method.
IFDM = integrated finite difference method.
FEM - finite element method.

Table 5.1-1. Cont'd.

Code		Spatial Characteristics										
		Dimensions			Discretization Method							
Name	No.	1	2	3	FDM	IFDM	FEM	Other	Special Features	Past Applications	Principal Contact	Comments
HANKS	1	X			X				Roots	Crop production studies	Hanks	
MARINO	53			X			X		1st-order reactions		Marino	
MCCANN	20		X		X				Heat transfer		McCann	
MOBIDIC	14		X		X				Roots		Couchat	European Code
NMODEL		X			X						Selim	
SEGOL	9			X			X				Segol	
SHAMTU	43	X			X					Water loss by evaporation	Vauclin	European Code
SUMATRA-1	11	X					X		0- & 1st-order decay		van Genuchten	
TARGET	18			X		X			Heat transfer, elegant numerical solution. 0- & 1st-order decay. Variable saturation. Radioactive decay products	Tailings and chemical waste disposal, radioactive waste disposal	Dames & Moore	Proprietary Code
TRANS	23		X				X				Walker	
TRANSONE	12	X					X				van Genuchten	
TRANSTWO	13		X		X						Shapiro	
UNFLW	3	X			X					Salinity studies	Kapuler	
WATSOL	16	X			X						Gaudet	European Code
WHC	34			X				X			Crooks	Integrated Compartment Method

KEY: FDM = finite difference method.
IFDM = integrated finite difference method.
FEM = finite element method.

TABLE 5.1.1. Cont'd.

Code		Spatial Characteristics										
		Dimensions			Discretization Method							
Name	No.	1	2	3	FDM	IFDM	FEM	Other	Special Features	Past Applications	Principal Contact	Comments
SESOIL (Seasonal Soil Model)		x							Single constituent migration through unsaturated zone; user-friendly	Hydrologic, Sediment and pollutant fate simulation	Bona Zountas, M. A.D. Little (617) 864-5770	Analytical Model
PRZM (Pesticide Root Zone Model)		x							Calculates soil moisture characteristics, crop root growth, pesticide application and soil transport	Pesticide migration through unsaturated root zone	Carsel, R.F. U.S. EPA Environmental Research Lab Athens, GA EPA Pub. No. 600/3-84-109	Numerical Model

important. Applicability involves consideration of such factors as dimensionality (e.g., one-dimensional flow versus two-dimensional flow) and complexity (e.g., number of layers, degree of inhomogeneity). Acceptability may also be an important consideration, particularly within a regulatory framework. In all cases, an effort should be made to select codes which have been fully documented and verified against standard solutions. Lastly, hardware requirements may be important. Codes which require large computer systems are inappropriate if such systems are not available.

The reader interested in evaluating and selecting an unsaturated flow code for a particular application is referred to the review of unsaturated codes prepared by Oster (1982).

Once a code has been selected, detailed instructions on operation and use should be obtained from the user's manual for the code. Availability of code documentation is summarized in Table 5.1-2. References to user's manuals for unsaturated flow codes are provided in Oster (1982).

Models are developed and applied to understand and predict the behavior of complex physical systems and processes. Physical systems, such as the unsaturated zone, display characteristic behavior in response to physical laws. This behavior is described (either exactly or approximately) in terms of mathematical expressions (e.g., differential equation describing flow). Many of these expressions are not amenable to analytical solution and are transformed into approximate solutions in the form of computer codes. These codes form the framework upon which models are developed. Models are developed through assignment of representative data to the computer code. These data are assigned to represent and describe the physical properties of the system being modeled (e.g., spatial distribution of hydraulic conductivities).

A model, therefore, consists of two components, the computer code and the input data for the code. The accuracy of a model is dependent on both of these components. Codes must adequately describe the processes of importance for the particular system being modeled. Input data must be provided which are representative of the properties of the system.

Model results are nothing more than solutions to complex mathematical expressions. The mere ability of a model to produce results says nothing

Table 5.1-2. Summary of Unsaturated Code Documentation and Availability (Source: Oster, 1982)

Code		Documentation			Applications		Code Availability	
No.	Name	Model Description	Published Applications	User's Manual	Laboratory Data	Field Data	Available	Proprietary
1	HANKS	X	X		X		X	
2	TRNMOL	X			X			
3	UNFLW	X			X	X		
4	TRUST	X	X	X		X	X	
5	FLUMP	X	X	X		X	X	
6	BACHMAT						X	
7	UNFLOW	X	X			X	X	
8	VERGE	X	X	X		X	X	
9	SEGOL	X	X	X		X	X	
10	UNSAT1D	X	X	X		X	X	
11	SUMATRA-1	X	X	X		X	X	
12	TRANSONE							
13	TRANSTWO							
14	MOBIDIC	X				X		
15	NMODEL						X	
16	WATSOL	X	X		X		X	
17	FECTRA	X		X			X	
18	TARGET	X				X		X
19	DUGUID-REEVES	X	X				X	
20	MCCANN	X				X	X	
21	ALPURS	X						X
22	REEVES-DUGUID	X		X			X	
23	TRANS	X			X		X	
24	FEMWATER	X	X	X		X	X	
25	FEMWASTE	X	X	X		X	X	
26	UNSAT2	X	X	X		X	X	
27	STGWT/MOGWT	X		X	X			X
28	UNSAT1	X	X	X			X	
29	COOK	X						X
30	GANDALF	X					X	
31	GPSIM	X						X
32	TS&E	X						X
33	BRUTSAERT1	X					X	
34	WHC	X		X			X	
35	SCAT1D	X					X	
36	SCAT2D	X					X	
37	AMOCO							X
38	CMG							X
39	BRUTSAERT2				X		X	
40	BETA II							X
41	SSC							X
42	SHELL							X
43	SHAMTU	X	X	X		X	X	
44	MMT-DPRW	X				X	X	
45	VS2D	X		X		X	X	
46	SUM-2		X				X	
47	SUPERMOCK	X		X		X	X	
48	DELAAT		X			X		
49	PORES					X		
50	WAFE					X		
51	TRIPM	X	X			X		
52	MOMOLS	X					X	
53	MARINO	X						
54	MLTRAN	X	X	X		X	X	
55	TRACR3D					X		

with respect to the accuracy or validity of those results. The accuracy of model results and, hence, the accuracy of the model itself are typically assessed through the process of calibration. During calibration, the model input data are adjusted until the model accurately predicts conditions which are known to exist. Calibration itself, however, is still not proof of model accuracy. Accuracy can be further tested through the process of verification. During verification, the calibrated model is used to predict known conditions at a different time than that tested in the calibration process.

The processes of calibration and verification are often time-consuming and expensive. Therefore, many times they are not performed. Lack of calibration does not necessarily mean that the model is inaccurate, only that the accuracy of the model has not been established.

Because of the large number of unsaturated flow codes currently available, and for simplicity of discussion, only one code representative of each type of model will be examined: UNSAT1D (UNSATurated 1 Dimensional), an example of a numerical code; and HELP (Hydrologic Evaluation of Landfill Performance), an example of a water balance code. Characteristics of the codes, as well as the required input data, input data sources, and output data, will be discussed to provide permit writers and applicants with a description of the approach to unsaturated flow modeling. The limitations and applicability of each code for the determination of TOT will also be discussed.

5.2 EXAMPLE NUMERICAL CODE - UNSAT1D

5.2.1 General Characteristics

The UNSAT1D code was originally developed to describe water movement under typical agriculatural conditions (Gupta, et al, 1978). The code and its auxilliary programs were later revised and incorporated into an unsaturated flow modeling system (Bond, Cole, and Gutknecht, 1982).

UNSAT1D is a one-dimensional, finite difference code which solves the differential equation for ground-water flow under saturated and unsaturated conditions. It simulates infiltration, vertical seepage, and plant root uptake as a function of the hydraulic properties of a soil, soil layering, root growth characteristics, evapotranspiration rates, and frequency, rate, and amount of precipitation and/or irrigation. UNSAT1D can be used to estimate ground-water recharge, irrigation and consumptive use of water, irrigation return flows, and other processes associated with unsaturated and saturated soils which can be represented as one-dimensional (Bond, Freshley, and Gee, 1982).

The UNSAT1D modeling system consists of one computer code which solves the flow equation and several supporting codes which are used for the preparation of input data and for evaluation and display of model results. Use of UNSAT1D requires site-specific input data and an understanding of ground-water flow theory. Input data requirements depend on the problem being solved, but in most cases include the soil profile description of the site; the hydraulic properites of each layer of the profile; characteristics of vegetation at the site; the means by which water is applied to the site; and climatic data for the site. The model output includes soil-water potential (suction), moisture content, and water flux at each node (depth increment) for each time interval considered by the model.

Table 5.2-1 provides a summary of the important characteristics and capabilities of UNSAT1D.

TABLE 5.2-1. Important Characteristics and Capabilities of UNSAT1D

1) Simulates partially-saturated ground-water flow.
2) Simulates infiltration, vertical seepage, and plant root uptake.
3) Derives solution using a finite difference, fully implicit method.
4) Describes one-dimensional flow in a vertical or horizontal direction.
5) Accomodates homogeneous, heterogeneous, or layered soil profiles.
6) Simulates up to ten soil layers.
7) Simulates rain, sprinkler or flood irrigation, or constant head condition for the upper boundary.
8) Simulates lower boundary conditions as water table, dynamic, quasi-dynamic, or unit gradient.

5.2.2 General Approach to Application

The first step in application of a numerical model is development of a conceptual model of the site being considered. A conceptual model must identify the important features and characteristics of the site and describe, in a qualitative way, the relationships between the various components and processes. The conceptual model of a site must be developed before an analyst can develop a mathematical approximation of the system. For unsaturated flow, important data required to develop a conceptual model include stratigraphic data describing soil layering at the site and climatic data describing net precipitation and evaporation. It should be apparent that substantial knowledge of geohydrology is required to develop a conceptual model.

Once a conceptual model has been developed, the analyst must translate the conceptual model to a mathematical model by supplying appropriate input data to the computer code. The first step in developing a numerical model is development of a finite difference or finite element grid network. UNSAT1D is a one dimensional finite difference code, so grid development involves specifying a vertical or horizontal array of nodes (depending on the application).

Once the grid has been established, input data must be supplied to the model. Data describing soil properties and characteristics must be supplied at each node in the grid. Input data may be obtained in the field, measured in the laboratory, or obtained theoretically. The necessary input data for UNSAT1D and their sources or methods of estimation are summarized in Table 5.2-2.

As indicated in Table 5.2-2 a considerable amount of data are required to operate the UNSAT1D Model Sequence. One of the difficulties of unsaturated flow modeling is that data requirements often exceed the amount of available measured data. Various theoretical and laboratory techniques may be used to estimate some of these data, and some data may be generated or estimated using the supporting programs contained within the UNSAT1D Model Sequence. These programs must be run before UNSAT1D can be used to simulate a particular unsaturated flow problem.

Table 5.2-2. Summary of UNSAT1D Input Data and Sources

Input Parameter	Data Source or Estimation[a]
• Depth of soil layers and lower boundary condition	• Must be known or measured via field drilling
• Soil hydraulic properties	
1) soil-water retention relationship, saturated volumetric moisture content (θ_s), and saturated hydraulic conductivity.	1) laboratory measurements of moisture contents at various suction heads. θ_s may be assumed to be porosity.
2) hydraulic conductivity vs. water content.	2) calculated from soil-water retention relationship and saturated hydraulic conductivity.
3) initial moisture content	3) measured from samples or estimated from water balance history.
4) field density	4) measured from samples.
• Precipitation and irrigation with hourly distribution	• Obtain from nearest weather station and agricultural sources.
• Potential evapotranspiration with diurnal variation	• Obtain from weather/experimental station or calculate with detailed climatic data.
• Plant growth behavior	
1) leaf-area index	1) published for some plants.
2) root growth and density	2) published for some plants. May be assumed over growing season.
3) growing season	3) available from weather service or agricultural organizations

[a]The degree of estimation acceptable depends on accuracy required in model.

There are four data preparation programs within the model sequence. Brief descriptions of these programs and their functions are given below.

HYDRAK - This program estimates the hydraulic conductivity versus water content or matric potential relationships for each soil.

EXTEND - This program extrapolates additional data points from the high suction head/low water content end of the soil moisture characteristic curve.

POLYFIT - This program enters the soil moisture characteristic data into the UNSAT1D code in the form of polynomial expressions, the preferred form for these data.

FAOPET - This program estimates daily potential evapotranspiration (PET) for the site, as required by the model when these data are not specifically available.

Output from UNSAT1D includes the soil water potential (suction), moisture content, and soil water flux rates at each node for each time step. Examples of graphical output from UNSAT1D showing moisture content versus depth and cumulative drainage or flux versus time past certain elevations within an unsaturated soil profile are shown in Figures 5.2-1a and 5.2-1b.

5.2.3 Determination of TOT from Model Results

The output of UNSAT1D does not include TOT for the unsaturated zone. Therefore, the model results must be analyzed using one of the techniques described in Section 3.2 to determine TOT. For transient simulations, TOT can be estimated by following the migration of the wetting front. For steady state simulations, the steady state model solutions for nodal values of matric potential and moisture content can be used to calculate velocities and travel times across each model element.

5.2.4 Limitations

UNSAT1D was developed to predict the amount and rate of water entering and moving through a partially saturated flow system. The code accomplishes this task by simulating one-dimensional flow through the system using the differential equation

$$C(\theta) \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z} \{K (\theta) \frac{\partial H}{\partial z}\} - S$$

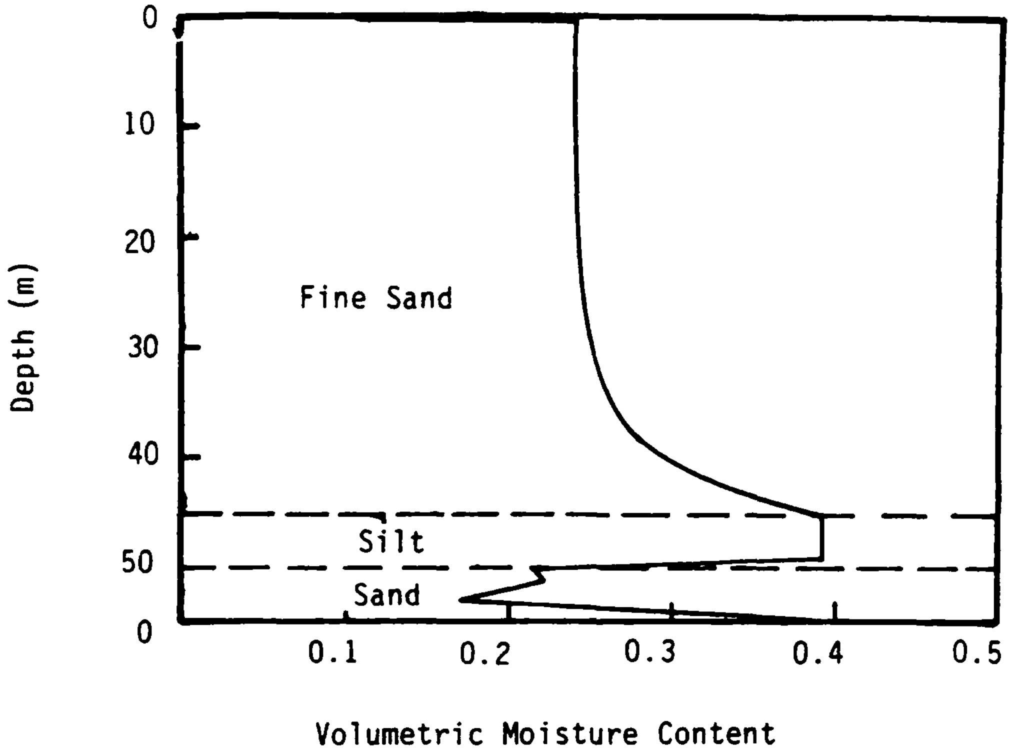


Figure 5.2-1a. Moisture Profile for a Three Layer Unsaturated Flow System

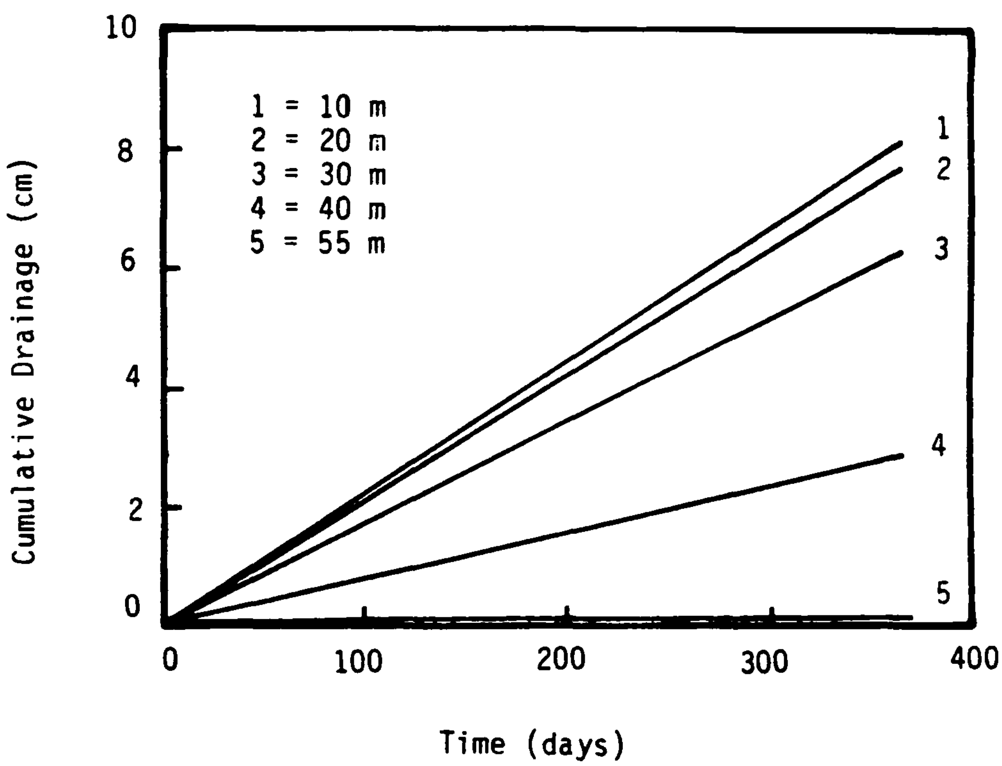


Figure 5.2-1b. Cumulative Water Flux Versus Time Past Several Elevations in an Unsaturated Flow System

where

$C(\theta)$ = soil water differential capacity;

θ = volumetric water content;

ψ = pressure head;

t = time;

z = vertical coordinate;

$K(\theta)$ = hydraulic conductivity;

H = hydraulic head; and

S = source/sink term.

The above equation is a general solution for one-dimensional flow in the unsaturated zone. The only limitations to this solution are that it is a one-dimensional solution and that it does not account for migration of water in the vapor phase.

The use of a one-dimensional solution may or may not pose limitations, depending on the characteristics of the site. If materials present at the site are highly inhomogenous, a two-dimensional model may be more appropriate (assuming, of course, that there are adequate data to define the inhomogeneity). A two-dimensional model may also be more appropriate for cases where there may be significant lateral flow. For example, leaks from a surface impoundment located above dry soil would be expected to undergo significant lateral migration due to capillarity.

Numerical methods of solution require finer resolution of data than other methods. This increases the amount of data that must be obtained to set up a model. In addition, the numerical solution of the nonlinear unsaturated flow problem is quite sensitive to input data. Values of input data must be reasonably close to actual values in order to obtain a solution. Therefore, numerical models are difficult to use with "default" data values since such values may not yield a solution.

The numerical method of solution also requires a great deal of computational time. The methods are most appropriate for large minicomputers or main-frame computers. Even with such computers, solutions may require several hours of central processing unit (CPU) time.

Lastly, numerical models are very complex and require a good deal of understanding on the part of the analyst. The analyst must have significant experience and understanding in order to develop the conceptual model of a site and set up the finite difference or finite element grid. In addition, several runs of the model are often required before input data sets are adequately adjusted to produce a solution. The analyst must have enough understanding of the workings of the model to be able to adjust and calibrate the model.

With the exception of the limitation due to one-dimensional flow, the above limitations apply to all numerical models.

5.3 EXAMPLE WATER BALANCE CODE - HELP

The HELP code was developed and adapted from the EPA's Hydrologic Simulation Model for Estimating Percolation at Solid Waste Disposal Sites (HSSWDS) and from the U. S. Department of Agriculture's Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) code (Walski et al., 1983). HELP is a quasi-two-dimensional hydrologic model which rapidly and economically estimates the amount of runoff, drainage, and leachate that may be expected to result from operation of landfills. HELP performs a sequential daily analysis of water inflow and outflow that takes into account the effects of runoff, evapotranspiration, percolation, and lateral drainage on the water balance for a particular site. The code was not developed to account for lateral inflow and surface runon.

HELP produces daily, monthly, and annual water budgets which describe both vertical flow through a landfill profile and horizontal flow through its drainage layers. The model requires climatological data and soil and landfill design data. Site-specific data should be used for the analysis; however, if these data are not available a substantial amount of climatic and soil data are maintained within the model, as well as default options for vegetative covers. The model's output includes summary data describing the water balance for each layer in the model. These data can be provided on a daily, monthly, or yearly basis depending on the needs of the user.

Table 5.3-1 provides a summary of the important characteristics and capabilities of HELP.

5.3.1 General Approach to Application

As with numerical models, application of water balance models requires formulation of a conceptual model of the site and representation of this conceptual model within the framework of the mathematical model. The HELP model represents the system as a series of layers. Four types of layers are allowed:

1) those which only allow vertical percolation;
2) those which inhibit vertical percolation (barrier layers);
3) those which allow lateral drainage; and
4) waste layers.

Application of the model requires the analyst to review the stratigraphy of the site and translate the stratigraphy into a series of layers of the appropriate type.

Table 5.3-1. Summary of Characteristics and Capabilities of HELP

1) Simulates partially-saturated ground-water flow.
2) Performs a sequential daily analysis to determine runoff, evapotranspiration, percolation, and lateral drainage.
3) Uses a quasi-two-dimensional water budget approach.
4) Describes two-dimensional flow for both vertical flow through the profile and horizontal flow through drainage layers.
5) Applies to a wide variety of landfill designs.
6) Simulates up to nine layers.
7) Maintains default climatic and soil data, as well as default options for site vegetation.
8) Assumes gravitational forces to be the most important force for fluid movement (capillary forces are ignored) thereby greatly simplifying the unsaturated flow solution.

HELP requires input data similar to those for UNSAT1D, but with less spatial resolution. One advantage of the less stringent data requirements and less complex numerics of the water balance models is that it makes it easier to use default values. The HELP model maintains an internal data base of default data values. This data base includes five years of climatic data for 102 cities in the United States and default characteristics for 21 soil types. The model also makes available seven default options for site vegetation. The necessary input data and their sources and methods of estimation are summarized in Table 5.3.1-1.

HELP model output consists of a summary of all default or user-provided input information (except daily precipitation) used for the simulation and a summary of the analysis computed by the model. The analysis summary includes a table of annual totals for each year of simulation; a table of average monthly totals for all years simulated by the model; a table of average annual totals for all years of simulation; and a table of peak daily values for all years of simulation. A summary of the information contained in each table is provided in Table 5.3.1-2. If the user is interested in monthly output, HELP can produce tables which report monthly totals for all years of simulation. These tables include:

- precipitation;
- runoff;
- evapotranspiration;
- percolation from base of landfill cover;
- percolation from base of landfill;
- lateral drainage from base of landfill cover; and
- lateral drainage from base of landfill.

If daily output is desired, the model provides daily values for each Julian date of each year of simulation. In addition to the above data, these tables include:

- head at base of landfill cover;
- head at base of landfill; and
- soil moisture content of the evaporative zone.

Table 5.3.1-1. Summary of Input Data and Sources for HELP

Climatologic Data

Daily precipitation values

All can be obtained from data base or measured for each year of interest (2 - 20 year) -- libraries, universities, agricultural and climatologic research facilities, and the National Climatic Center are possible sources.

Mean monthly temperature

Measured for each year or single set of data for all years -- libraries, universities, agricultural and climatologic research facilities, and the National Climatic Center are possible sources.

Mean monthly solar radiation factors

Measured for each year or single set of data for all years -- agricultural publications, solar heating hand books, and general reference works are possible sources.

Winter cover factors

Measured for each year or single set of data for all years -- libraries, universities, agricultural and climatologic research facilities, and the National Climatic Center are possible sources.

Leaf area indices (LAI)

Measured for each year or single set of data for all years -- various references, including USDA's publication, "Climate and Man, Year Book of Agriculture," are possible sources.

Vegetative Cover Data

Root zones or evaporative zone depth

Choose some of seven vegetative cover options from data base, or must be known or measured/observed on site.

Design and Soil Data

Landfill profile

Modeled from data base or observed/measured on site.

Table 5.3.1-1. Cont'd.

Soil data

From data base (21 default soil types available) or observed/measured on site. Observations/measurements must include: porosity, field capacity, wilting point, hydraulic conductivity. and evaporation coeffecients for each soil layer of profile.

Soil compaction

From data base or use soil data representative or compacted soil (from observation of site).

Design data -- Number of layers and their descriptions -- type, thickness, slope, and maximum lateral distance to a drain (if applicable).

Observed/measured on site.

Design data -- Whether or not synthetic membranes used in the landfill cover and/or liner

Observed/measured on site.

Table 5.3.1-2. Summary of Output Data from HELP

Analysis Summary Table No. 1

Table of annual totals for each year of operation simulated by the model:

a) precipitation;
b) runoff;
c) evapotranspiration (total of surface and soil evaporation and plant transpiration);
d) percolation from base of cover;
e) drainage from base of cover;
f) soil water at beginning of year;
g) soil water at end of year;
h) snow water at beginning of year; and
i) snow water at end of year.

Analysis Summary Table No. 2

Table of average monthly totals for all years of operation simulated by the model:

a) precipitation;
b) runoff;
c) evapotranspiration;
d) percolation from base of cover; and
e) drainage from base of cover.

Analysis Summary Table No. 3

Table of average annual totals for all years of operation simulated by the model:

a) Precipitation;
b) runoff;
c) evapotranspiration;
d) percolation from base of cover; and
e) drainage from base of cover.

Analysis Summary Table No. 4

Table of peak daily values for all years of operation simulated by the model:

a) precipitation;
b) runoff;
c) percolation from base of cover;
d) drainage from base of cover;
e) maximum head on base of cover;
f) snow water;
g) maximum soil moisture for vegetative layer; and
h) minimum soil mositure for vegetative layer.

5.3.2 Determination of TOT from Model Results

As discussed earlier, travel times can be determined as particle travel times, travel times associated with instantaneous loadings, or steady state conditions. Application of the first approach requires that model outputs include the moisture content within a layer and the flux out of the layer. Since water balance models assume average conditions throughout a layer, the instantaneous pore water velocity through a layer can be approximated as the flux out of the layer divided by the average moisture content of the layer.

Determination of the travel times associated with instantaneous (pulse) loadings may not be appropriate with water balance models. Because of the averaging that occurs within a layer, there is a loss of resolution. Therefore, it is difficult to detect the migration of wetting fronts.

Water balance models can be used to solve for steady state moisture content for each layer. These steady state conditions can be used to determine steady state travel times through the landfill soil column. As discussed in Section 3.2, however, this TOT is the steady state TOT and not the TOT of the first particle of water leaving the site.

Water balance models are not suited for contaminant transport problems so that TOT cannot be determined from contaminant TOT.

5.3.3 Limitations

The HELP code was designed to develop long-term water balance models for landfills to predict generation of leachate from landfills. The soil profile and landfill are divided into layers and water is budgeted to each layer based on a mass balance between water flowing into each layer and water flowing out of each layer. The code allows for lateral drainage from some layers, giving it quasi-two-dimensional capabilities.

Unlike numerical models, HELP is not based on a general solution to unsaturated flow and, therefore, has several limitations with respect to its analytical capabilities. For example, HELP simplifies unsaturated flow by assuming that gravity is the driving force for all fluid movement; capillary forces and the effects of vegetation are ignored by the model. Therefore, the solution obtained by HELP is no more rigorous than those obtained by analytical methods.

The water balance approach also lacks the resolution possible with numerical models. In the water balance solution, soil properties are assigned by layer and the solution yields the average moisture content for the entire layer. Using such an approach, subtle effects such as the migration of a wetting front may not be seen.

The HELP code was developed to simulate the migration of leachate from landfills. Application of the code to include migration through the unsaturated zone beneath a landfill will require addition of several soil layers beneath the landfill. There are internal limits to the number of layers that can be simulated and internal requirements for certain types of layers. Therefore, it is not possible to simulate a large number of soil layers beneath the landfill. Because of limited spatial resolution, the code is probably best applied to sites in humid areas having thin unsaturated zones. This limitation was confirmed by a recent comparison between HELP and the UNSAT1D numerical code (Thompson and Tyler, 1983).

SECTION 6.0

EXAMPLES OF TOT DETERMINATION

This section presents examples of determining unsaturated zone TOT for several proposed hazardous waste facilities. Examples 1 and 2 demonstrate the use of analytical solutions for determining steady state TOT at proposed hazardous waste disposal facilities in the Gulf Coastal Plain and Basin and Range physiographic regions. Example 3 demonstrates the use of the UNSAT1D numerical model for determining TOT associated with an accidental spill at a proposed hazardous waste site in the Columbia-Snake River plateau physiographic region.

6.1 EXAMPLE 1 - Case Study G

Case study G is a land disposal facility located near the northern edge of the Gulf Coastal Plain. A review of the data provided in the Part B permit application for this facility is presented in the Case Study Appendix to the Phase II Location Guidance (see Appendix C).

The case study G facility is underlain by approximately 21 to 34 m of fine to medium grained quartz sand, with limited occurrences of silt, clay, and lignite beds. This sand layer beneath the facility forms the water-table aquifer. Depths to ground water at the facility range from 6 to 15 m. This shallow aquifer is recharged by rainfall which averages 119 cm/yr at the facility.

6.1.1 Description of Method and Data

Unsaturated TOT was calculated using the one-dimensional steady state analytical solution described by Heller, Gee, and Myers (1985). This solution assumes that the hydraulic gradient in the unsaturated zone is equal to one. The unit gradient assumption implies that flow in the unsaturated zone is dominated by gravity (i.e., capillary forces are negligible).

Because the site is located in a humid region having a moderately high rainfall (119 cm/yr), soils in the unsaturated zone should be fairly moist (i.e., at or above field capacity). Therefore, the unit gradient assumption is probably valid for this site.

As discussed in Section 4.0, this analytical solution requires relatively few input data compared to other methods. These data are:

- soil profile and depth;
- soil characteristics (saturated hydraulic conductivity, saturated water content, moisture content versus pressure head); and
- steady state moisture flux.

The assumptions used to develop input data and the limitations resulting from these assumptions are described below.

Soil Profile and Depth--

The analytical method may be applied to single- or multi-layered soil profiles. Geologic cross sections of the site identify lenses of clay and silt within the sand. However, these lenses are not continuous over the site. Therefore, a uniform profile of sand was assumed. In view of the higher permeability of sand compared to silt and clay, this is a conservative assumption (i.e., yields lower TOT).

The thickness of the unsaturated zone was estimated from the geologic cross sections and reported ground-water surface elevations. The minimum distance from the bottom of the faciilty to groundwater was estimated to be 6 m. This minimum distance was selected for the analysis to yield a worst case.

Soil Characteristics--

Saturated hydraulic conductivities for soils at the facility were determined by aquifer tests. The geometric mean conductivity from tests of shallow wells was 0.079 cm/sec. For lack of other data, this value was used for saturated conductivity in TOT calculations.

It should be noted that laboratory permeameter results are the preferred source of saturated conductivity data. Field measurements from aquifer tests are easier to obtain, however, and are expected to be the major source of such data presented in Part B applications. The following limitations to the use of these data should be recognized:

- Aquifer test results indicate the hydraulic conductivity of material in the saturated zone. Unsaturated TOT calculations require the saturated conductivity of material in the unsaturated zone. In this example, materials in the two zones are very similar and the use of saturated conductivities is not expected to be a major source of error.
- Aquifer test results represent horizontal saturated conductivity. Unsaturated TOT calculations require vertical hydraulic conductivity. There can be significant differences (e.g., order of magnitude) between vertical and horizontal conductivity for some materials. The relationship between vertical and horizontal conductivity for the materials at the site is not known. Use of aquifer test results should be recognized as a potential source of error.

No saturated moisture content data were presented in the Part B application. As described in Section 4.0, total porosity is a good approximation to saturated moisture content. Because no porosity data were presented in the permit application, the default values presented in Section 4.0 were used. A value of 0.41 was used to represent the average saturated moisture content based on the default porosities for fine sand and medium sand.

No data describing the moisture retention characteristics of soils at the site were provided in the Part B permit application. Typical values of the slope of the moisture retention curves ("b" values) for different soil textures are presented by Hall et al. (1977). These values are shown in Table 6.1.1-1. A value of 4.0 was selected as representative of the sandy soil at the site.

Moisture Flux--

No information was presented in the Part B application describing moisture flow through the unsaturated zone. The yearly average rainfall for the site was reported to be 119 cm. A conservative assumption would be to ignore runoff, evaporation, and transpiration and assume that all precipitation is available for recharge. This assumption would tend to maximize the unsaturated TOT.

Table 6.1.1-1. Typical Values for Slope of Soil Moisture Retention Curve (b) Source: Hall et al., 1977

Soil Texture	b
Clay	11.7
Silty Clay	9.9
Silty Clay Loam	7.5
Clay Loam	8.5
Sandy Clay Loam	7.5
Sandy Silt Loam	5.4
Silt Loam	4.8
Sandy Loam	6.3
Loamy Sand	5.6
Sand	4.0

Summary--

The following summarizes the input parameters for the analytical solution:

- depth to ground water, L = 6.0 m;
- saturated hydraulic conductivity, K_{sat} = 0.079 cm/sec;
- saturated moisture content, θ_{sat} = 0.41;
- negative one times the slope of log-log characteristic curve, b = 4.0; and
- moisture flux, q = 119 cm/yr.

6.1.2 Solution of TOT

The following solution follows the same steps as those presented in Section 4.0.

Step 1: Calculate m

$$m = \frac{1}{2b + 3} = \frac{1}{(2)(4.0) + 3} = 0.091$$

Step 2: Calculate Moisture Content θ

$$\theta = \left(\frac{q}{K_{sat}}\right)^m \theta_{sat}$$

$$= \left[\frac{(119\ \text{cm/yr})}{(0.079\ \text{cm/sec})(31{,}536{,}000\ \text{sec/yr})}\right]^{0.091} (0.41)$$

$$= 0.16$$

Step 3: Calculate Travel Time (T)

$$T = \frac{L\ \theta}{q}$$

$$= \frac{(6.0\ \text{m})(0.16)}{(119\ \text{cm/yr})(0.01\ \text{m/cm})} = 0.81\ \text{yr} = 290\ \text{days}$$

6.2 EXAMPLE 2 - Case Study D

This Case Study D Facility is a landfill located in the Amargosa Desert, in the Basin and Range physiographic province. A review of the data provided in the Part B permit application for this facility is presented in the Case Study Appendix and the Phase II Location Guidance Manual (see Appendix C). This review constitutes the only source of site-specific data for the unsaturated TOT calculation presented below.

The site is underlain by at least 170 m of alluvial and valley-fill deposits, primarily sands, gravels, and cobbles of local origin. These alluvial and valley-fill materials form the water-table aquifer at the site. The depth to ground-water at the site is approximately 90 m.

The climate at the site is characterized by very low rainfall and high evaporation. The average rainfall at the site is 11.4 cm/yr, with evaporation and potential evapotranspiration estimated at 254 cm/yr and 91 cm/yr, respectively.

Analytical methods of unsaturated travel time are based on steady state flow through the unsaturated zone. If the steady state flux is not known, it can be estimated as the net recharge at the site. A value of net recharge for the site of 0.064 cm/yr is reported in Appendix C. Because of this very low flux, the assumption of a unit hydraulic gradient may not be valid. Therefore, unsaturated travel time was calculated using both analytical solutions presented in Section 4.0

6.2.1 Unit Gradient Analytical Solution

The data requirements for this analytical method were described in Example 1. Soil characteristic data for the site (Appendix C) were used to construct soil characteristic curves for a typical soil at the site. A plot of suction head versus moisture content is shown in Figure 6.2-1. The slope of the linear portion of this curve was measured to obtain a "b" value of 3.3. The saturated moisture content and saturated hydraulic conductivity of this soil are 0.40 and 265 cm/day, respectively. From the cross-section data for the site, the average depth from the bottom of the landfill to the water table is 76 m. The above data were used to calculate the travel time for the steady state flux of 0.064 cm/yr.

Step 1: Calculate m

$$m = \frac{1}{2b + 3} = \frac{1}{(2)(3.3) + 3} = 0.10$$

Step 2: Calculate Moisture Content θ

$$\theta = \left(\frac{q}{K_{sat}}\right)^m \theta_{sat}$$

$$= \left(\frac{0.064\ \text{cm/yr}}{(265\ \text{cm/day})(365\ \text{cm/yr})}\right)^{0.10} (0.40)$$

$$= 0.10$$

Step 3: Calculate Travel Time (T)

$$T = \frac{L\ \theta}{q}$$

$$= \frac{(76\ \text{m})\ (0.10)}{(0.064\ \text{cm/yr})(0.01\ \text{m/cm})}$$

$$= 12{,}000\ \text{yrs}$$

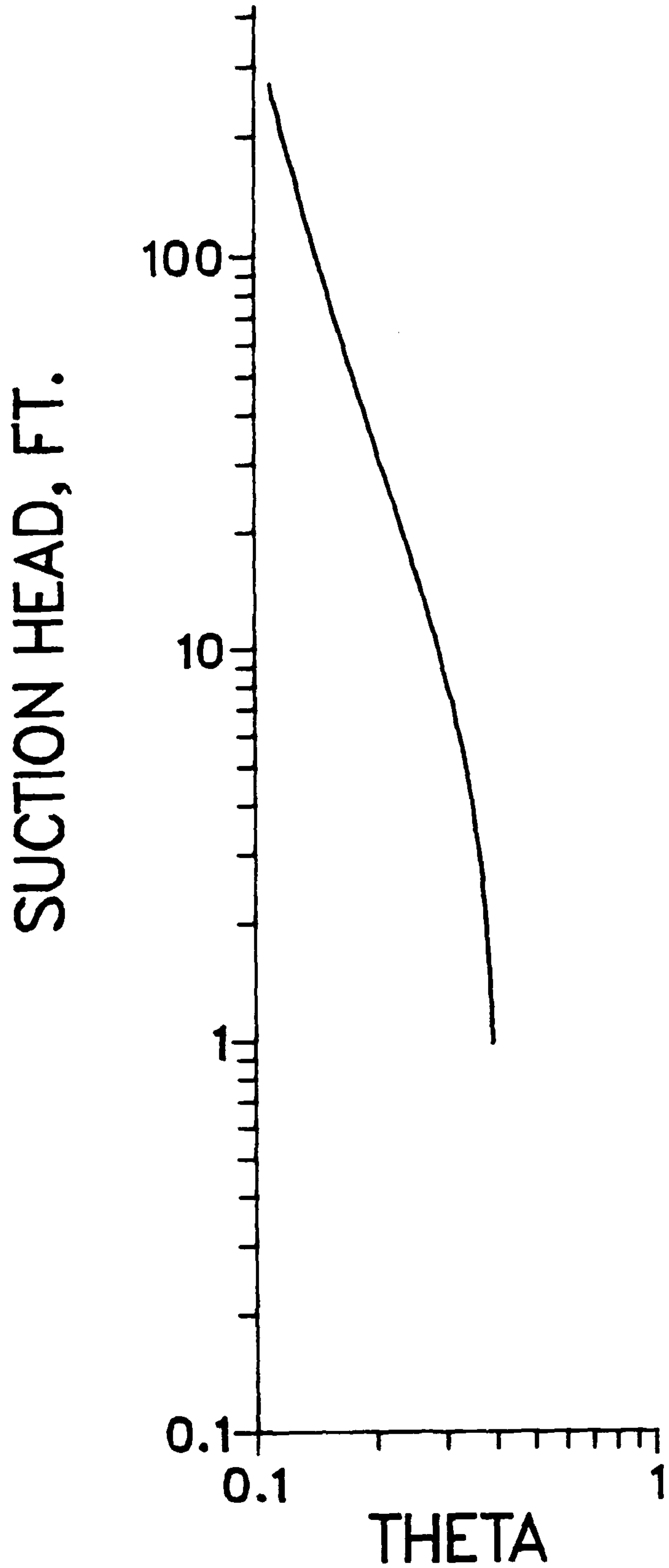


Figure 6.2-1. Plot of Suction Head Versus Moisture Content for Case Study D

The above equation can also be used to solve for a travel time for the first 100 ft below the facility. This 100 ft travel time is 4,800 years, which is well above the 100-yr location guidance criterion.

It should be noted that this analytical solution is not strictly applicable at the site. The steady state moisture content is so low that it does not fall within the linear, central portion of the curve where the solution technique is applicable. At this low moisture content (moisture contents measured at the site were all at or below the wilting point), capillary forces would be significant and the unit gradient assumption is not appropriate.

6.2.2 Iterative Analytical Solution

Because of the low moisture contents at the site, the iterative analytical solution described by Jacobson, Freshley, and Dove (1985) is probably more appropriate. This solution allows for variable moisture contents within the soil profile. The data requirement for this method, in addition to the steady state flux, are soil characteristics curves for moisture content and hydraulic conductivity. The curve for suction head versus moisture content was shown previously in Figure 6.2.1-1. A plot of hydraulic conductivity versus suction head for a typical soil at the site is shown in Figure 6.2.2-1. The data from these curves were used to generate tables of suction head and moisture content, and suction head and hydraulic conductivity for use in the solution.

The above data were used with the iterative solution to calculate travel time for a steady state flux of 0.064 cm/yr. To employ the iterative solution, a grid system was constructed to represent the site. The grid system was constructed to represent the site. The grid consisted of 251 nodes, uniformly spaced at 1 ft, for a total depth of 250 ft. A boundary condition of 0 suction head (saturation) was set for the bottom node to represent the water table. The iterative solution was then applied to solve for the steady state moisture profile in the soil column. This profile is shown in Figure 6.2.2-2. Knowing the steady state moisture content and suction head at each node, the travel time between each pair of nodes was calculated, and these nodal travel times summed to give the total travel time

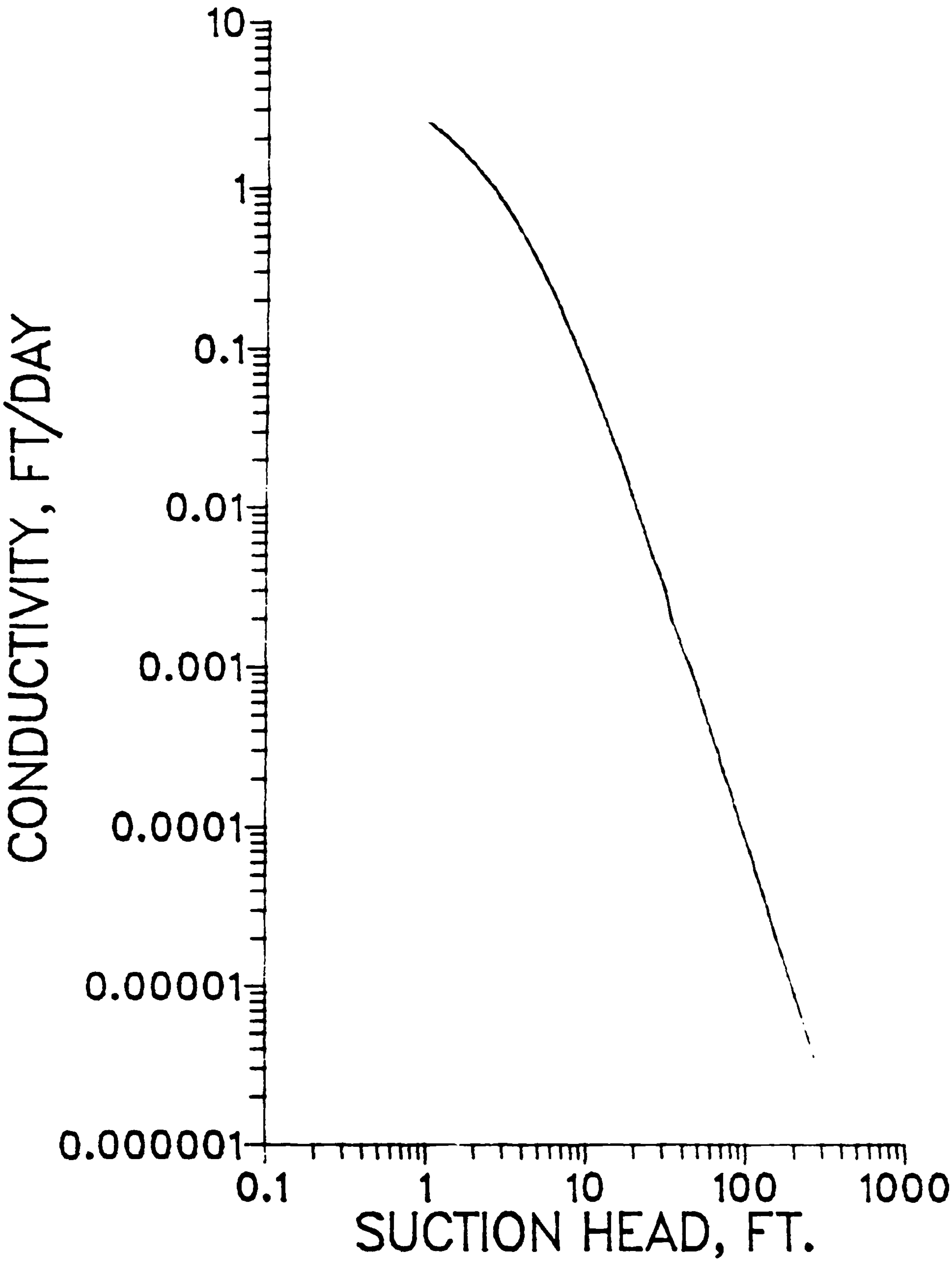


Figure 6.2.2-1. Plot of Hydraulic Conductivity Versus Suction Head for Case Study D

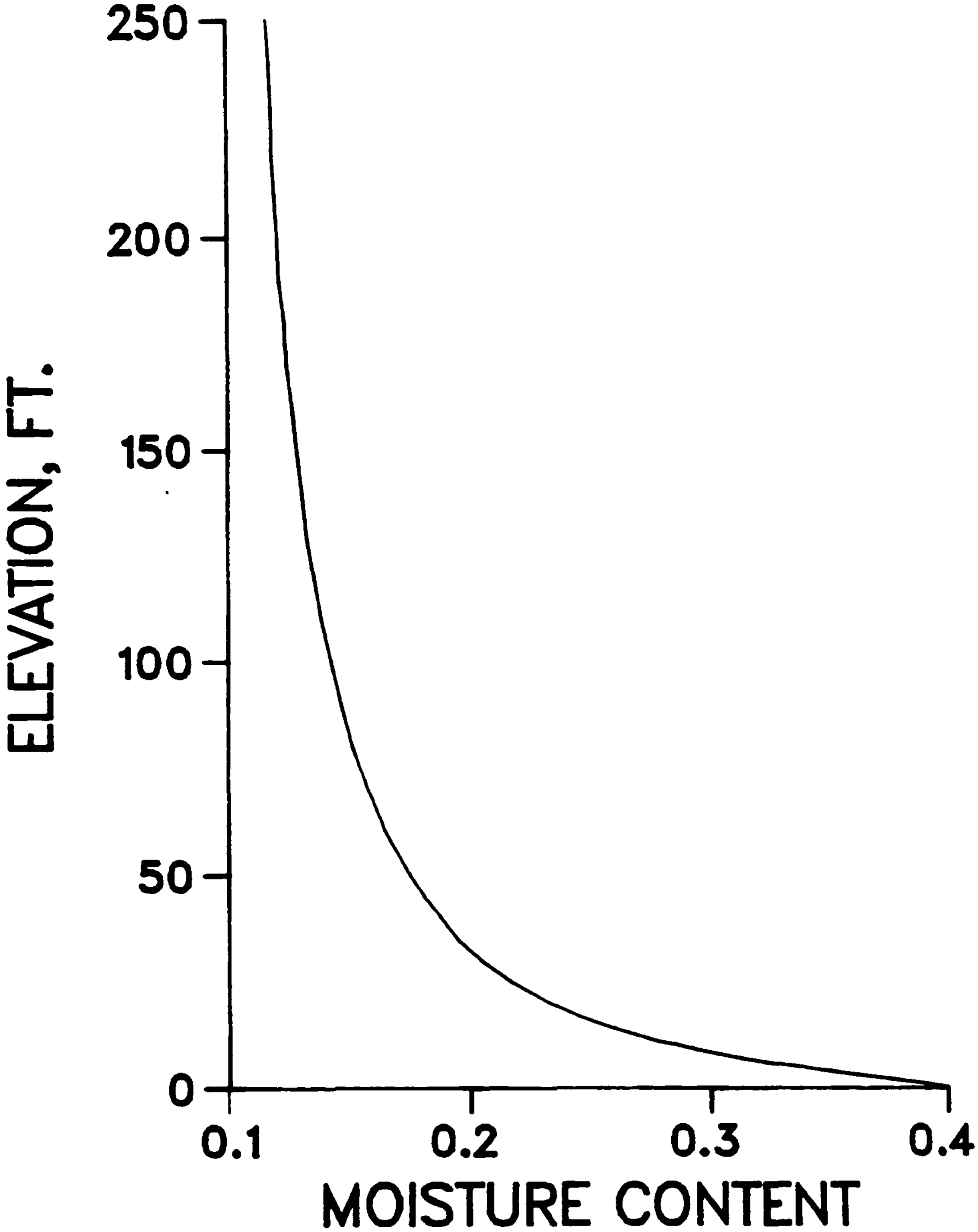


Figure 6.2.2-2. Steady State Moisture Profile from Iterative Analytical Solution for Case Study D

through the soil column. The steady state travel time was 16,000 yrs. The travel times for the first 101 nodes were summed to give the 100 ft travel time. This travel time is 5,100 yrs, which is much greater than the location guidance criterion of 100 yrs.

It should be noted that the travel times obtained from this iterative solution are greater than those obtained from the unit gradient assumption. The reason for this is the nonuniform distribution of moisture contents in the soil column. Because of this moisture distribution, the suction head is not uniform through the soil column and the hydraulic gradient is less than 1, giving longer travel times. Use of the unit hydraulic gradient solution, therefore, yields a conservative answer.

6.3 EXAMPLE 3 - Pulse Loading to the Unsaturated Zone

The following example uses an actual case study to illustrate how the UNSAT1D code can be used to estimate TOT through the unsaturated zone associated with a pulse loading (i.e., transient flow). The example selected was performed for the Washington Department of Ecology (1979) to determine the environmental impacts of establishing a hazardous waste disposal facility at a site in south central Washington.

The study addressed the potential adverse impacts that might occur in a number of different areas, to include: earth, air, water, flora, fauna, and elements of the human environment. The portion of the study dealing with water looked at the potential for migration from a surface spill, through the unsaturated zone, into the saturated zone, and eventually to a discharge point; in this case the Columbia River. The purpose of the unsaturated flow modeling was specifically to estimate the TOT from a hypothetical accidental liquid spill at the surface vertically downward through the unsaturated zone to the water table.

6.3.1 Simulation Details

The scenario simulated with the UNSAT1D code was a hypothetical accidental liquid spill of 424,000 liters spread over an area of 930 square meters. For a one-dimensional simulation, this volume of spill is equivalent to an initial ponding of 37.5 cm. Based on percolation rates for the soil at the proposed facility, the depth of the ponding was linearly reduced over a

10 day period until it had all infiltrated. After infiltration, a condition of no surface evaporation was assumed in the model, which gave a conservative drainage prediction.

One-dimensional vertical flow beneath the spill was assumed. Neglecting the lateral movement of the infiltrate due to capillary forces further contributed to a conservative estimate of TOT.

The vertical distance between the spill and the constant water table was 52 m. A homogeneous soil profile was assumed. The soil moisture retention characteristics (Figure 6.3.1-1) and the hydraulic conductivity versus water content relationship (Figure 6.3.1-2) for the soil were obtained from laboratory measurements of soil samples taken from a well constructed near the proposed site. The saturated hydraulic conductivity equaled 1.7×10^{-4} cm/sec throughout the entire soil profile. For use in the model, the soil properties (Figures 6.3.1-1 and 6.3.1-2) were fit with logarithmic polynomials.

The vertical column was defined with 53 nodes in the UNSAT1D model. The node spacing was uniform at 1 m. The initial pressure conditions (pressure head) in the model were set to equilibrium (i.e., pressure head equal to negative one times the elevation above the water table), as shown in Figure 6.3.1-3.

During the time that the spill was infiltrating, changes in pressure head near the surface were rapid and, therefore, a small time step of 0.02 hours was used. This time step was used for the first 20 days of the simulation. After 20 days the time step was doubled after every iteration until a maximum time step of 24 hours was reached. The simulation was run for a total time period of 300 years.

6.3.2 Model Predictions

The UNSAT1D model results, in terms of pressure head versus depth in the soil profile at various points in time, are shown in Figure 6.3.1-3. This figure illustrates the advance of the wetting front at 0 and 10 days, and at 10, 100, and 300 years.

Figure 6.3.2-1 illustrates the advance of the wetting front with time. This figure shows the time required for 5 cm of leachate to seep past a given

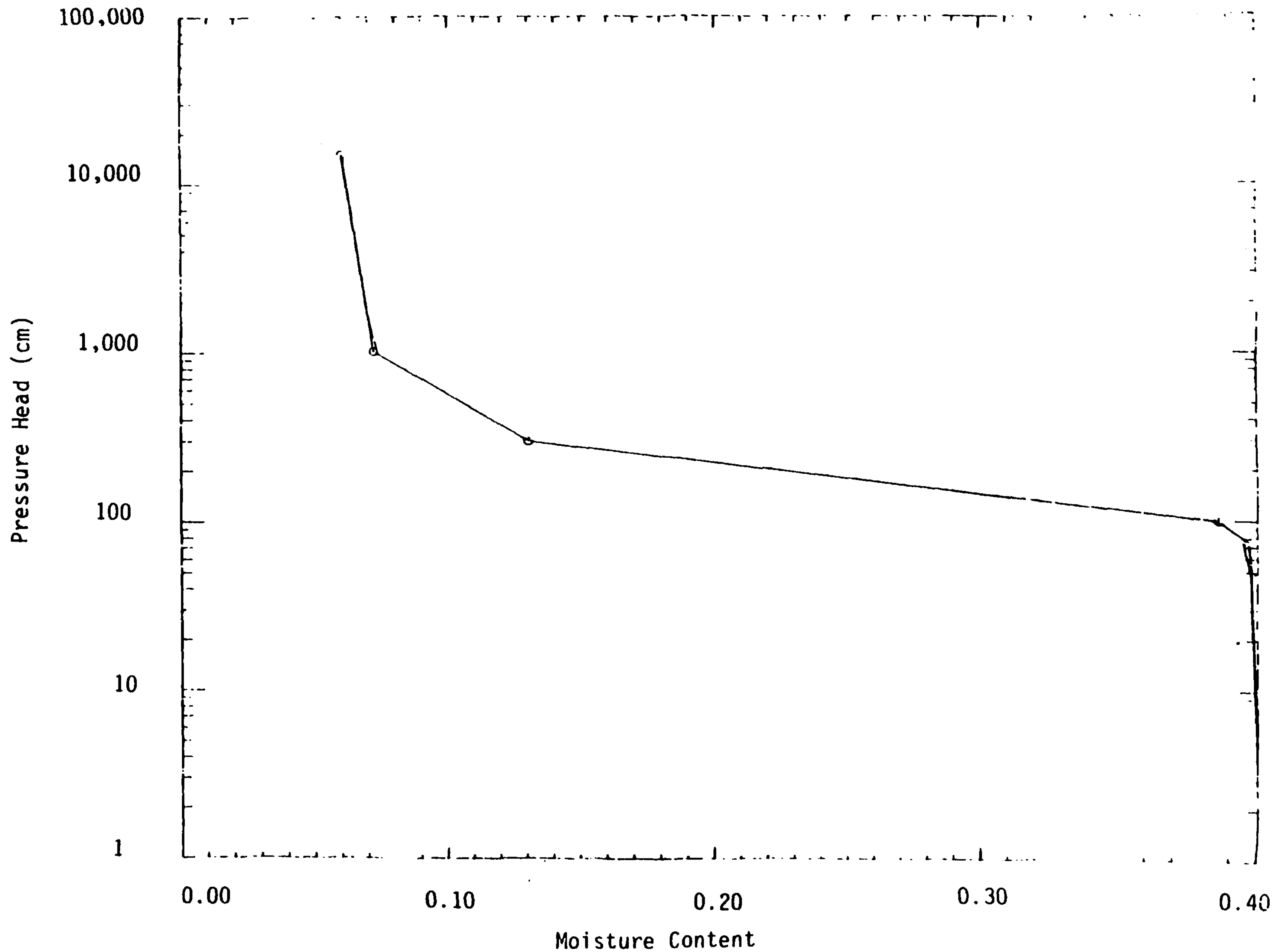


Figure 6.3.1-1. Soil Water Characteristic Curve for Soil at Proposed Hanford Hazardous Waste Site (Source: Washington Department of Ecology, 1979)

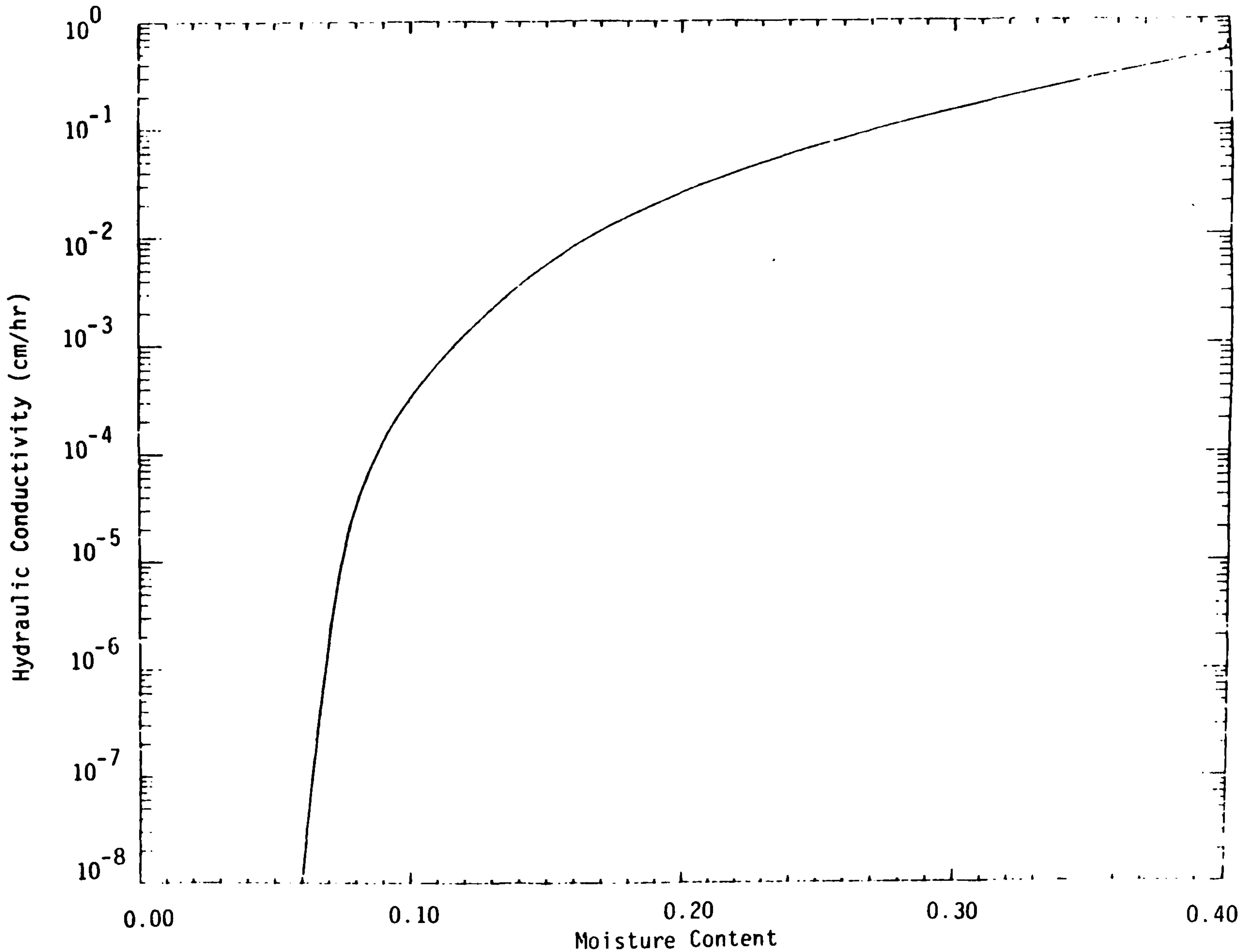


Figure 6.3.1-2. Hydraulic Conductivity Versus Water Content Curve for Soil at Proposed Hanford Hazardous Waste Site (Source: Washington Department of Ecology, 1979)

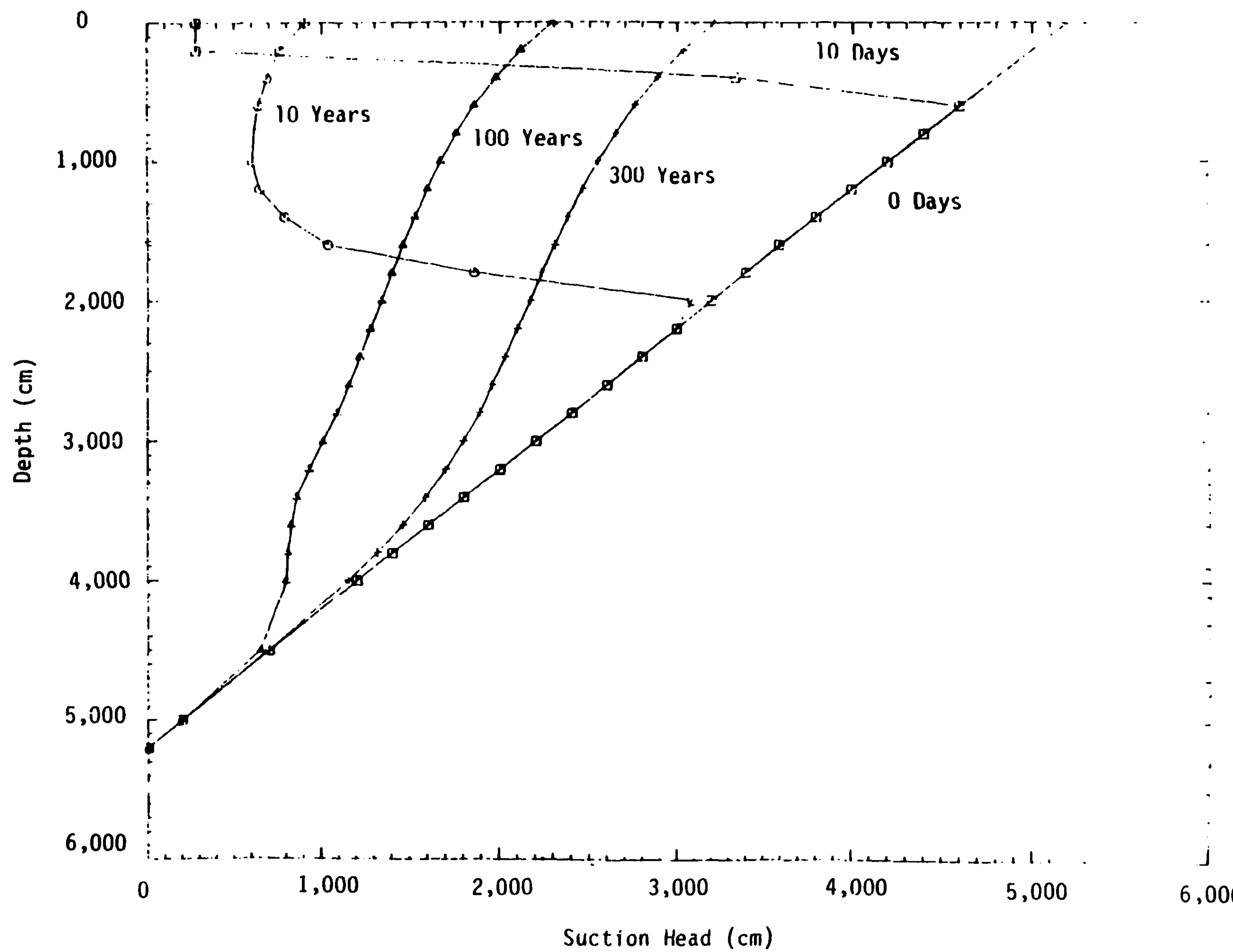


Figure 6.3.1-3. Simulated Pressure Head Versus Depth with Time at Proposed Hanford Hazardous Waste Site (Source: Washington Department of Ecology, 1979)

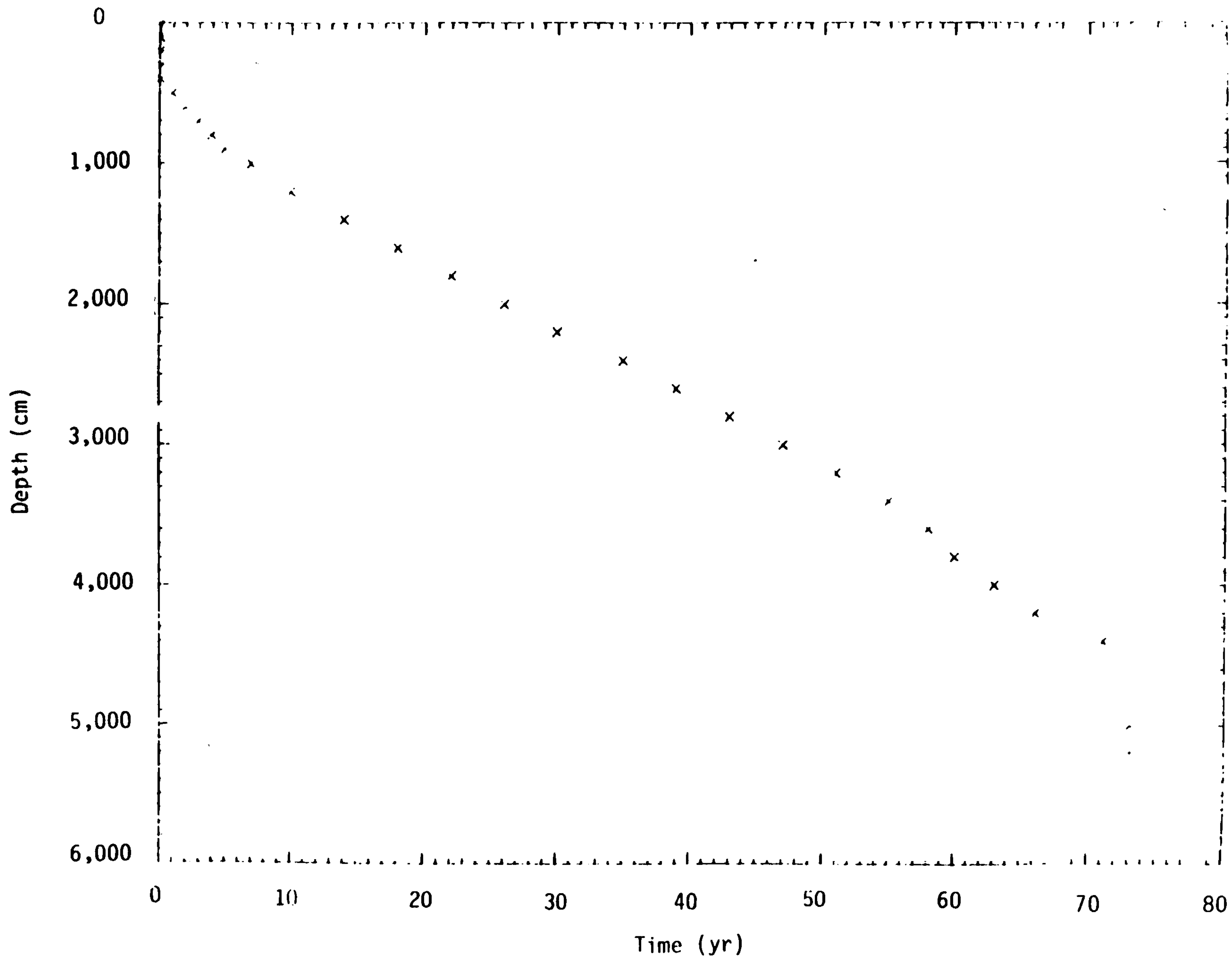


Figure 6.3.2-1. Simulated Advance of Wetting Front at Proposed Hanford Hazardous Waste Site (Source: Washington Department of Ecology, 1979)

depth (depth of leachate in a one-dimensional case is equal to volume of leachate in a three-dimensional case). Based on the data shown in Figure 6.3.2-1 the model predicted that approximately 73 years would be required for 5 cm of leachate from the spill to reach the water table.

The seepage rate of leachate into the water table (depth of leachate per 10 year interval) is shown in Figure 6.3.2-2. Although the first arrival of leachate occurs in 40 years, the maximum rate occurs at 100 years. The maximum leakage rate over the entire 930 m^2 area was approximately 3.5 m^3/yr.

The time required for percentages of the total leachate from the spill to arrive at the water table is illustrated in Figure 6.3.2-3. The results indicate that after 300 years (the total simulation period), about 80% of the leachate has reached the water table.

6.3.3 Summary

The results of the TOT estimates with the UNSAT1D model show that the first arrival of infiltrate from the spill was approximately 40 years after the spill occurred, the maximum seepage rate occurred approximately 100 years after the spill, and more than 300 years are required for all of the infiltrate to reach the water table. This case study provides an excellent example of how a numerical model can be used to estimate the travel time for a pulse loading.

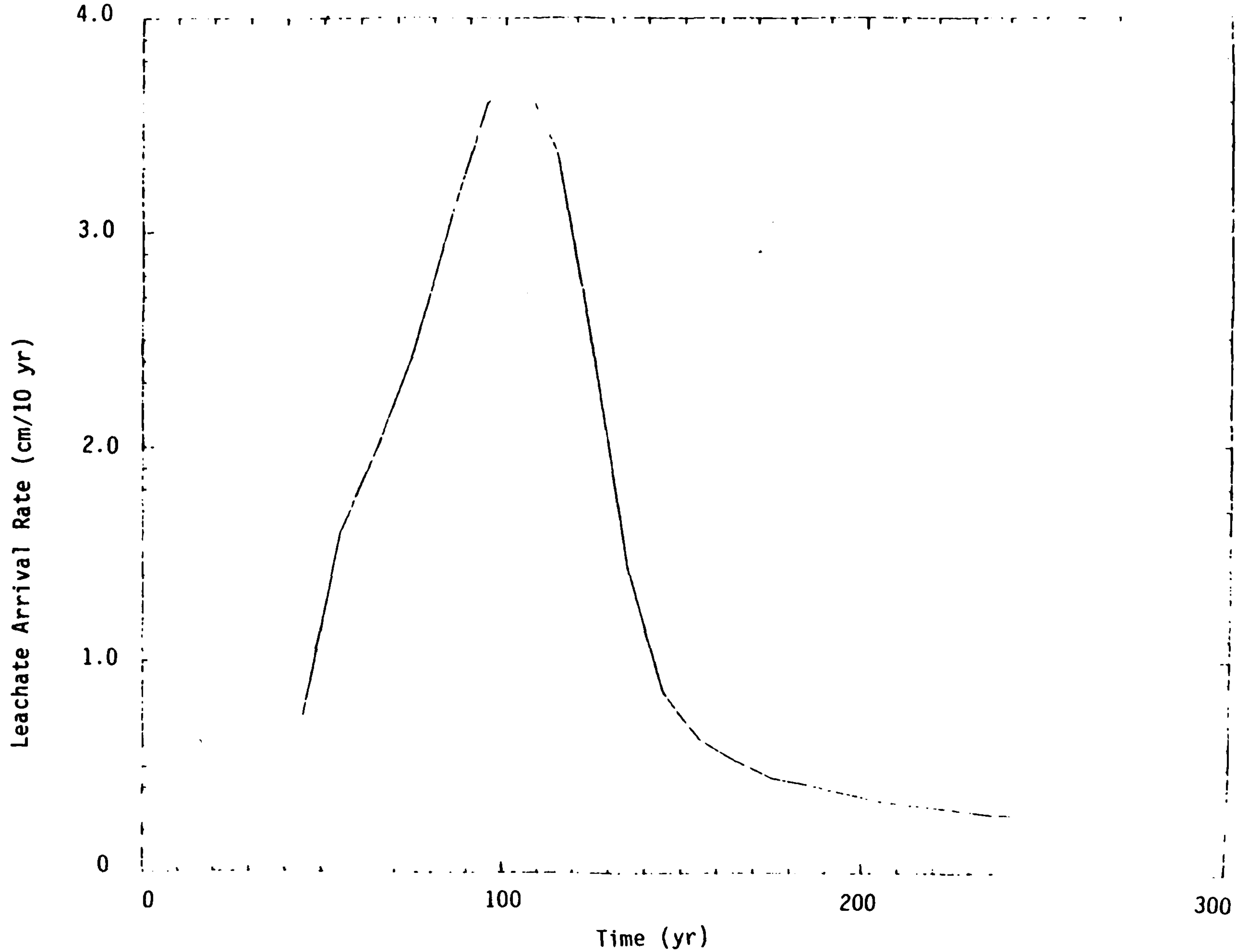


Figure 6.3.2-2. Simulated Rate of Leachate Discharge at Proposed Hanford Hazardous Waste Site

(Source: Washington Department of Ecology, 1979)

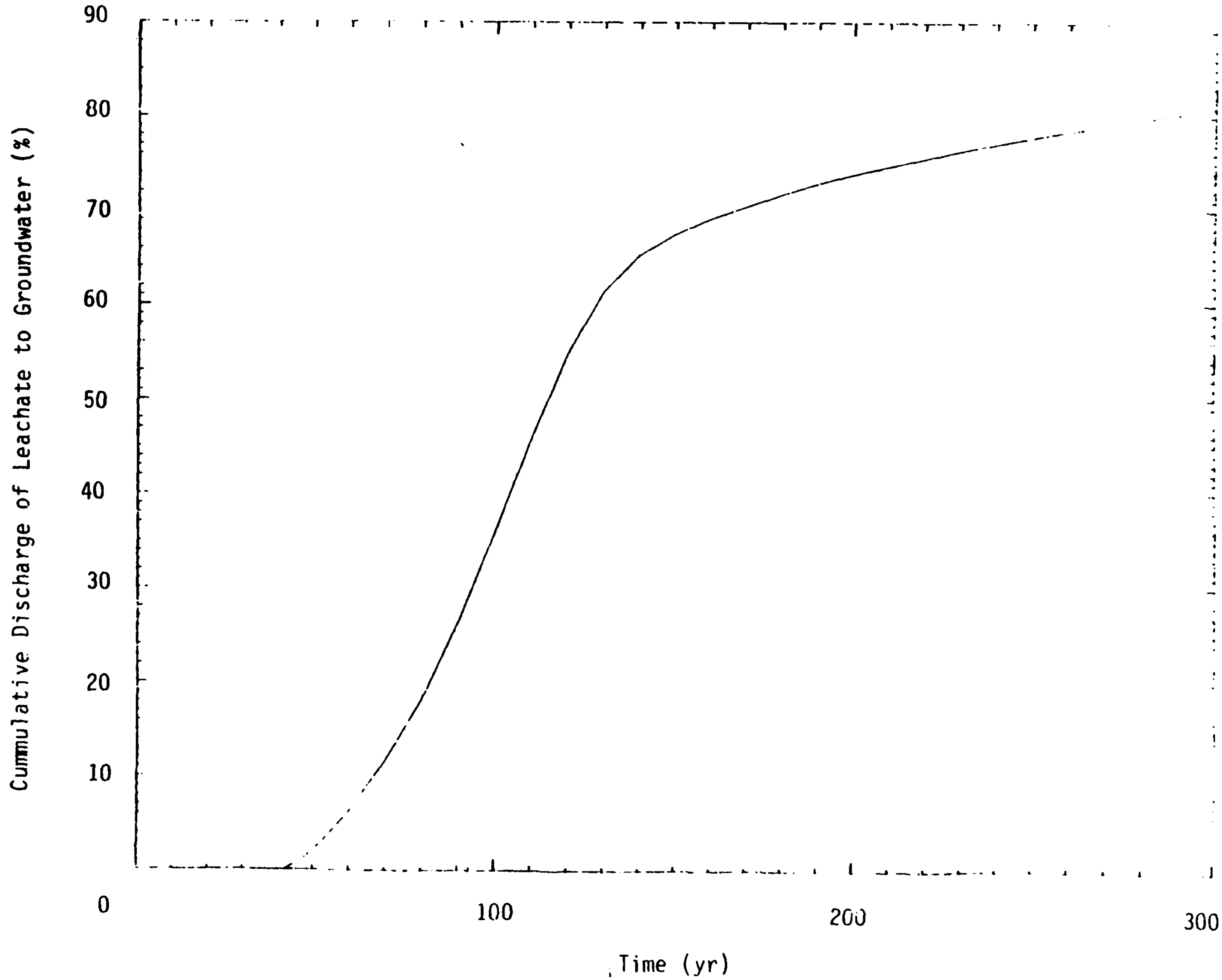


Figure 6 3.2-3. Simulated Cumulative Leachate Discharge at Proposed Hanford Hazardous Waste Site (Source: Washington Department of Ecology, 1979)

SECTION 7.0

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