Numerical Modelling of Leachate Production and Movement within Landfill Sites

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Declaration of Author's Rights

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ABSTRACT

This research project considers the development of numerical simulation processes of the production and management of leachate from landfill sites. The existing landfill leachate management models are reviewed and analysed on the basis of their applicability and effectiveness, identifying a number of important deficiencies in these models. These models simplify the actual flow process in the waste matrix and assume the same density throughout the simulation period.

Moisture flow through waste material is investigated through experiments, and as a result different mathematical models were developed. These models represent the effect of density on the hydraulic properties of waste material such as: moisture capacities, drainage rates and saturated hydraulic conductivity. The effect of density is identified as the fundamental parameter governing the flow phenomena in waste material. A large database of information obtained provides a better interpretation of statistical analyses, in fitting statistical distributions to parameters and to cover the variability of waste material.

A basic applied numerical model named NUMMOL (*NUMerical MOdelling of Leachate*) is developed based on the water balance approach, which simulates the leachate production, movement and distribution within landfill sites. NUMMOL incorporates the most appropriate mathematical models representing the various landfill hydrological processes. The moisture flow through waste layers is modelled using the models derived through experimental investigation. The model's limitations and assumptions are discussed with suggestions for future work that is necessary to enhance further its applicability.

Sensitivity analysis and evaluation of the simulation capabilities of the NUMMOL model are included. It was found that correct identification of the hydraulic properties of the landfill material is very important. To investigate model usefulness and efficiency as an environmental planning tool, the individual components of the model are evaluated. It was found that the model iterative scheme is very effective in simulating leachate movement in a cell and leachate distribution within cells. The model was applied to the landfill site in order to compare the effect of layers on leachate distribution.

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LIST OF SYMBOLS

Symbol	***Description***
a	cross-sectional area of standpipe (cm^2)
A	the cross-sectional area of the waste sample (cm^2)
A_c	the plan area of a cell [L^2]
A_u	the cross-sectional area of the unsaturated zone [L^2]
AW_i	water available for evapotranspiration on day i [cm]
C_s	surface zone coefficient (normally taken as 0.1)
C_v	coefficient of variation
dh	differential head applied to the sample [L]
D	depth of soil cover segment [cm]
$D(\theta)$	diffusivity coefficient [L^2/T] ($= -K(\theta)(\partial\psi/\partial\theta)$)
dL	the length of the flow path (thickness of barrier) [L]
DR_i	drainage out of segment on day i [cm]
D_s	depth of surface zone (2 to 5 cm)
ET_i	evapotranspiration from soil segment on day i [cm]
F	is the infiltration rate or inflow rate [$L^3/T/L^2$]
h	pressure head [L]
h_1	final head difference between standpipe and overflow tank (cm)
H_1	water level in the upper water tank of two reservoir model measured relative to the base of waste sample (cm)
H_2	water level in the lower water tank of two reservoir model measured relative to the base of waste sample (cm)
h_g	the ground water level measured relative to the base [L]
h_l	the cell leachate level measured relative to the base [L]
$H_L(i)$	leachate level in cell i [cm]
h_o	initial head difference between standpipe and overflow tank (cm)
h_w	average hydraulic head on clay liner [cm]
i	hydraulic gradient
I_a	initial abstraction [cm]
IN_i	input to soil segment during day i [cm]
K	coefficient of permeability [L/T]
$K(\theta)$	unsaturated hydraulic conductivity [L/T]
K_b	saturated hydraulic conductivity of barrier between two cells [cm/day]
K_D	saturated hydraulic conductivity of drain layer [cm/sec]
K_s	saturated hydraulic conductivity [cm/day]
l	distance along liner surface in the direction of drainage [cm]
L	length of the sample (cm)
$L(i,j)$	length of side j of cell i [cm]
L_j	lateral flow from root zone [m^3/sec/m width]
m	number of the lowest unsaturated segment in soil cover
n	exponent depending on the type and density of waste material
n	number of the segment directly above the clay liner used in NUMMOL model
P	daily precipitation [cm]
P	the perimeter of a landfill cell [L]
P	percolation rate from landfill cover [mm/day]

Symbol	*Description*
q	infiltration rate [L/T]
Q	volumetric discharge through the sample (cm^3/sec)
q_D	lateral drainage rate [cm/sec]
q_s	daily water movement from surface to root zone [L/T]
$Q_s(i)$	seepage flow rate from cell i [cm^3/day]
R	daily runoff [cm]
S	retention parameter or catchment storage [cm]
S_{mx}	maximum value of the retention parameter [cm]
S_p	saturation by volume in root zone
S_s	saturation by volume in surface zone
t	time (sec)
T_b	thickness of barrier between two cells [cm]
TT	travel time through a soil layer [hr]
V	the volume of water transmitted through the sample in time t (cm^3)
V_s	is the storage volume [L^3/L^2]
V_u	the total volume of the unsaturated zone [L^3]
W_j	weighting factor for segment j
X	difference of water levels in water tanks (cm)
$\bar{y}$	average thickness of water profile [cm]
y_o	thickness of water profile above barrier soil at crest [cm]
z	medium depth (positive downward) [L]
z_j	depth to the centre of segment j [m]
Z	depth of the root zone [m]
α	void ratio
Δh	difference of head in two manometers across the sample (cm)
Δt	is the routing interval used in the CREAMS Model (1 day)
Δz_j	thickness of segment j [m]
θ	volumetric moisture content [vol/vol]
θ_f	field capacity [vol/vol]
θ_s	total porosity [vol/vol]
θ_s	saturation capacity of soil cover [vol/vol]
θ_w	wilting point moisture content [vol/vol]
λ	pore-size distribution index [dimensionless]
ρ_d	dry density of waste material [kg/m^3]
ρ_w	density of water equal to 1000 kg/m^3
σ	storage coefficient used in CREAMS model [dimensionless]
σ	standard deviation
ϕ	porosity
ψ	suction head [L]

Chapter 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

Landfill is a common and effective method for the disposal of waste in many parts of the World. In the United Kingdom, around 90% of controlled waste is presently disposed to landfill (DoE, 1992). The disposal of waste by landfilling gives rise to a number of environmental hazards associated with the production of landfill gas and leachate during waste decomposition. Where the landfills are not properly designed and managed, they may pose a severe pollution threat to the environment.

The increased awareness and understanding of the environmental problems of waste disposal to land has led to the progressive introduction of specific legislation aimed at the control of pollution and the limitation of adverse environmental impacts. Regulatory authorities issue licences and impose appropriate conditions aimed at minimising the environmental risks associated with landfilling of waste. Landfill operators have a number of statutory obligations, amongst which is the need to predict leachate volumes generated by a site throughout its active life. Effective measures must also be taken to eliminate the associated risk of pollution.

Developments in landfill technology have tended to proceed on two tracks, with one concentrating on minimizing the potential for external contamination and the other on stabilizing the contents of an enclosure. The contaminants are released from waste to surrounding areas by physical processes and may pose a severe pollution threat to the ground and surface water. Whether leachate is to be collected and treated or is allowed to discharge to the surrounding soil and water, it is essential to have estimates of leachate flow and strength and the variation of these with time as the site develops, and also post-closure. While these estimates are essential to proper landfill design and management, their preparation is a difficult and uncertain process.

A hydrogeological study is an essential part of any proposal to undertake a landfill operation. In a hydrogeological study identification of the metrological variables, precipitation and evaporation, together with an assessment of specific hydrogeological conditions, e.g. factors affecting land surface infiltration and runoff are made. This is important in order to make a quantitative assessment of the volume of water entering the waste body over a period of time, and to determine the potential for leachate occurrence, based on waste properties and site conditions. Hydrology has an important role to play during the existence and on long term stabilisation in the landfill, since water is the principal agent in the biological, physical and chemical processes that take place.

The quantity of leachate generated depends on the water balance of the area in which the landfill is located and on the operational policy (Fleming, 1992). The primary sources of water for leachate formation are:

- precipitation onto the operating landfill
- infiltration through the cover of the completed landfill
- groundwater which may flow laterally from the geological formation

surrounding the landfill

- surface runoff into the landfill from exterior areas.

Liquid waste, if added, contributes to the leachate generation, and to a lesser extent, water contained within the solid waste deposited in the landfill.

The problem of predicting leachate quantities discharged from landfills has been addressed by several investigators. Several laboratory and field models have been constructed in the past to study the relationship between water inputs and leachate production in landfills. The dominant hydrologic considerations include precipitation of any form, surface storage, interception, surface evaporation, runoff, snowmelt, infiltration, vegetation, rooting depth, plant transpiration, soil evaporation, soil moisture storage, soil moisture potential, unsaturated flow, and vertical and lateral saturated flow.

A number of leachate management models (Buchanan and Khan, 1995) have been developed in recent years. These models allow different engineering schemes to be evaluated and are essential tools for the design and operational management of modern landfills. These are of varying sophistication, ranging from relatively simple water balance models, to complex numerical schemes using finite difference, finite element and boundary integral approaches. Most models include a default data base which is often used due to a lack of accurate field data.

Water budget methods have been used to predict leachate quantities discharged from landfills. However, determining the water balance is not a simple task. The interrelationships between climate, vegetation and soil characteristics, and their effects on runoff, evapotranspiration and vertical drainage, are complex. The formulation of a practical model requires some simplifications of these relationships. Therefore, to ensure adequate designs that are practical and economical, it is essential to have reliable accurate design tools and models available to estimate the water-balance components and to predict liquid movement into, through, and out of landfills having a variety of designs.

The theory of flow through porous media has been used in the development of different sophisticated models describing the movement of leachate through waste materials and through hydrological formations. Different complex numerical schemes have been utilized to solve the governing Richard's equation (Richards, 1931) with appropriate boundary conditions. It is not necessarily the case that these models will always be the most appropriate. However, these models are rarely used in practice because of numerical complications and a scarcity of data.

Available data on landfill leachate production are very limited, especially for periods of record that extend significantly beyond the initial water-balance equilibration period, which may last up to several years. Available data on other important facets of the water-balance, such as runoff, evaporation, rainfall, soil moisture, leachate ponding depths, percolation rates, and detailed soil characteristics, are even more limited. Nevertheless, the level of field verification of the existing models and the resulting level of understanding of the important processes involved in leachate production and migration are highly dependent on obtaining such information.

These data limitations affect the verification study in two ways. First, the lack of descriptive landfill information requires the frequent use of default values in the existing models; these introduce uncertainty into the verification. Second, the lack of out-flow measurements for all water-balance components limits the number of model outflow predictions that can be verified. These limitations restrict the ability of a study to isolate and test mathematical characterizations of specific physical processes, such as moisture storage and routing, evapotranspiration demand and its distribution through the soil profile, unsaturated vertical flow, and details of the lateral drainage/vertical percolation partitioning.

Generally landfill wastes are highly heterogeneous, anisotropic, and very porous and have a different composition to typical soils. The degree of compaction, age and degree of decomposition, gas content and temperature all influence the hydraulic characteristics of refuse. The moisture transport due to the spatial variability of solid waste hydraulic properties, i.e., hydraulic conductivity and porosity, plays an essential role in landfill hydrology.

The application of these computer models in practice requires modelling parameters to be identified, defining the waste's ability to retain and convey water. These include; drainage, saturated hydraulic conductivity and moisture capacities of waste. At present, these parameters cannot be estimated with any confidence, due to the current, limited understanding of the behaviour of water in waste.

A factor which is thought to be highly significant in this respect is the in-situ density of the waste. There is thus a need to undertake research which will allow appropriate model parameters to be estimated from a knowledge of waste type and placement conditions.

The primary objective of this research project is to investigate the significance of placement density on the hydraulic characteristics of waste. The results of this research will lead to the development of mathematical models describing the relationship between density and those parameters describing the retention and movement of water in waste. These basic individual models will aid in the development of an applied numerical model for simulating the leachate production and movement within landfill sites. This will facilitate the routine assessment of leachate distribution and occurrence in landfill sites as an aid to effective pollution control and environmental improvement. The research will have significant benefits in planning, assessment, design and management of landfill sites, providing an objective basis for undertaking and evaluating environmental impact assessments and for implementation of improved pollution control strategies.

1.2 Present Status of the Research

The water balance method is a simple standard procedure to compute leachate flow from a landfill. The amount of water percolating into the waste is obtained by subtracting surface runoff, change in soil moisture of the cover soil and evapotranspiration from the total precipitation. In this method, moisture movement through the refuse is not considered. This method was first used in the

Environmental Protection Agency (EPA) model developed by Fenn et al. (1975). The EPA model was used in a number of studies to estimate generation rates for landfills in Cincinnati, Ohio; Orlando, Florida; and Los Angeles, California. Later models developed by Dass et al. (1977), Perrier and Gibson (1980), and Gee (1981) were also based on the water balance techniques. None of the aforementioned models includes leachate flow in the unsaturated zone and computation of leachate mound-head generated due to leachate accumulation at the bottom of a landfill.

Recent mathematical models consider moisture-flow through the landfill in both steady and unsteady state flow conditions, and estimate leachate flow vertically and laterally in a landfill. Schroeder et al. (1984) developed the Hydrologic Evaluation of Landfill Performance (HELP) model, for estimating leachate flow from waste disposal sites. The model is quasi two-dimensional, computing the vertical and lateral components of flow in each layer of the landfill profile. However, these processes are not modelled simultaneously.

The Strathclyde Land Management System (SLAMS) developed by Dickson (1987) and subsequently modified by Buchanan (1990), is a computer-based modelling system for simulating waste deposition and surface hydrology processes, allowing the accumulation of moisture within active landfill sites to be predicted. The SLAMS model uses a cellular geometry and provides information on the spatial and temporal variation of moisture through the landfill.

Application of flow models to simulate and estimate unsteady, unsaturated flow in a solid waste landfill is still at an early stage. The governing equation used to characterize the leachate accretion on the leachate mound in the unsaturated zone is a second order partial differential equation. There are few analytical solutions for the unsaturated moisture-flow equation due to the nonlinearity and heterogeneities involved in the properties (for example hydraulic conductivity and diffusivity) of the landfill wastes. Exact analytical solutions can be obtained by making simplifying assumptions regarding soil moisture characteristics and the flow domain. Some of the analytical solutions are described in Philip (1968, 1971), Braester (1973), Batu (1982), Broadbridge and White (1988), and Barry and Sander (1991).

Since the irregularities in the domain and the complexities in the moisture-flow equation limit the representation of the real flow field by analytical models, many researchers have attempted to develop numerical models. Abbott et al. (1986) described the numerical solution of one-dimensional unsaturated moisture-flow equation by direct explicit schemes for which a stability criteria has to be satisfied to compute the moisture content. A time-varying, one dimensional leachate flow model was developed by Korfiatis (1984) using the finite-difference numerical technique. Demetracopoulos et al. (1986) described the implicit finite-difference scheme for the one-dimensional unsteady state moisture-flow equation which is solved to obtain the leachate accretion on the leachate mound. The implicit finite-difference expression for the moisture-flow equation was solved by the successive application of the Gaussian elimination method. Korfiatis et al. (1984) performed an experimental investigation with a small solid waste column which was used to calibrate and verify the unsteady one-dimensional leachate flow model. The measured and predicted results were reasonably close to each other (Korfiatis et al., 1984).

Recently Ahmed et al. (1992) developed a numerical model that computes the time variation of leachate flow in landfills using Richard's two-dimensional moisture-transport equation, along with the boundary conditions, and which is solved using an implicit finite difference scheme in the vertical plane. Their model is basically an extension of Korfiatis's model (Korfiatis, 1984) from one to two-dimensions. More recently Ahmed et al. (1993) applied a boundary integral solution to the unsaturated moisture flow equation. Their method is capable of generating moisture fluxes in the unsaturated flow domain of a landfill. The fluxes obtained are compared with the analytical solution and show close agreement.

Those leachate management models using Richard's equation require a large number of parameters which are seldom available in practice. In addition, several of these parameters influence the models in a highly nonlinear manner, and results can be very sensitive to parameter changes. It is extremely difficult to assess these parameters at unsampled locations. Therefore, the application of these models to real life cases is presently limited.

1.3 Problem Identification

The problem of predicting leachate quantities discharged from landfills has been addressed by several investigators. Most of them have used the traditional hydrologic approach, commonly employed in surface water analysis. Various volumetric leachate flow models have been developed in different parts of the world to cope with the circumstances and practices used for landfilling in those areas. As practices of landfill technology differ in many aspects, the general applicability of these models to a wide range of situations is often not possible. This restricts the development of a generalized model which is universally accepted and applicable to all situations.

As the use of computer models in the design of landfills continues to increase, the question arises whether these models are accurate predictors of actual field conditions. The degree to which computer models are able to predict field conditions is affected not only by the model itself, but also by the assumptions and design input of the user. For this reason, it is important to investigate the sensitivity of key input parameters and their potential effects on the model's output in addition to the model's overall predictive ability. This study is undertaken to investigate such key parameters and their effects on leachate simulation.

This research is directed towards the development of simulation technology for production and management of leachate. A better understanding of the different mechanisms operative in landfill systems is required in order to construct more efficient and reliable simulation models. In addition, the effect of compaction on these processes will be investigated by experimentation. In particular, modelling efforts will be concerned with deterministic types, rather than complex approaches which are both unwieldily and impractical.

1.4 Objectives of the Study

This research aims to develop a better understanding of moisture flow processes in waste materials. The methodology, based on experimental investigation, is mainly focused on the effect of density on waste properties. This study is directed at fulfilling the following main objectives:

- Review of existing landfill leachate management models in order to identify their limitations, deficiencies and usefulness.
- Determine the effect of compaction on the horizontal and vertical hydraulic conductivity of waste material and develop mathematical models for describing the effect of compaction on the horizontal and vertical hydraulic conductivity of waste.
- Develop a practical and more accurate numerical model for simulating leachate production and movement within landfill sites, by incorporating the developed experimental models. Further, the model should be highly visual and simple to apply to aid viability.
- Perform a sensitivity analysis to examine the response of new developed model (called NUMMOL) to changes in the values of various simulation parameters.

- Establish guidelines and procedures for evaluating different modelling parameters used in models for the design and evaluation of landfill sites.

- Apply the developed model to the actual design of a landfill site to verify the model's operation at field scale.

1.5 Brief Description of the Study

The research undertaken to fulfil the above mentioned objectives is divided into three major parts.

Literature Review

Different landfill hydrological processes and mathematical models describing those processes have been reviewed. The aim of this is to provide information which might assist in identifying and selecting a suitable model. In addition to this, a review and description of different leachate management models have also been made to identify deficiencies of existing models. Particular consideration was given to the relative importance of a models applicability to the real situation and its input parameters that control or strongly influence the leachate movement and distribution within landfill sites. Review of literature is organised as:

Chapter 2	reviews various hydrological processes.
Chapter 3	describes landfill management practices commonly used in landfilling.
Chapter 4	reviews leachate management models using different approaches.

Experimental Work

Different physical properties of waste material are investigated with respect to the density of waste. Those properties include moisture capacities and drainage rates. The effect of compaction on both vertical and horizontal saturated hydraulic conductivities was thoroughly investigated through a series of laboratory investigations. A large database of information from those investigations has been obtained, allowing for interpretation and statistical analysis, and to some extent cover the variability of waste material. Statistical characteristics of the data have also been summarized. "Goodness of fit" analyses have been performed on each set of data to determine a distributional form that can be used to describe the spatial variability of hydraulic conductivity. Experimental investigation is organised as:

Chapter 5	outlines the result of a survey of existing hydraulic characteristics of waste material.
Chapter 6	describes the instrumentation used for determining the horizontal and vertical saturated hydraulic conductivities of waste material and statistical analysis of the results obtained from experimentation.

Model Development

A new applied simulation model called NUMMOL (NUMerical MOdelling of Leachate) is developed, which simulates the leachate production, movement and distribution within landfill sites. A sensitivity analysis has been performed to examine the model behaviour to changing in the input parameters. This information can provide insight on the importance and interaction of specific design variables on the water balance and assist in evaluating the suitability of methodologies used in the NUMMOL model.

The model is applied to the landfill sites at Mid Auchencarroch, which are under development. Two different scenarios were compared by considering the leachate simulation results. This was performed to illustrate the effectiveness of the model in providing comparative information regarding the real field situation. This preliminary application of the model and its simulation results are encouraging. The model's importance is vital and its availability will be of great use to the concerned departments. The model's theory and development are covered in the following chapters.

Chapter 7	describes the theory and procedures of the new developed model.
Chapter 8	presents sensitivity analyses of the developed model and a case study undertaken to show the applicability of the model.
Chapter 9	summarizes the conclusions and recommendations of the study.

Chapter 2

LANDFILL HYDROLOGICAL PROCESSES

The objective of this chapter is to analyse the available hydrological models mainly concerned with land surface hydrology. This introduction reviews the mathematical techniques available to represent different landfill hydrological processes, that is, infiltration, runoff, subsurface flow and percolation. This will enable us to select an appropriate model where possible or to choose individual processes which will aid in the development of a new model for the movement and distribution of leachate production in a landfill site.

Prior to the discussion it is worthwhile to state the factors which will be considered in the selection of individual model.

- Is the model approach practical and physically relevant ?
- Are the model results accurate and computationally efficient ?
- Is the model is simple to use and compatible with other components ?
- Are the model data requirements suitable and easily available ?

2.1 Hydrological Processes

Hydrology deals with surface water and ground water, their interdependence, and their interaction with earth materials. The study of hydrology includes all aspects of the hydrological cycle, including atmospheric phenomena such as precipitation and evapotranspiration. The hydrological cycle is a term used to describe the distribution and movement of water on earth. Its dynamic operation and the interactive processes that control it frame the entire theoretical study of hydrology. Furthermore, the fact that it constitutes a highly refined cycling system in a delicate state of equilibrium should be taken into account in all aspects of applied hydrology. The cycle includes a large number of interrelated and interacting processes which are dependent on each other and vary both in time and space. An understanding of the various processes evident within the hydrological cycle is fundamental to many engineering studies. The main processes are: evaporation, transpiration, precipitation, infiltration, runoff, percolation, groundwater flow.

Engineering hydrology is primarily concerned with land phase processes, i.e. with surface and subsurface processes, and, in particular, with aspects relating to infiltration and to the prediction of runoff. Four basic hydrological concerns can be identified in relation to engineering problems:

Occurrence	the amount of water existing in a particular system.
Distribution	the spatial distribution of this water.
Movement	the transfer of water from one location to another.
Quality	the nature and degree of contamination.

A hydrological study, whether of global or regional scale, will generally attempt to assess the quantity and quality of water occurring and the variation of hydrological parameters in time and space.

2.2 General Overview of Hydrological Processes

In undertaking a hydrological investigation, it is necessary to evaluate the rate at which water is supplied to the site under consideration and to consider the subsequent movement of this water over and through the land surface. Major processes to be considered are:

Precipitation:

Precipitation occurs when a body of moist air is cooled to dew point; that is, the temperature at which condensation occurs. It is a primary input to most hydrological models.

Evapotranspiration

Evapotranspiration is a combined name of evaporation (loss of water from soil and water surfaces) and transpiration (loss of water from a soil system due to uptake of water by plants and vegetation). This parameter is easily available from Metrological Office.

Infiltration

The process whereby precipitation falling on the land surface permeates into underlying soil formations. The rate at which infiltration takes place is dependent on the available supply of moisture (precipitation less actual evapotranspiration) and on the potential of underlying soils to take-up moisture.

Runoff

The precipitation available after satisfying evapotranspiration demands and infiltration is termed the effective precipitation; this is the water available to generate runoff.

Subsurface flow

The lateral and vertical movement of water within the soil and waste systems is termed subsurface flow.

The need to predict the relative amounts of infiltration and runoff for given rainfall events has resulted in the development of a number of hydrological models. In general these models attempts to define the various hydrological storage systems and transfer mechanisms as a set of mathematical equations. The majority of these models are of the deterministic type, whereby the response of a given system to a known set of inputs can be estimated. The first stage in developing such a model is the conceptualisation of all physical processes and their interaction, as a simplified model.

Mathematical models can be developed to describe all of the hydrological processes included in a hydrological cycle. However, consideration here is solely given to the development of models which can be used to predict the landfill hydrological processes. The relevant hydrological processes i.e., infiltration, runoff, sub-surface lateral flow etc. are discussed below.

2.3 Infiltration Models

Infiltration is the process of water penetrating from the ground surface into the soil. Many factors influence the infiltration rate, including the condition of the soil surface and its vegetative cover, the properties of the soil, such as its porosity and hydraulic conductivity and the current moisture content of the soil.

The infiltration rate f, expressed in cm per hr, is the rate at which water enters the soil at the surface. If water is ponded on the surface, the infiltration occurs at the potential infiltration rate. If the rainfall intensity at the surface is less than the potential infiltration rate then the actual infiltration rate will also be less than the potential rate. The cumulative infiltration F is the accumulated depth of water infiltrated during a given period and is equal to the integral of the infiltration rate over the period,

$$F(t) = \int_0^t f(\tau)\,d\tau \tag{2.1}$$

where τ is a dummy variable of time in the integration. Conversely, the infiltration rate is the time derivative of the cumulative infiltration:

$$f(t) = \frac{dF(t)}{dt} \tag{2.2}$$

The fundamental law governing the movement of fluids through porous medium is credited to Darcy (1856), commonly expressed as:

$$Q = KA\frac{dh}{L} \tag{2.3}$$

where

Q = flow rate [L^3 /T]

K = coefficient of permeability [L/T]

A = surface area [L^2]

dh = differential head applied to the sample [L]

L = length of the flow path [L]

Equation 2.3 can be further reduced to:

$$Q = K\,A\,i \tag{2.4}$$

where i = (dh/L) is the hydraulic gradient.

Equation 2.4 is the familiar form of Darcy's law. The model structure of Darcy's law is expressed as a linear relationship between Q and i, intercepting the origin with a slope of KA. This structure is unique, that is, for any values of K, A, i, dh, and L the model predicts a straight line with a (0,0) intercept. Physically this model translates into the flux of water being directly proportional to the hydraulic gradient, with K being the empirical proportionality constant. Obviously, if no gradient exists then flow will not occur.

A number of infiltration equations have been developed in the past. They are generally classed in two broad categories, those which are empirical in nature or require fitted parameters or both, and those which are derived from the theory of flow in porous media and utilize measured parameters. Equations in the first category have often involved simplified concepts which permit the infiltration rate to be expressed algebraically as a function of time and empirical constants or soil parameters. Models in the second category are developed from approximate solutions of Richard's equation.

2.3.1 Solutions of Richard's equation

Richard's equation (1931) for one-dimensional flow of water in porous media is a combination of Darcy's law with the continuity equation as:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} \tag{2.5}$$

where:

θ = volumetric moisture content [vol/vol]

$K(\theta)$ = unsaturated hydraulic conductivity [L/T]

$D(\theta)$ = diffusivity coefficient [L^2/T] (= $-K(\theta)(\partial\psi/\partial\theta)$)

ψ = suction head [L]

z = medium depth (positive downward) [L]

The infiltration rate is given by $\partial\theta/\partial t$ for the uppermost soil layer.

Richard's equation is a nonlinear second order partial differential equation. Up to now, this equation has been the most common basic mathematical expression for unsaturated flow phenomena in porous media. This equation describes unsteady flow in a one-dimensional anisotropic and nonhomogeneous soil matrix by means of a partial differential equation. For the modelling of water dynamics in the unsaturated zone, one has to solve this equation with the help of suitable algorithms. The models can be grouped into analytical and numerical approaches, with the latter being far more popular. Analytical solutions are often more difficult to obtain because the coefficients of Richard's equation are functions of the dependent variables.

2.3.2 The Philip Equation

Philip (1957, 1969) solved Richard's equation under less restrictive conditions by assuming that K and D can vary with the moisture content θ. Philip employed the Boltzman transformation $B(\theta) = z\, t^{-1/2}$ to convert (Equation 2.5) into an ordinary differential equation in B, and solved this equation to yield an infinite series for cumulative infiltration F(t), which is approximated by

$$F(t) = S t^{1/2} + A t \tag{2.6}$$

Where S is a parameter called sorptivity, which is a function of moisture content (θ) and the soil suction potential (ψ), and A is called transmissivity. Both S and A depend on soil properties and initial moisture content. Differentiating the above equation with respect to t yields infiltration rate f(t) as:

$$f(t) = \frac{1}{2} S t^{-1/2} + A \tag{2.7}$$

As t approaches ∞, f(t) tends to A. The two terms in Philip's equation represent the effects of soil suction head and gravity head, respectively. The two parameters 'S' and 'A' are estimated from K-θ and ψ-θ relationships.

2.3.3 Green-Ampt Method

A conceptual model utilizing Darcy's law was proposed by Green and Ampt (1911) as:

$$f(t) = K\left(\frac{\psi\,\Delta\theta}{F(t)} + 1\right) \tag{2.8}$$

$$F(t) = Kt + \psi\,\Delta\theta\,\ln\left(1 + \frac{F(t)}{\psi\,\Delta\theta}\right) \tag{2.9}$$

Given K, t, ψ, and $\Delta\theta$, a value of F is calculated by successive substitution from Equation 2.9, which is then substituted into Equation 2.8 to determine the corresponding potential infiltration rate f.

The formulation was intended for sandy soils or those with uniform pore space, but its use now extends outwith these bounds. The method can be used when sufficiently detailed rainfall data is available.

2.3.4 The Horton Equation

One of the earliest infiltration equations was developed by Horton (1933), who observed that infiltration begins at some rate f_0 and exponentially decreases until it reaches a constant rate f_c:

$$f(t) = f_c + (f_o - f_c)\,e^{-kt} \tag{2.10}$$

where k is a decay constant having dimensions [1/T].

The Horton model is strictly only valid for cases where the available supply of moisture exceeds the infiltration capacity of the soil system. Eagleson (1970) has shown that Horton's equation can be derived from Richard's equation (Eq. 2.5) by assuming that K and D are constants independent of the moisture content of the soil.

Lee and Musiake (1992) modified the Hortonian model to work with naturally occurring variable-pattern hyetographs. The structure of the model is hypothesized based on a physical appreciation of the Hortonian infiltration process, which is then refined through repeated testing to simulate the overland flow data associated with the process. Model adequacy in simulating reality was checked by comparing its simulations with observed, tensiometer-measures, hydraulic potential profiles in the field. The model performance seems to be reasonably good up to the 20-min interval. Beyond this time interval, the model performance deteriorates.

2.3.5 The SCS method

The Soil Conservation Service (USDA, 1972) developed a method for computing abstractions from storm rainfall. The runoff depth is calculated by the expression:

$$R = \frac{(P - I_a)^2}{P + S - I_a} \tag{2.11}$$

where:

R = daily runoff [cm]

P = daily precipitation [cm]

I_a = initial abstraction [cm]

S = retention parameter or catchment storage [cm]

In most cases, initial abstraction is estimated as a function of catchment storage, typically taken to be 10% of catchment storage, so the SCS equation becomes.

$$R = \frac{(P - 0.1S)^2}{P + 0.9S} \tag{2.12}$$

The storage index S is transformed to the more intuitively pleasing coefficient curve number (CN) in the definition

$$S = 2.54\left[\frac{1000}{CN} - 10\right] \tag{2.13}$$

Curve numbers are dimensionless, and can vary from 0 (no runoff) to 100(all rainfall becomes runoff). Curve numbers have been tabulated by the Soil Conservation Service on the basis of soil type and land use. Typical values of CN for various soil types and land-uses are given in Table 2.1.

The calculation by SCS method is much more sensitive to the CN chosen than it is to the rainfall depths (Hawkins, 1993). That is, error analysis and sensitivity calculus show that errors in CN have a much more serious effect on the runoff calculation than do similar levels of error in the storm rainfall P.

Table 2.1. Typical values of CN for use with the SCS Model (USDA, 1972).

Land Use	Soil Type			
	A	B	C	D
Residential - roofs, roads, etc.	98	98	98	98
Residential - pervious fraction	51	68	79	84
Industrial	81	88	91	93
Commercial	89	92	94	95
Parkland (75% grass cover)	39	61	74	80
Parkland (50% grass cover)	49	69	79	84
Pasture	39	61	74	81
Cultivated land	62	71	78	81
Woodland - poor cover	45	66	77	83
Woodland - good cover	25	55	70	77

Soil types
A Deep, well drained sands and gravels
B Moderately well drained, medium texture soil
C Fine soils with infiltration impeding layer
D Clay, soils with permanently high water table, soils overlying rocks

The above values of CN are for normal antecedent soil moisture conditions (AMC II). For particularly wet or dry soils, the resulting value of S should be modified by applying a multiplication factor of 2.38 (in the case of dry soils) or 0.435 (in the case of wet soils).

2.3.6 Lumped Parameter Model for Infiltration

The model proposed by Pingoud (1982) is an approximate lumped type model which uses the conservation equation to derive an analytical formula for the flow rate from one storage to another. The soil is divided into layers having certain physical soil constants. Each layer is considered to be a storage for moisture. The flow rate from one layer to the next is assumed to be proportional to the gradient in moisture content between layers.

The soil is divided into N layers each with a thickness Δz_i. Each layer is considered to be a moisture storage with an effective volumetric moisture content θ_i and the corresponding values of the diffusivity and the hydraulic conductivity are $D(\theta_i)$ and $K(\theta_i)$, respectively.

The mass conservation equation of the storage i is given by:

$$\frac{d\theta_i}{dt} = \frac{(v_i - v_{i+1})}{\Delta z_i} \tag{2.14}$$

where v_i and v_{i+1} are the inflow and outflow rates of the storage and i is number of layer from 1 to N.

The flow rate v_i from the storage i-1 is approximated by the equation:

$$v_i = -\tfrac{1}{2}[D(\theta_i) + D(\theta_{i-1})]\,\frac{\theta_i - \theta_{i-1}}{\tfrac{1}{2}(\Delta z_i + \Delta z_{i-1})} + \tfrac{1}{2}[K(\theta_i) + K(\theta_{i-1})] \tag{2.15}$$

where:

K = hydraulic conductivity for specified θ [L/T]

D = diffusivity for specified θ [L^2/T]

The flow rate into the first soil storage layer is estimated by setting Δz_{i-1} to zero and θ_{i-1} as θ_o where this is estimated by:

$$\theta_o = \phi [1 - \exp(-\beta h)] \tag{2.16}$$

where:

ϕ = is the effective soil porosity at the surface

h = is the ponding height at the surface [L]

ß = is a large positive constant.

The flow rate v_{N+1} from the lowest storage is determined by gravity alone and is equal to $K(\theta_N)$.

The model was tested by Pingoud (1982) and later was subjected to sensitivity analyses (Pingoud, 1984). He expected the model to be utilized as part of a larger rainfall-runoff type of model and has expressed confidence in the results displayed from the production and sensitivity tests.

2.4 Flow through the Vegetative Zone

It is commonly assumed that the flow of water through a soil is vertical when the soil is unsaturated and two dimensional when the soil is saturated (Kirkby, 1985). This is a convenient assumption for the study purposes since it fits well with the concept of an impermeable barrier, such as two layer landfill caps, specifically designed to encourage saturation and lateral flow in the caps. The variation of soil moisture throughout a soil profile is gradual, and the distinction between saturated and unsaturated zones is not always clear; thus, it is essential to model this to assess levels of percolation, lateral flow and the effect on infiltration.

The different techniques employed to estimate the moisture storage in the soil cover, determination of percolation water from unsaturated zone and lateral subsurface or return flow are classed as:

- Storage Routing Technique
- Lumped Parameter Model (LPM) approach
- Storage-Discharge Models

Different models have been developed using the above mentioned techniques and are considered here for potential use as part of this study. A brief description of those models is described in the next subsection.

2.4.1 Storage Routing Technique

2.4.1.3 CREAMS Model

The CREAMS (Chemicals, Runoff and Erosion from Agricultural management Systems) model (Knisel, 1980) was developed in the U.S. principally over concern about the effects of non-point source pollution. Its primary role therefore is to assess non-point source pollution under various land management practices. The role of hydrology was recognised as being the primary motivator in non-point source pollution so that the principal hydrology model was developed using an up to date understanding of soil water physics (option-2) (Smith and Williams, 1980). A cruder hydrology option, based on the SCS curve number technique (USDA, 1972), can also be used when only daily data is available (option-1). The model is well documented and most of the inputs to the model can be measured, or estimated, for a desired location.

The hydrologic components consist of two versions. The first, option 1, uses daily rainfall to predict runoff volume and peak discharge rates. The second, option 2, uses breakpoint precipitation data for individual events, and also produces runoff volumes and peak discharge rates as output. Both options also predict daily plant transpiration, potential transpiration, average soil moisture, and percolation. A flow chart of the hydrology section of the CREAMS model is shown in Figure 2.1. The percolation components of the model for both options are briefly presented here.

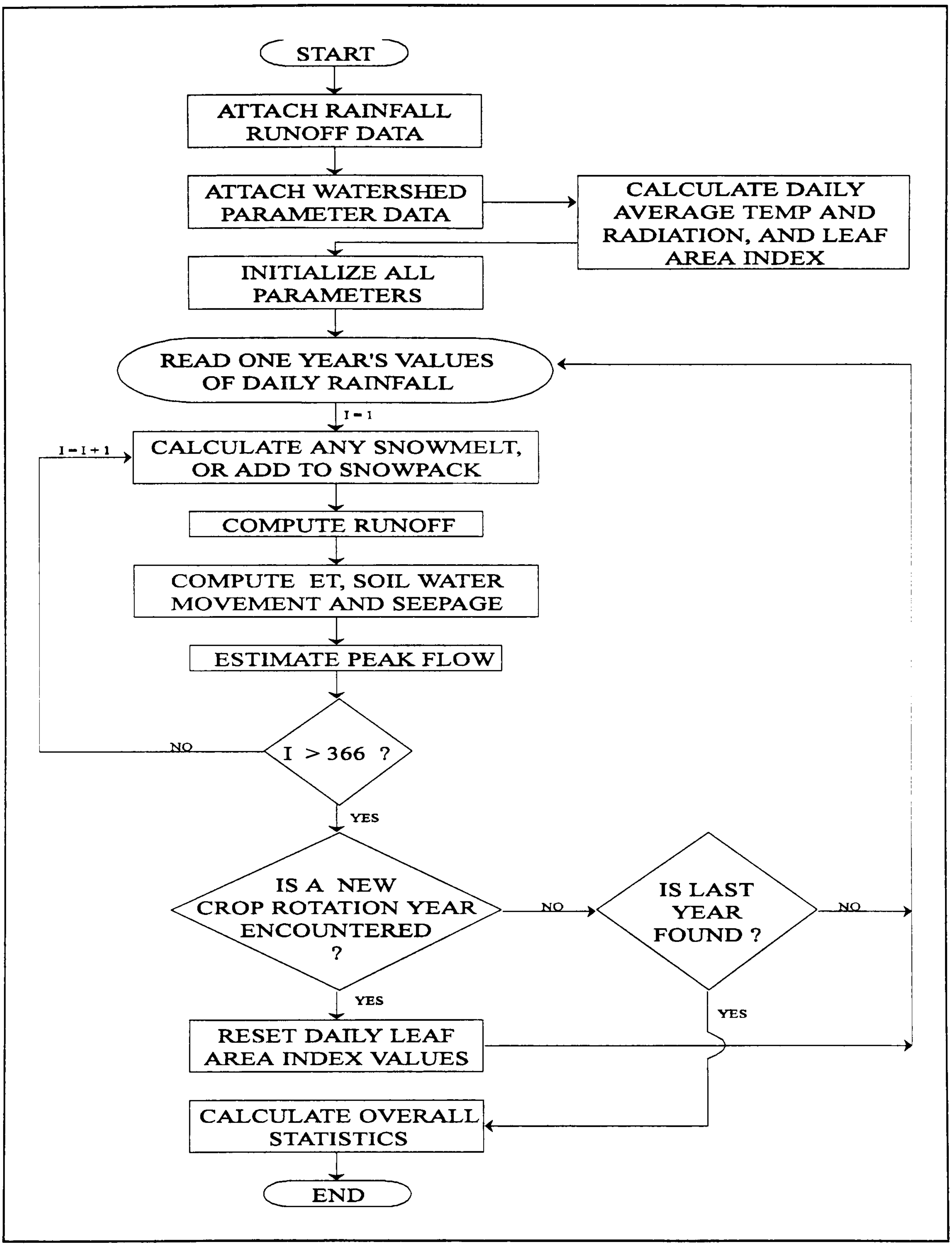


Figure 2.1. Generalized Flow Chart of CREAMS Model Hydrology option I (Knisel, 1980).

Percolation (Option-1)

The CREAMS model uses a soil storage routing technique to predict flow through the root zone. When the SCS curve number method is used, the root zone is divided into seven layers or storages for routing. Root-zone depth is usually estimated to be three feet, although it may vary with various crops and soils. The routing equation is

$$q = \sigma \left(F + \frac{V_s}{\Delta t} \right) \qquad for \quad \left(F + \frac{V_s}{\Delta t} \right) > \theta_f \tag{2.17}$$

where

q = percolation rate from root zone [L/T]

F = is the infiltration rate or inflow rate [$L^3/T/L^2$]

V_s = is the storage volume [L^3/L^2]

σ = is the storage coefficient [dimensionless]

Δt = is the routing interval (1 day)

If inflow plus storage does not exceed field capacity (θ_f), percolation is not predicted to occur. The storage coefficient is a function of the travel time through the storage expressed by the equation:

$$\sigma = \frac{2 \Delta t}{2t + \Delta t} \tag{2.18}$$

where t is the travel time through a storage, which is estimated with the equation:

$$t = \frac{\theta - \theta_f}{K_s} \tag{2.19}$$

where θ is soil water storage, and K_s is the saturated conductivity of the soil.

Percolation (Option-2)

Option 2 of the CREAMS model uses an analogy to Darcy's law to simulate vertical water movement in the soil profile. Two principles are used, firstly that flow will occur downwards from a layer with a higher degree of saturation; secondly, that beneath the root zone there is free drainage and that the root zone will consistently drain to field capacity. This second principle prevents saturation occurring throughout the profile, and consequently prevents the occurrence of saturation restricted infiltration.

When the breakpoint infiltration model is used for runoff calculations, the soil water movement and percolation calculation involves only two storage elements, a surface soil zone, and a root soil zone. The surface soil zone is subject to soil evaporation from the evapotranspiration model, plus a portion of the plant root extraction. It is the region of the soil which determines initial conditions to which the infiltration model is sensitive. The lower zone is subject to root extraction during the growing season. A root growth model is used in this option which simulates relative root depth proportional to relative leaf area index.

Water moves from the upper soil zone to the root zone as a function of the positive difference in saturation between the two zones as:

$$q_s = C_s S_s^3 (S_s - S_p) \phi D_s \qquad for \qquad S_s > S_p \tag{2.20}$$

where

q_s = daily water movement from surface to root zone

C_s = coefficient (normally taken as 0.1)

S_s = saturation by volume in surface zone

S_p = saturation by volume in root zone

ϕ = porosity

D_s = depth of surface zone (2 to 5 cm)

The depth of water given by the above equation is deducted from the surface zone and added to the root zone. A check is then made to see if the root zone exceeds field capacity, in which case the excess is presumed to drain and become percolation. The soil moisture in these zones is also depleted by evaporation or transpiration both of which are evaluated prior to any percolation calculations.

2.4.1.2 ILWAS Model

The ILWAS model (EPRI, 1983) provides an approximate physical solution for lateral flow and percolation from temporary saturated zones. The main assumption for the percolation is that the sublayer is always saturated. Thus when the root zone exceeds field capacity, and percolation is occurring, the flow is governed by the saturated conductivity of the underlying sublayer. For the lateral flow calculation it is assumed that the flow of saturated soil water is parallel to the ground surface and that it one dimensional. The model using the following two equations for percolation and lateral subsurface flow.

$$P_{j+1} = K_{j+1}\left(\frac{\theta - \theta_f}{\theta_s - \theta_f}\right) \tag{2.21}$$

$$L_j = K_j\ S\ Z_j\left(\frac{\theta - \theta_f}{\theta_s - \theta_f}\right) \tag{2.22}$$

where,

P_{j+1} = percolation into layer below root zone [m/sec]

K_{j+1} = saturated hydraulic conductivity of layer below root zone [m/sec]

L_j = lateral flow from root zone [m^3/sec/m width]

S = slope of effective saturated level, assumed to be parallel to the ground slope.

Z_j = depth of the root zone [m]

θ = current moisture content of root zone [vol/vol]

θ_f = field capacity of soil in root zone [vol/vol]

θ_s = saturation capacity of root zone [vol/vol]

This conceptualisation of lateral flow is based on the assumption that a temporary saturated zone is formed and the equivalent depth of this zone is linearly related to the moisture content.

2.4.1.3 SWRRB Model

The SWRRB (Simulator for Water Resources in Rural Basins) model was developed for simulating hydrologic and related processes in rural basins by Williams et al. (1985). It is used to predict the effect of management decisions on water and sediment yields with reasonable accuracy for ungaged rural basins. The major processes included in the model are surface runoff, percolation, return flow, evapotranspiration, pond and reservoir storage and sedimentation. The model was developed by modifying the CREAMS model (Knisel, 1980). Only two hydrological processes of the model i.e., percolation and return flow are discussed here.

Percolation

The percolation component of SWRRB uses a storage routing technique to predict flow through each soil layer in the root zone. Percolation is computed using the equation

$$P = \theta_o \left[1 - \exp\left(\frac{-\Delta t}{TT} \right) \right] \tag{2.23}$$

in which

P = percolation rate in mm/day;

θ_o = soil water content at the beginning of the day in mm;

Δt = travel interval (24 h); and

TT = travel time through a soil layer in hr.

The travel time, TT, is computed for each soil layer with the linear storage equation

$$TT_i = \frac{\theta(i) - \theta_f(i)}{K(i)} \tag{2.24}$$

in which

K(i) = hydraulic conductivity in mm/hr; and

$\theta_f(i)$ = field capacity water content for layer i in mm.

The hydraulic conductivity is varied from the saturated conductivity value at saturation to near zero at field capacity.

$$K(i) = K_s(i)\left(\frac{\theta(i)}{\theta_s(i)}\right)^{\beta_i} \qquad (2.25)$$

in which

$\theta_s(i)$ = soil porosity in mm;

$K_s(i)$ = saturated conductivity for layer i in mm/hr; and

β_i = a parameter that causes K(i) to approach zero as $\theta(i)$ approaches θ_f.

If the layer immediately below the layer being considered is saturated, no flow can occur regardless of the results from Equation 2.24. The effect of lower layer water content is expressed as:

$$P_c(i) = P(i)\sqrt{1 - \frac{\theta(i+1)}{\theta_s(i+1)}} \qquad (2.26)$$

in which

$P_c(i)$ = percolation rate for layer i in mm/day corrected for layer i+1 water content; and

P(i) = percolation computed with Equation 2.24.

Return Flow

Return flow is calculated simultaneously with percolation. Each water input is given the opportunity to percolate first, and, then the remainder is subjected to the lateral flow function. Thus, lateral flow can occur when the storage in any layer exceeds field capacity after percolation. The lateral flow function for layer i is expressed in the equation

$$Q = (\theta - \theta_f)\left[1 - \exp\left(\frac{-\Delta t}{TT_L}\right)\right] \tag{2.27}$$

in which

Q = lateral flow rate for soil layer i in mm/day; and

TT_L = lateral flow travel in day.

The lateral flow travel time is used to partition flow between percolation and lateral flow. High values of (TT_L) (~1,000 days) give little or no lateral flow, and low values (1-10 days) give high lateral flow rates in relation to percolation.

2.4.2 Lumped Parameter Model

The lumped parameter model (LPM) assumes that the entire unsaturated zone can be lumped together as one homogeneous unit and that the recharge (r) to the saturated zone is a function of volume of water stored in the unsaturated zone, i.e.

$$r = K(\theta_u) \tag{2.28}$$

where

θ_u = the average volumetric water content in the unsaturated zone; and

$K(\theta_u)$ = the unsaturated hydraulic conductivity at water content θ_u [L/T].

The water content, θ_u, is simulated using mass balance:

$$\theta_{u2} = \left[\theta_{u1} + \frac{A_u \Delta t (q - r)}{V_u}\right] \tag{2.29}$$

where

V_u = the total volume of the unsaturated zone [L^3];

q = the infiltration rate [L/T];

A_u = the cross-sectional area of the unsaturated zone [L^2]; and

Δt = time increment between subscripts 1 and 2.

The LPM thus assumes a gravity flow with the moisture regime of the unsaturated zone revised at the end of every pulse of a given rainfall event. No provisions can be made for nonuniform initial water contents or the heterogeneous soil conditions. This model was used by Sloan and Moore (1984) in conjunction with saturated flow models in their studies on storm-flows on sloping watersheds, and by Reddi and Wu (1991) and Danda and Reddi (1992) in their sensitivity analysis of recharge due to rainfall.

2.4.3 Storage-Discharge Models

The two simple storage-discharge models developed by Sloan et al. (1983) are based on a water balance. The models uses the mass balance equation with the entire hill slope being the controlled volume. The idealized hill slope segment has an impermeable boundary or bed, of slope α and length L, and a soil profile of constant thickness, D, as shown in Figure 2.2. The mass balance equation can be expressed in mixed finite difference form as

$$\frac{S_2 - S_1}{t_2 - t_1} = iL - \frac{(q_1 + q_2)}{2} \tag{2.30}$$

where S is the drainable volume of water stored in the saturated zone per unit width, t is time, q is the discharge from the hill slope per unit width, i is the rate of water input to the saturated zone from the unsaturated zone per unit area, and subscripts 1 and 2 refer to the beginning and end of the time period, respectively.

The kinematic storage model assumes that the water table has a constant slope between the upslope and downslope boundaries of the sloping soil layer, as shown in Figure. 2.2a. The hydraulic gradient is assumed to be equal to the slope of the impermeable bed (the kinematic assumption). The drainable volume of water stored in the saturated zone of the hill slope is

$$S = \frac{H_o \theta_d L}{2} \tag{2.32}$$

where H_o is the saturated thickness normal to the hill slope at the outlet and θ_d is the drainable porosity of the soil. At the outlet, assuming free discharge, $q = H_o v$, where $v = K_s \sin \alpha$, which combined with equation 1 and 2 allows the hydraulic head at the outlet at the end of each time increment, dt, to be expressed explicitly as

$$[H_o]_2 = \frac{[H_o]_1 (L \theta_d - v \Delta t) + 2 L i \Delta t}{L \theta_d + v \Delta t} \tag{2.33}$$

When the saturated zone rises so that the water table intersects the soil surface, Equations 2.32 and 2.33 must be modified, so that

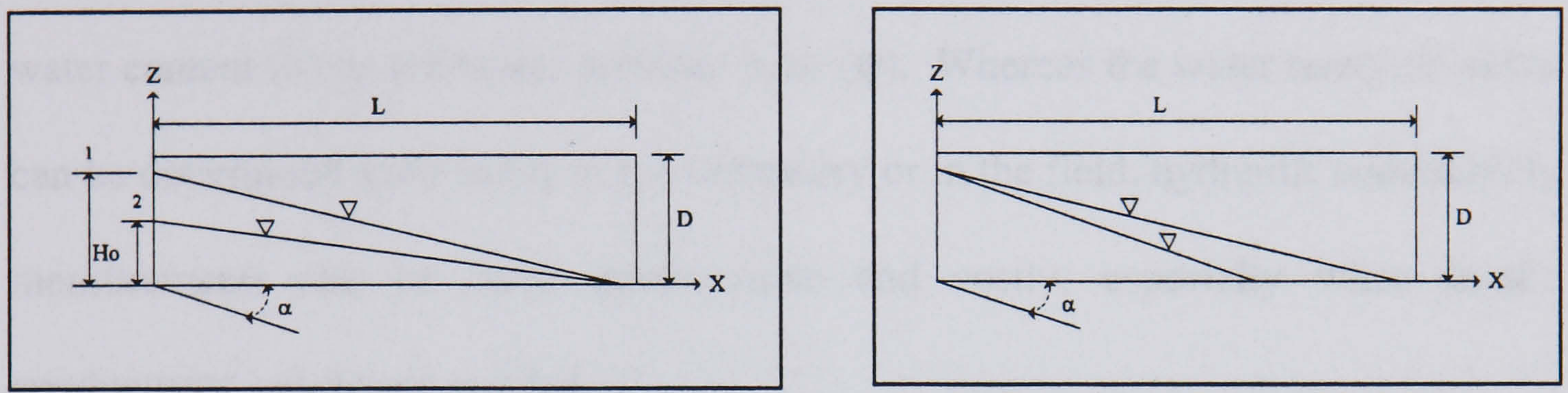
$$S = \frac{D \theta_d (L + L_s)}{2} \tag{2.34}$$

$$q = i L_s + D v \tag{2.35}$$

where L_s is the saturated slope length.

The Boussinesq storage model assumes that the water table has a constant slope (as shown in Figure 2.2b) and that the hydraulic gradient is equal to this slope (Boussinesq assumption), so that $v = K_s \sin ß$, where ß is the angle of the water table to the horizontal. At the outlet, $q = Dv = DK_s \sin ß$. The drainable volume of water stored in the saturated zone of the hill slope is

$$
\begin{aligned}
S &= \frac{D^2 \theta_d}{2 \tan(\alpha - \beta)} && \tan(\alpha - \beta) < D/L \\
S &= L\theta_d\left(D - \frac{L}{2}\tan(\alpha - \beta)\right) && \tan(\alpha - \beta) > D/L
\end{aligned}
\qquad (2.36)
$$



(a) the Kinematic Storage Model

(b) the Boussinesq Storage Model

Figure 2.2. Conceptual Representation of the Hill slope Segment.

2.5 Drainage Models

2.5.1 Solutions of Richard's equation

Richard's equation (Equation 2.5) can be utilized for flow through an unsaturated zone. The equation may be solved by a number of numerical methods using small increments of depth and time. Once moisture contents at the grid points are determined, then drainage rates or moisture fluxes can easily be calculated. The volume of drainage is given by flux density from the bottom soil layer. The flux density of water is the volume of water flowing past a certain point in the porous media per unit cross-sectional area (normal to the flow direction) of media per unit time. It is positive in the direction of the z-axis. For simplicity, flux is often used instead of flux density to describe the same phenomena. The moisture flux (q) equation was formulated from Darcy's law as

$$q = K(\theta) - D(\theta)\frac{\partial \theta}{\partial z} \tag{2.37}$$

The hydraulic properties of an unsaturated porous media are characterized by a water retention curve and the hydraulic conductivity (K) as a function of volumetric water content (θ) or soil-water pressure head (ψ). Whereas the water retention curve can be determined quite easily in the laboratory or in the field, hydraulic conductivity measurements can be more cumbersome and costly, especially when in-situ conductivity values are needed.

2.5.2 Baver's Model

The mathematical description of the water movement in the transmission zone is simplified by using the assumption that the gravity forces dominate over the matric forces, making the hydraulic gradient close to unity. With these assumptions, water loss from a column of length L, together with Darcy's equation reduces to (Baver et al., 1972):

$$L\frac{d\bar{\theta}}{dt} = -K(\theta_b) \tag{2.38}$$

where

L = length of soil column [L];

$\bar{\theta}$ = average moisture content in soil column [vol/vol];

θ_b = moisture content at bottom of column [vol/vol]; and

$K(\theta)$ = unsaturated conductivity as a function of moisture content [L/T].

For soils near field capacity, with downward movement of moisture, no great variation in volumetric moisture content, θ, is to be expected, and $\theta_b \approx \bar{\theta} = \theta$, thus:

$$L \frac{d\theta}{dt} = -K(\theta) \tag{2.39}$$

2.5.3 Boussinesq Lateral Drainage Models

Unconfined lateral drainage from porous media is modelled by the Boussinesq equation (Darcy's law coupled with the continuity equation), employing the Dupuit-Forcheimer (D-F) assumptions (Skaggs, 1982). The D-F assumptions are that, for gravity flow to a shallow sink, the flow is parallel to the liner and that the velocity is in proportion to the slope of the water table surface and independent of depth of flow. These assumptions imply the head loss due to flow normal to the liner is negligible, which is valid for drain layers with high hydraulic conductivity and for shallow depths of flow, depths much shorter than the length of the drainage path. The Boussinesq equation may be written as follows (See Figure 2.3 for definition sketch) for steady state assumption:

$$\frac{\partial}{\partial l}\left[(h - l\sin\alpha)\frac{\partial h}{\partial l}\right] = -\frac{R}{K_D} \tag{2.40}$$

where

h = elevation of phreatic surface above liner at edge of drain [cm]

K_D = saturated hydraulic conductivity of drain layer [cm/sec]

l = distance along liner surface in the direction of drainage [cm]

α = inclination angle of liner surface

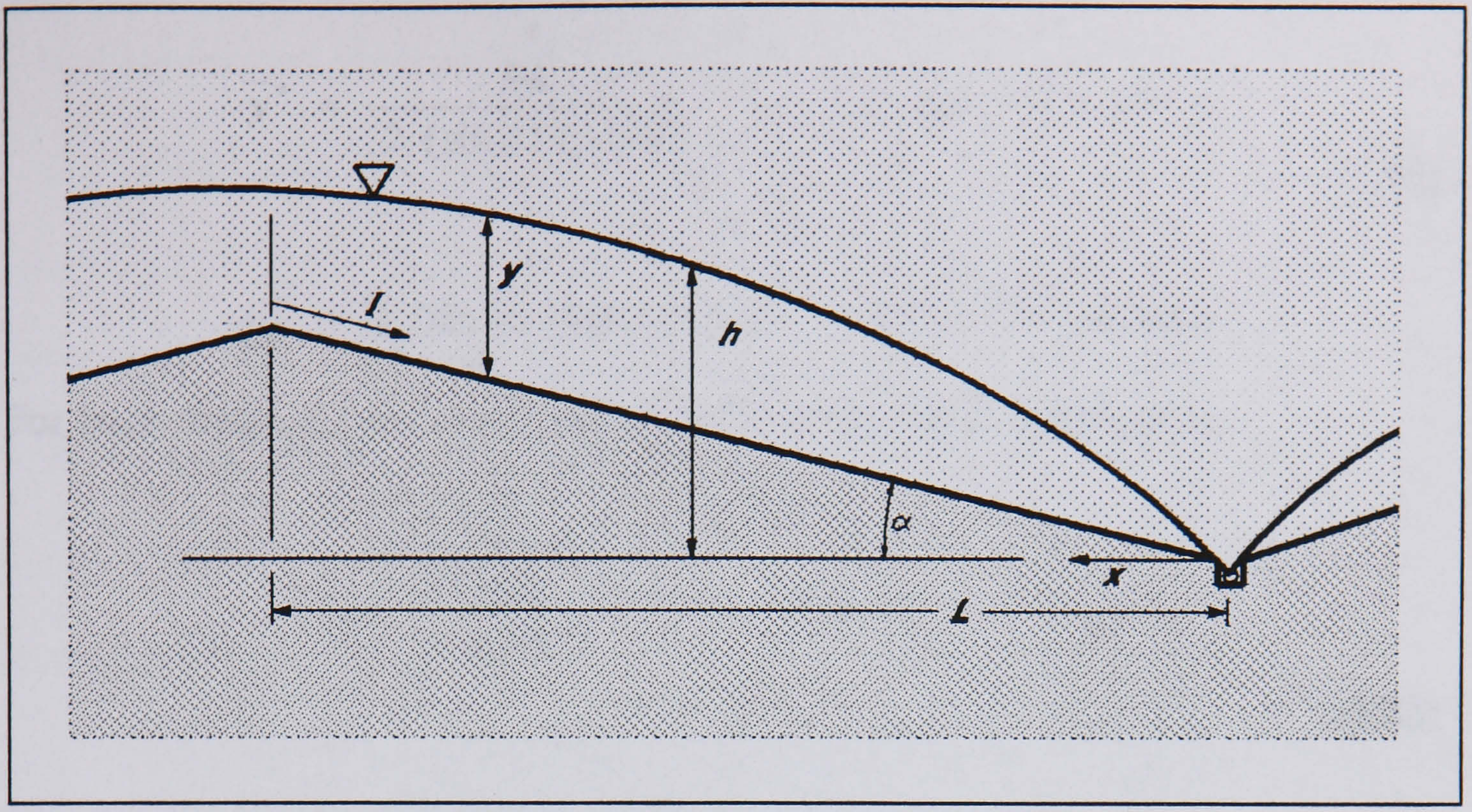


Figure 2.3. Lateral Drainage Definition Sketch.

R = net recharge (impingement minus leakage) [cm/sec]

Equation 2.40 was linearized by Skaggs (1982) to the following form:

$$q_D = \frac{2K\bar{y}(y_o + \alpha L)}{L^2} \tag{2.41}$$

where

q_D = lateral drainage rate [cm/sec]

y_o = thickness of water profile above barrier soil at crest [cm]

$\bar{y}$ = average thickness of water profile [cm]

Although Skaggs (1982) used an elliptical profile in the linearization of Equation 2.41, the shape of the profile deviates from the ellipse as $\bar{y}$, L, and α vary.

For small drain rates or shallow saturated depths, such that $q_D^* < 0.4(\sin^2 \alpha)$ or $\bar{y}^* < 0.2 \tan \alpha$ ($\bar{y}^*$ = average depth of saturation above the entire liner),

$$\bar{y}^* = \frac{q_D^*}{2\,(\sin\alpha)\,(\cos\alpha)} \qquad for\ q_D^* < 0.4\,\sin^2\alpha$$

$$or \qquad (2.42)$$

$$q_D^* = 2\,(\sin\alpha)\,(\cos\alpha)\,\bar{y}^* \qquad for\ \bar{y}^* < 0.2\,\tan\alpha$$

For large drainage rates, such that $q_D^* \gg 0.4(\sin^2\alpha)$ or $\bar{y}^* \gg 0.2\tan\alpha$,

$$\bar{y}^* = \frac{\pi\sqrt{q_D^*}}{4\,\cos\alpha} \qquad for\ q_D^* \gg 0.4\,\sin^2\alpha$$

$$or \qquad (2.43)$$

$$q_D^* = \left(\frac{4\,\bar{y}^*\,\cos\alpha}{\pi}\right)^2 \qquad for\ \bar{y}^* \gg 0.2\,\tan\alpha$$

The following analytical solution for $\bar{y}^*$ was developed by McEnroe and Schroeder (1988):

$$\bar{y}^* = \left[\frac{\pi\sqrt{q_D^*}}{4\cos\alpha}\right] \cdot (0.403)^{\left(\frac{q_D^*}{0.4\sin^2\alpha}\right)^{-0.55}} \qquad for \quad q_D^* \geq 0.4\sin^2\alpha \qquad (2.44)$$

where

y^* = y / L, nondimensional depth of saturation above liner

q_D^* = q_D / K_D, nondimensional lateral drainage rate

This two-part function is continuous and smooth. The equations can be solved by iterations.

2.6 Unsaturated Hydraulic Conductivity

Knowledge of hydraulic properties, expressing water pressure head, ψ(cm), as a function of volumetric water content, θ(cm^3 cm^{-3}) and hydraulic conductivity, K(cm/sec) as a function of θ, is of prime importance in many field studies dealing with water transport in the unsaturated zone. The many relations proposed in the literature, can be divided into four groups based on their dependent variables (Fuentes et al., 1992):

1. $\theta(\psi)$ (e.g. Brooks and Corey, 1964; van Genuchten, 1980; Haverkamp and Parlange, 1986);
2. $K(\theta)$ (e.g. Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980; Broadbridge and White, 1988);
3. $K(\psi)$ (e.g. Gardner, 1958); and
4. $D(\theta)$ (e.g. Gardner and Mayhugh, 1958).

The solution of Richard's equation requires only two functional relations, but the number of fitting parameters involved can be of the order of four to five depending on the relation chosen. Most parameters are pure fitting parameters without any physical meaning. Some of the most frequently used expressions are considered and are discussed in the following paragraphs.

Gardner (1958) proposed a relation between K and ψ of the form:

$$K(h) = K_s e^{\alpha \psi} \qquad with \quad \alpha > 0 \tag{2.45}$$

where α is a constant depending on soil type and the above equation is only applicable for value greater than zero.

Brooks and Corey (1964) assumed that:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_b}{\psi}\right)^{\lambda} \qquad (2.46)$$

where ψ_b is a parameter commonly termed the 'air entry or bubbling pressure' and λ is a positive soil index, being small for clay soils and large for sandy soils.

Clapp and Hornberger (1978) employed an exponential relation of the form:

$$\psi = \psi_s \left(\frac{\theta}{\theta_s}\right)^{-b} \qquad (2.47)$$

where ψ_s is the saturation suction and b is a constant depending on the soil type.

van Genuchten (1980) suggested a relationship for θ-ψ of the form:

$$\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) = \left[1 + (a\,\psi)^n\right]^{-m} \qquad (2.48)$$

where a, n, and m (=1-1/n) are empirical constants.

Irmay (1954) presented a model based on the development of Kozeny's theory, which considers the hydraulic conductivity as a power function of the effective saturation. He modelled the porous matrix by a cubic arrangement of spheres and assumed that the resistance to flow offered by the matrix is proportional to the solid-liquid interfacial area. This led to the equation:

$$K = K_s \left(\frac{\theta - \theta_f}{\theta_s - \theta_f}\right)^n \qquad (2.49)$$

where:

n = empirical constant

θ_f = field capacity moisture content [vol/vol]

θ_s = saturated moisture content [vol/vol]

K_s = saturated hydraulic conductivity [L/T]

For the hydraulic conductivity function, Brooks and Corey (1964) proposed:

$$K(\theta) = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{3+2/\lambda} \qquad for \quad h < h_{cr} \tag{2.50}$$

and

$$K(\theta) = K_s \qquad for \quad h_{cr} \le h \le 0 \tag{2.51}$$

Campbell (1974) suggested the following expression for hydraulic conductivity:

$$K(\theta) = K_s \left(\frac{\theta}{\theta_s} \right)^{2b+3} \tag{2.52}$$

where b is an empirical coefficient related to soil texture.

van Genuchten (1980) suggested the following equation for K-θ

$$K(\theta) = K_s S_e^{1/2} \left[1 - (1 - S_e^{1/m})^m \right]^2 \tag{2.53}$$

where

S_e = the effective saturation = $(\theta - \theta_r) / (\theta_s - \theta_r)$

n, m (=1-1/n) are empirical parameters.

Alessi et al. (1992) evaluate the effect of five different power-functions on infiltration using Richard's equation. No conclusive statement is made by them. However, the variability among these functions show that van Genuchten has the greatest utility in numerical modelling studies. Also Fuentes et al. (1992) carried out a comparison of eight different K-θ models mainly focusing on their fitting parameters. They concluded that Brooks and Corey's equation is a best choice having less parameters and can yield satisfactory results for infiltration and drainage.

2.7 Moisture Capacities of Soils

The soil water storage or content used throughout this thesis is on a per volume basis, that is, volume of water per total soil volume. All water occurring below the soil surface and above the water table is referred as soil water. In the soil water phase, the relative quantities of air and water will vary from time-to-time as a result of; recharge from infiltration, percolation to groundwater, uptake of water by plants, evaporation from the soil, etc. Immediately following a period of prolonged rainfall and subsequent infiltration, the upper soil layers would be expected to have a moisture content approaching the saturated moisture content (θ_s) for the soil, i.e. all voids will be filled with water. If the soil system is thereafter allowed to drain freely, with no further inputs of moisture, it might intuitively be thought that drainage will continue until soil reaches a moisture condition called field capacity (θ_f). Although the moisture content of a soil cannot be reduced below field capacity through natural drainage process, additional moisture may be extracted by plant uptake or by evaporation. This lower limit of moisture whereby no further loss is possible is called wilting point (θ_w).

Rawls et al. (1982) reported mean values for total porosity, residual volumetric water content, bubbling pressure, and pore-size distribution index, for the major US Department of Agriculture (USDA) soil texture classes. These values were compiled from 1,323 soils with about 5,350 horizons (or layers) from 32 states. The geometric mean of the bubbling pressure and pore-size distribution index and the arithmetic mean of total porosity and residual volumetric water content for each soil texture class were substituted into Equation 2.46 to calculate the field capacity (volumetric water content at a capillary pressure of 1/3 bar) and wilting point (volumetric water content at a capillary pressure of 15 bars) of each soil texture class. Rawls et al. (1982) also reported saturated hydraulic conductivity values for each major USDA uncompacted soil texture class. These values were derived from the results of numerous experiments and compared with similar data sets. Default characteristics for the coarse and fine sands (Co and F) were developed by interpolating between Rawls' data.

Freeze and Cherry (1979) reported that typical consolidated clay total porosities range from 0.40 to 0.70. Rawls' sandy clay, silty clay, and clay had total porosities of 0.43, 0.48, and 0.47, respectively. Therefore, Rawls' loam and clay soils data are considered to represent conditions typical of minimal densification efforts or low-density soils. Default characteristics for Rawls et al. (1982) low-density soil layers are summarized in Table 2.2.

Table 2.2. Default Low Density Soil Characteristics (Rawls et al. 1982).

Soil Texture Class		Total Porosity vol/vol	Field Capacity vol/vol	Wilting Point vol/vol	Saturated Hydraulic Conductivity cm/sec
No	USDA				
1	G	0.397	0.032	0.013	$2.0\text{x}10^{-1}$
2	CoS	0.417	0.045	0.018	$1.0\text{x}10^{-2}$
3	S	0.437	0.062	0.024	$5.8\text{x}10^{-3}$
4	FS	0.457	0.083	0.033	$3.1\text{x}10^{-3}$
5	LS	0.437	0.105	0.047	$1.7\text{x}10^{-3}$
6	LFS	0.457	0.131	0.058	$1.0\text{x}10^{-3}$
7	SL	0.453	0.190	0.085	$7.2\text{x}10^{-4}$
8	FSL	0.473	0.222	0.104	$5.2\text{x}10^{-4}$
9	L	0.463	0.232	0.116	$3.7\text{x}10^{-4}$
10	SiL	0.501	0.284	0.135	$1.9\text{x}10^{-4}$
11	SCL	0.398	0.244	0.136	$1.2\text{x}10^{-4}$
12	CL	0.464	0.310	0.187	$6.4\text{x}10^{-5}$
13	SiCL	0.471	0.342	0.210	$4.2\text{x}10^{-5}$
14	SC	0.430	0.321	0.221	$3.3\text{x}10^{-5}$
15	SiC	0.479	0.371	0.251	$2.5\text{x}10^{-5}$
16	C	0.475	0.378	0.251	$2.5\text{x}10^{-5}$

G (Gravel), S (Sand), Si (Silt), C (Clay), L (Loam), Co (Coarse), F (Fine)

2.8 Concluding Remarks

This chapter has outlined investigation of hydrological models which represent land phase processes both surface and subsurface, in particular infiltration, runoff, and percolation. Other individual processes were detailed including overland flow, unsaturated flow, saturated flow and subsurface lateral flow. This study reveals that considerable work has been done in this area. All the mentioned models have been previously developed and validated. No model was found suitable to represent completely the landfill hydrological processes. Therefore, individual processes were selected based on the selection criteria, which were outlined at the start of the chapter.

A daily time step for simulation was selected because firstly the precipitation and potential evapotranspiration data are available on a daily basis and secondly, the moisture changes inside the landfill are not sensitive to hourly time steps and are more sensitive to monthly time steps. The most appropriate models have been selected as:

⋆ **Infiltration :**

The SCS method (USDA, 1972) is selected for the calculation of infiltration because it is simple to use, requires less parameters and is computationally efficient. Moreover, this method is successfully adopted in most of the leachate production models, which will be discussed in Chapter 4.

⋆ Soil Moisture Storage in Landfill Cover :

The CREAMS model (Knisel, 1980) hydrology option 1 has been adopted in some of previous models such as HELP (Schroeder, 1984) and SLAMS (Dickson, 1987). The model approach is consistent with the landfill capping system including soil cover and clay liners having a certain slope. This model is selected and will be modified by including Brooks and Corey's model (1964) for drainage out from a soil layer.

⋆ Vertical Percolation and Lateral Drainage from soil cover:

The vertical percolation of water from top clay liner can be modelled by using Darcy's law, while the lateral drainage from soil cover is to be modelled by using Boussinesq's theory although the equation is nonlinear describing steady-state drainage on a sloping low-permeability liner. The approximate solution as proposed by McEnroe and Schroeder (1989) is to be used in this study.

Chapter 3

LANDFILL TECHNOLOGY AND LEACHATE MANAGEMENT

Landfills are a common and effective method for the disposal of waste. Landfill technology has evolved from the open, burning dump to highly engineered sites designed to minimize the impact of contaminants in the waste on the adjacent environment. Improved licensing powers provided for in the Environmental Protection Act 1990 will promote a stricter control and more uniform application of standards (NWWDO, 1991). Technical developments and increasing pressures for environmental protection have significantly raised the profile of leachate management as an important component in landfill development. Improvements in landfill engineering have been aimed primarily at reducing leachate production, collecting and treating leachate prior to discharge. Whether leachate is to be collected and treated or is allowed to discharge to the soil, it is essential to have estimates of leachate flow and strength and the variation of these with time as the site develops, and post-closure. This chapter addresses the current design practices used in landfilling as mentioned in DoE (1986), landfill components and leachate management.

3.1 Current Landfill Design Practices

The basic ideas in designing and setting various standards for waste landfills are threefold;

1. to protect and prevent ground and surface water in the immediate environment of a site from pollution and contamination,
2. to encourage the filled waste to decompose and settle down for assimilation

and stability, and

3. to prevent the site from causing hygienic and sanitary problems.

Landfill sites fall into two broad classes in terms of the extent to which leachate is contained within the landfill (Senior, 1990). These two classes are "containment sites", and "attenuate and disperse sites".

3.1.1 Containment sites

Waste is isolated from the environment for a considerable time (decades or hundreds of years) to prevent pollution of surrounding land and waters and to reduce groundwater ingress. This is achieved by the provision of impermeable or semi-impermeable barriers of natural or synthetic material. The lining material can be clay or shale, bentonite with polymer additives or a synthetic lining material such as high density polyethylene or butyl rubber. In those sites, attenuation processes will take place almost entirely within the body of the waste. These processes will reduce the strength of the leachate. Low permeability caps need to be employed at these sites, as well as leachate extraction systems for subsequent treatment and discharge. Leachate monitoring is needed and may be required to function for a considerable amount of time after landfill operations have ceased. Ground and surface water quality monitoring can be achieved by means of suitability located boreholes and selected sampling of watercourses (DoE, 1986).

3.1.2 Attenuate and disperse sites

Such sites allow the slow release of leachate from landfill and rely on various physico-chemical and microbiological (processes) operating within the body of the waste, and in the underlying strata, to ameliorate the polluting characteristics of the leachate. Here the slow leachate migration with dilution and dispersion help to decrease the effect of leachate on water courses (DoE, 1986; Senior, 1990).

3.2 Landfill Design

Currently, there are three variations in landfilling techniques:

1. Trench Method - this involves the excavation of a trench (which may be very large) into which waste is deposited. The excavated material is then used as cover. This technique is a variation of the cell method explained below.

2. Area Method - waste may be deposited in layers and to form terraces over the available area. However, with this type of operation, excessive leachate generation may occur unless high waste inputs are maintained thereby providing adequate absorptive capacity to account for rainfall. This method has been used widely in the UK but is no longer favoured since operational control may be difficult.

3. Cell Method - this method involves the deposition of waste within preconstructed bunded areas. It is now the preferred method since it encourages the concept of progressive filling and restoration. It is a method which is beginning to have widespread application and is accordingly described in more detail below.

In the cell method, the area intended for landfilling is broken down into manageable cells which are subsequently divided into layers, filled preferably on a daily basis. The sequence of landfilling will depend on many factors such as topography, traffic flow, rainfall and method of deposition. At a shallow site it is considered preferable to place one daily layer on top of another so that the cell is brought up to final level before moving onto the next cell therefore assuring progressive restoration. However, in a deep site having a relatively small area, such procedures may not be practicable and it may therefore be necessary to operate a cellular system of landfilling moving progressively across the site before moving onto the next lift. At the end of each working day, the completed layer within a cell is covered with an impermeable inert material such as clay. This minimises precipitation entering the cell either overnight or when filling of another cell is in operation. Operating a cellular method of filling enables waste to be deposited in a tidy manner since the bunds serve to both conceal the tipping operation and at the same time trap much of the litter which may be generated. When a cell is brought up to its final level, it can then be capped minimising moisture entering the cell over the rest of its life.

The size of the cells should be influenced by:

1. Rainfall,
2. Absorptive capacity of the solid waste,
3. Daily input of waste,
4. Number of incoming vehicles; and
5. Sufficient space for safe turn-round of vehicles.

By careful design and operational management it is possible to ensure that the moisture absorptive capacity of deposited waste is not exceeded and thus minimise the generation of leachate.

Cell walls should be at least 2-3 m higher than the height of the daily lift. Initially cell walls may be formed by pushing up material from the base of the site. Subsequently it will be necessary to raise the walls as filling proceeds. Ideally, low permeability material should be used in order to prevent leachate seepage through the walls which could contaminate clean surface water. Where there is a risk of groundwater ingress, low permeability cell walls will also reduce hydraulic continuity across the site. A disadvantage is that cells of low permeability material may encourage the build up of leachate at different heights within the site.

3.3 Modes of Operation and Site Management

The type, shape and depth of any landfill affect leachate production. In general deeper landfills will absorb more water before leaching occurs, but take a longer time to decompose, and so produce leachate over a longer period of time than shallower fills of the same surface area and conditions.

Preferably a cellular type of construction should be used. Cells have to be engineered to a size which limits the surface area receiving precipitation. This size is matched to the seasonal distribution of rainfall in order that waste moisture levels do not build up to saturation levels before the in filling period has been completed (Buchanan and Fleming, 1990).

Experimental data suggest that infiltration rates through typical daily cover range from 20% in summer month to 100% during winter which reflects the importance of limiting operational areas (Senior, 1990).

The quantity of leachate collected in a leachate collection system can be expected to follow some basic trends over the life time of the landfill;

- Prior to and during placement of the first lift of waste, leachate generation may closely correspond to precipitation, since the precipitation falls directly on the leachate collection system.

- As more waste is added, and collection system is covered, leachate generation drops to zero. Waste added will absorb most precipitation.

- As the landfill reaches field capacity an extended period of leaching contaminants commences.

- At some point, steady-state conditions may be reached where a correlation can be found between precipitation and leachate generation with a lag in time, this condition may continue until the landfill is closed by a final cover.

- After the landfill is closed with a final cover, the leachate generated will be reduced greatly. This will obviously depend on the efficiency of the cover in eliminating water infiltration to the waste. It should be noted that there is a period in which the leachate no longer represents a pollution threat (Bass, 1986).

3.4 Landfill Components

Typical landfill sites consist of a number of cells, each having its own geometry and configuration. Depending on the design practice being employed, a leachate drainage system is applied at the bottom of each cell or it is sealed only using low permeability lining material. On the top of each cell, a capping system is provided to minimize the infiltration of water. It mainly consists of a soil layer on the top of a clay barrier. Between the capping and bottom drainage system, a series of waste lifts together with an intermediate soil layer are deposited.

3.4.1 Landfill Lining and Capping systems

The principle aim of lining a landfill site and providing adequate cover material over the deposited waste is to ensure that any leachate or gas generated as a result of the degeneration of the waste is provided from polluting the surrounding environment. Landfill lining and capping systems are also designed to ensure that infiltrating rain or groundwater is prevented from coming into contact with the deposited waste.

The criteria for the design of landfill lining and capping systems depend upon:

1. Local legislation
2. The nature of the waste being deposited
3. The availability of material to line and/or cap a site
4. Estimated incurred costs

The capping should be laid to adequate gradients to promote runoff. Gradients should take account of settlement as the waste continues to degrade. Recommended gradients lie between 1 in 30 and 1 in 6 (Department of the Environment, 1986)

Capping should incorporate a low permeability layer which, in the case of clay, should normally have a hydraulic conductivity of not greater than 1×10^{-9} m/sec and a thickness of not less than 1 m (NWWDO, 1991). Sub-soil and topsoil cover should not be less than 750 mm in thickness in order to protect the low permeability barrier. It is essential that clay barriers are also covered immediately after placement to prevent them drying and cracking, otherwise wetting of the surface may be necessary as an interim measure. Under-drainage of the subsoil layer will further minimise infiltration through the cap and prevent waterlogging of the surface.

3.4.2 Leachate Collection and Drainage System

The leachate collection system is designed to facilitate leachate flow over the liner and out of the system. Leachate flows out of the waste and through the drainage layer to a collection point (sump) where it is pumped out of the containment area for treatment. Layout of the system should provide alternative paths for leachate to flow to the collection point, should allow for access to the drainage layer and collection sump for inspection and maintenance, and should allow for minor subsidence of the drainage layer.

The criteria for determining the required leachate head level control in a site will depend on the particular hydraulic relationships of the locality, the sensitivity of the site location and the type of liner being used. Nil or minimal leachate heads pose the least immediate environmental risk.

3.5 Landfill Bottom Liner Hydraulics

The important component in the design of solid waste landfills is the bottom collection system. A typical landfill bottom liner consists of a series of contiguous, alternating-direction sloping layers, constructed from material of low permeability (compacted clay), and overlaid by a layer of higher permeability (gravel or sand). The liner is equipped with perforated drainage pipes, along its lines of lowest elevation, which facilitate collection of the leachate. In recent applications, the use of synthetic membranes underneath the clay layer is becoming common (McEnroe, 1993).

An understanding of the hydraulics of liners is essential in the correct analysis and design of such systems. In a very general sense, the problem of leachate drainage and leakage, over and through a liner, can be tackled in a manner similar to the classic infiltration problem, i.e. overland flow (corresponding to the flow in the drainage layer), coupled with flow through a partially saturated porous medium (corresponding to leakage through the clay layer).

3.5.1 Steady State Models

The simplest liner configuration consists of a horizontal clay layer, overlaid by a drainage layer. Drainage pipes are located transversely for leachate collection (Figure 3.1). For a constant leachate supply to the drainage layer and no leakage through the liner, a series of steady state mounds will eventually be formed and the input rate will equal the drainage rate. The maximum head of the steady state mound is given by (Harr, 1962):

$$h_m = \frac{L}{2}\sqrt{\frac{N_l}{K_d}} \tag{3.1}$$

where:

h_m = leachate head above liner [cm]

L = distance between adjacent drains [cm]

N_l = rate of leachate input onto the drainage layer [cm/day]

K_d = horizontal hydraulic conductivity of the drainage layer [cm/day]

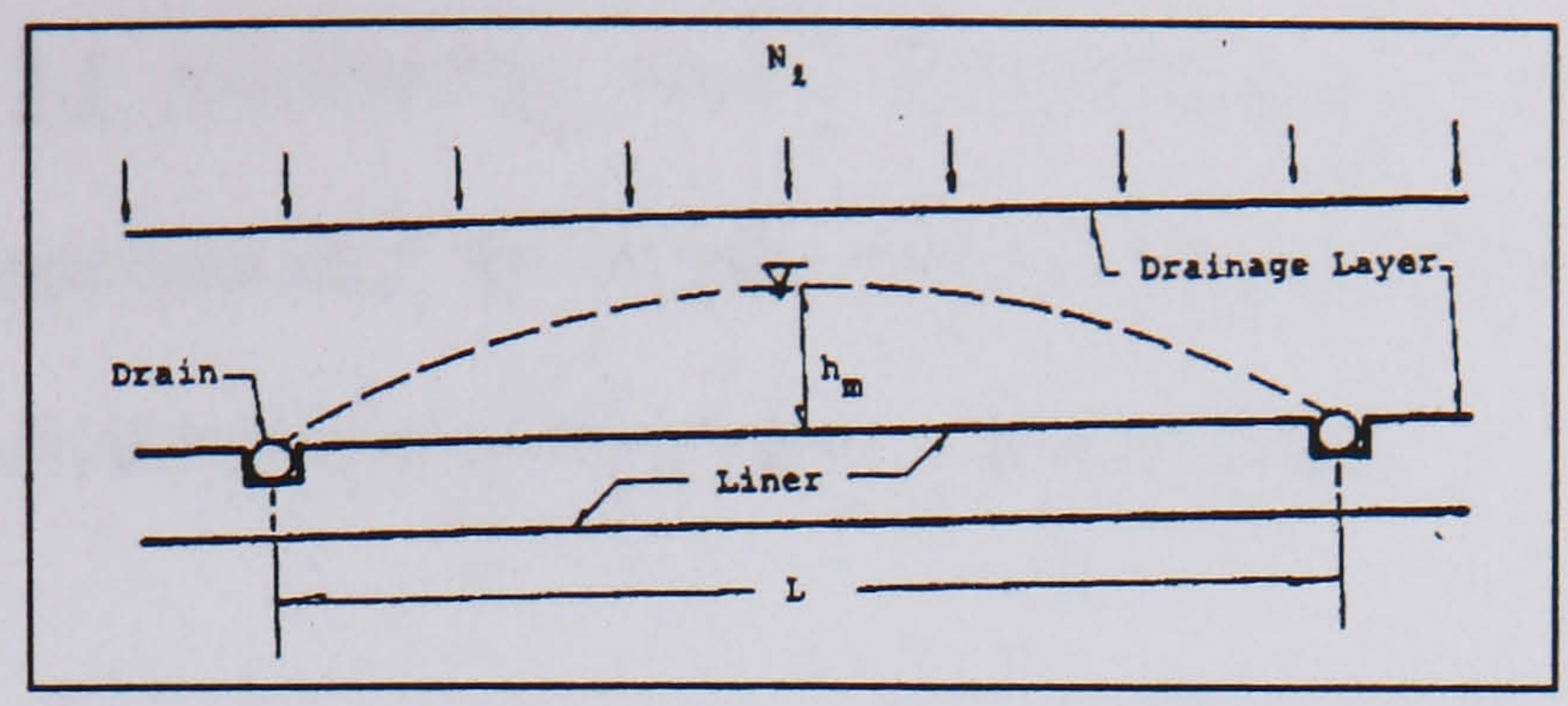


Figure 3.1. Horizontal Clay Liner and Collection System.

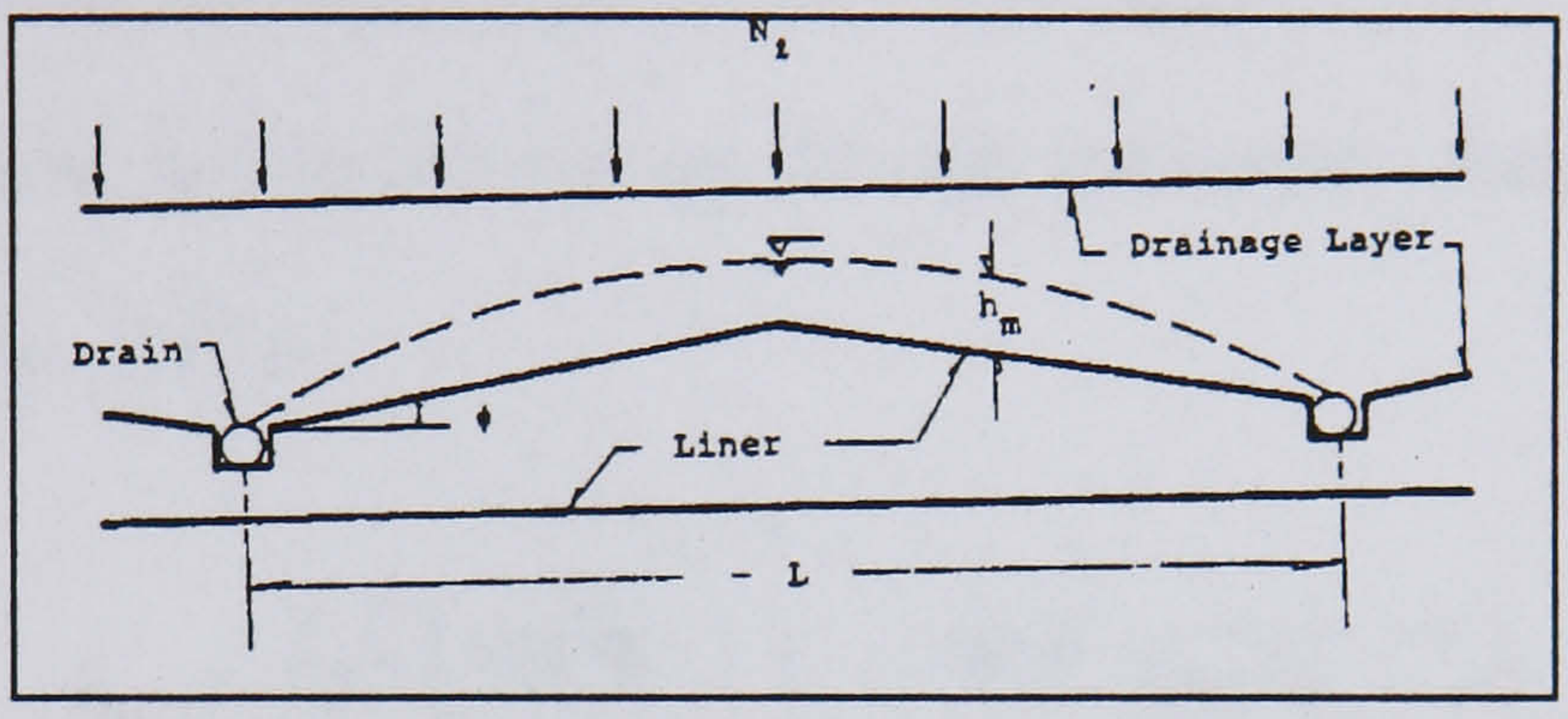


Figure 3.2. Sloping Clay Liner and Collection System.

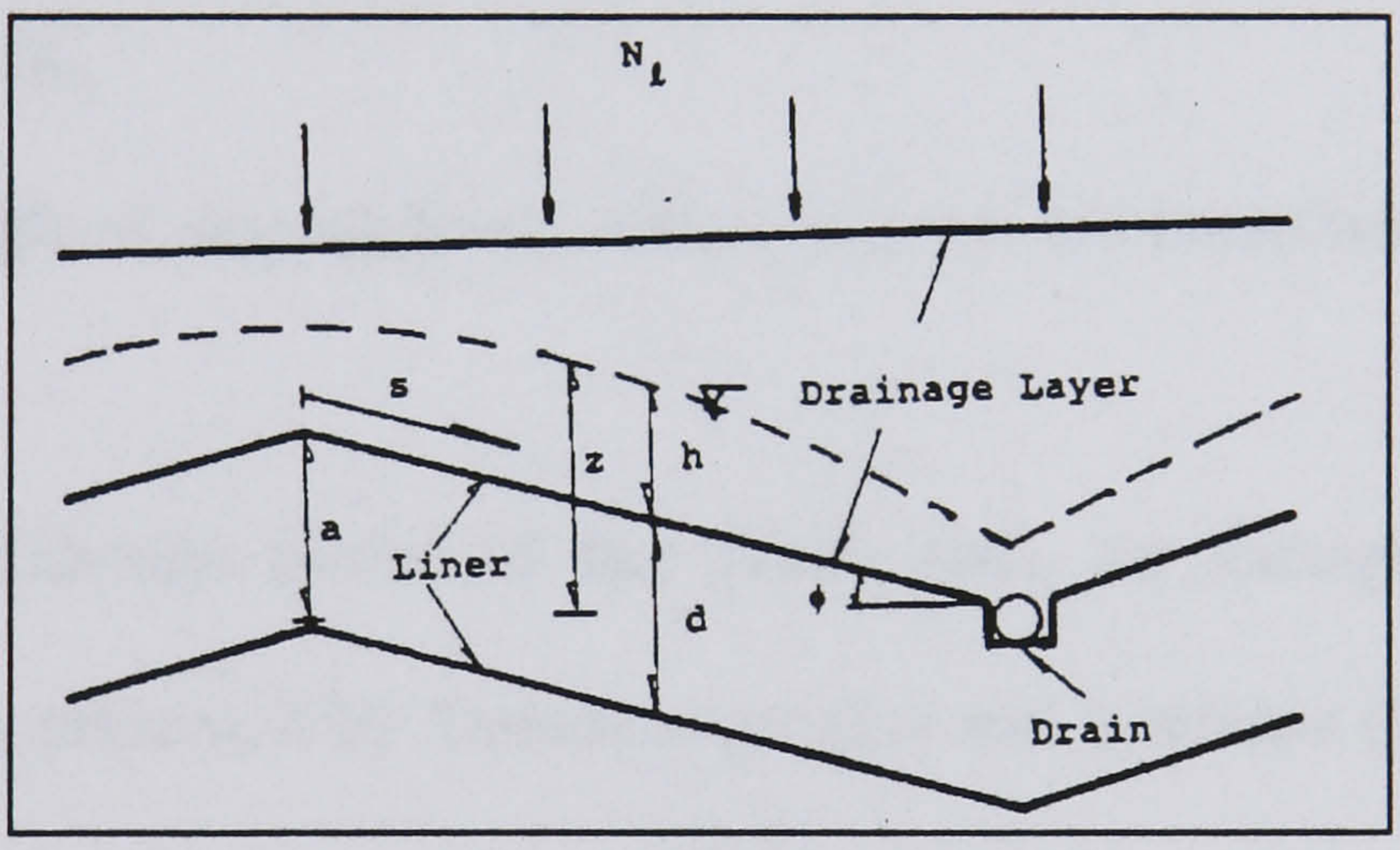


Figure 3.3. Longitudinal Section of Sloping Liner and Leachate Collection System.

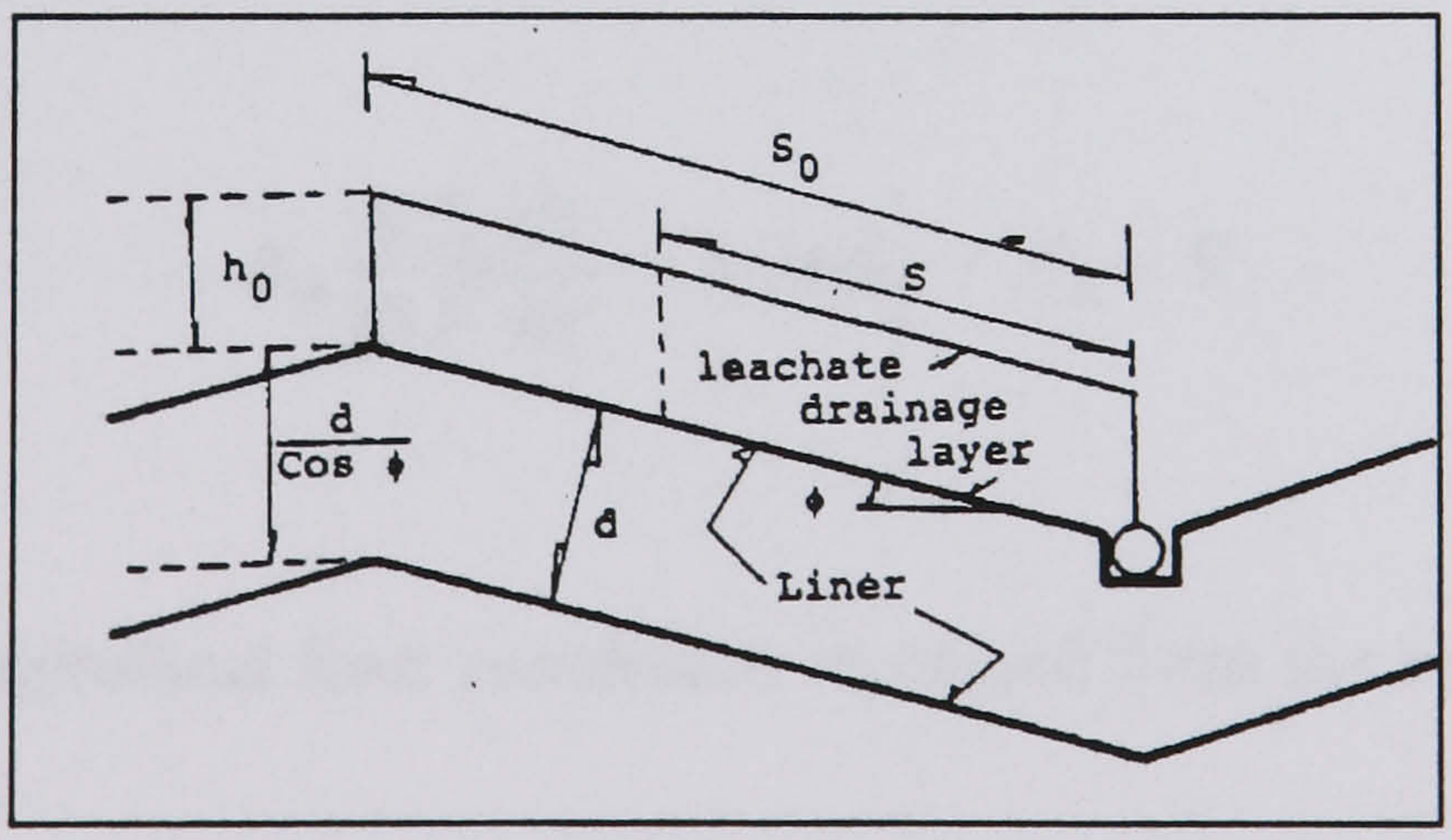


Figure 3.4. Liner Geometry and Hydraulic Configuration for Quasi-Steady State Model.

Equation 3.1 provides the means for estimation of the drainage layer thickness; it is important that the mound does not extend into the landfill refuse where additional dissolution of contaminants will take place.

Nevertheless, the afore described liner configuration is impractical; in most situations the sloping geometry depicted in Figure 3.2 is used. For a steady state mound over the liner, and for no leakage through the bottom, the maximum head in this case is (Moore, 1983):

$$h_m = \frac{L\sqrt{c}}{2}\left(\frac{\tan^2\phi}{c} + 1 - \frac{\tan\phi}{c}\sqrt{\tan^2\phi + c}\right) \tag{3.2}$$

where:

c = N_l / K_d

ϕ = angle of sloping liner, measured from the horizontal (degrees)

A more elaborate model of the steady state, no leakage mound over an inclined liner was presented by Demetracopoulos and Korfiatis (1984). It is based on the liquid mass balance over an inclined liner (Figure 3.3) and its governing equation is:

$$K_d \frac{d}{ds}\left(h\frac{dh}{ds} - h\sin\phi\right) + N_l = 0 \tag{3.3}$$

in which

s = longitudinal liner coordinate, measured from the upstream end.

The boundary conditions of the problem have been expressed as:

$$\begin{aligned} \frac{dh}{ds} &= \sin\phi \qquad at \quad s = 0 \\ h &= h_o \qquad at \quad s = s_o \end{aligned} \tag{3.4}$$

where:

s_o = length of liner (L)

h_o = head at drainage pipe (L)

The solution of Equation 3.3 is given by

$$s = s_o\, e^{\left(-\frac{1}{2}\ln\frac{R}{R_o} - \frac{\sin\phi}{2}(Q - Q_o)\right)} \tag{3.5}$$

where:

$R = V^2 - V\sin\phi + \alpha$

$V = h/s$ and $\alpha = N_l/K_d$

$$Q = \begin{cases} \dfrac{-2}{\sqrt{\sin^2\phi - 4\alpha}}\,\mathrm{arc\,tanh}\left(\dfrac{-\sin\phi + 2V}{\sqrt{\sin^2\phi - 4\alpha}}\right) & for\ \Delta < 0 \\ \dfrac{-2}{-\sin\phi + 2V} & for\ \Delta = 0 \\ \dfrac{2}{\sqrt{4\alpha - \sin^2\phi}}\,\mathrm{arc\,tan}\left(\dfrac{-\sin\phi + 2V}{\sqrt{4\alpha - \sin^2\phi}}\right) & for\ \Delta > 0 \end{cases} \tag{3.6}$$

$$\Delta = 4\alpha - \sin^2\phi$$

The quantities R_o and Q_o are obtained from above equations, by using $V_o = h_o/s_o$ instead of $V = h/s$.

3.5.2 Quasi-Steady Model

A quasi-steady state model has been presented by Demetracopoulos et al. (1984). The model is based on a steady state model developed by Wong (1977).

The analysis is based on the hypothesis that the liquid moves over an inclined liner as a slab, with a free surface profile parallel to the liner surface. It is also assumed that the liner is at 100% saturation. The following equations are used to compute the liquid balance:

$$V_d = V_o \left[\frac{1}{k} \left(\exp(-\frac{kt}{t_1}) - 1 \right) \left(1 + \frac{d}{h_o} \right) + \frac{d}{h_o}\frac{t}{t_1} \right] \qquad (3.7)$$

$$V_l = V_o \left[(1 + \frac{d}{h_o}) \frac{1}{k} \right] \left[\exp(-\frac{kt}{t_1})(-k + k\frac{t}{t_1} + 1) + (k-1) \right] \qquad (3.8)$$

$$\frac{h}{h_o} = \left(1 + \frac{d}{h_o \cos\phi} \right) \exp(-\frac{kt}{t_1}) - \frac{d}{h_o \cos\phi} \qquad for\ 0 < t < t_1 \qquad (3.9)$$

where:

h = liquid depth over liner of time t

h_o, s_o = initial dimensions of saturated volume

V_d = Volume drained into the drainage pipe at time t

V_l = Volume leaked through the liner at time t

t_1 = $s_o n_e/(K_d \sin \phi)$

k = $(s_o/d)(K_l/K_d) \cot \phi$

K_d = hydraulic conductivity of drainage layer

K_l = hydraulic conductivity of clay liner

n_e = effective porosity of drainage layer

ϕ = inclination angle of the liner

V_o = $h_o\ s_o$ = initial saturated volume per unit width.

With the accretion rate onto the bottom collection system known at relatively small time increments from hydrologic computations, Equations 3.7 and 3.8 are solved for each time step. At the end of a time increment the liquid present over the liner is added to the liquid supplied during the next time increment and is redistributed over the whole area of the liner. A new head is computed via Equation 3.9, and Equations 3.7 and 3.8 are solved again. This procedure provides a quasi-steady simulation of liquid movement over and through the liner and computes the head variations over the liner surface.

3.5.3 Transient Model

A more detailed description of the hydraulics of a bottom collection system is obtained by performing a liquid balance on a longitudinally differential control volume (Figure 3.2). From the mass conservation principle, the sum of all flow rates into the control volume must equal the rate of volume change in the control volume. This yields (Korfiatis and Demetracopoulos, 1986):

$$K_d \frac{\partial}{\partial s}\left(h \frac{\partial h}{\partial s} - h \sin\phi\right) + N_l - K_l\left(\frac{h}{d} + 1\right) = n_e \frac{\partial h}{\partial t} \qquad (3.10)$$

subject to the following initial and boundary conditions:

$$\begin{aligned} h(s,0) &= h_o(s) && \\ \frac{\partial h}{\partial s} &= \sin\phi && at \quad s = 0 \\ \frac{\partial h}{\partial s} &= f_{ds} && at \quad s = s_o \end{aligned} \qquad (3.11)$$

where:

K_l = saturated hydraulic conductivity of the liner

d = thickness of the clay liner

n_e = effective porosity of the drainage layer

t = time

h_o = head over liner at time zero

s_o = length of liner element

f_{de} = downstream head gradient

The behaviour of the models was compared with experimental data from a laboratory liner model (Korfiatis, et al., 1986). The liner was 152.4 cm long, 30.5 cm wide and had a thickness of 2.54 cm. It was placed under a 7.6 cm gravel layer at an angle of 3°. The transient model predicts rates slightly better than the other two models.

Six primary factors affect collection system performance under steady-state conditions: the rate at which leachate drains from the waste layer into the drain layer (termed the impingement rate); the distance between the parallel drains; the saturated hydraulic conductivity of the drain layer; and the hydraulic conductivity, slope, and thickness of the liner.

3.5.4 Maximum Saturated Depth over Landfill Liner

Several different methods for estimating the steady-state maximum saturated depth over a landfill liner have been proposed. McEnroe (1989) presents an analytical solution for the saturated depth at any point along the liner. However, the determination of the maximum saturated depth from this general solution can be tedious. Furthermore, because this solution is based on the standard Dupuit assumptions for unconfined seepage, it underestimates saturated depths for liner slopes greater than about 10% (6°).

An explicit formula for the maximum saturated depth over a sloping liner appears in several technical guidance documents of the U.S. Environmental Protection Agency (USEPA) (Moore 1983). This formula is

$$y_{\max} = L\left(\frac{r}{K}\right)^{½}\left[\frac{KS^2}{r} + 1 - \frac{KS}{r}\left(S^2 + \frac{r}{K}\right)^{½}\right] \tag{3.12}$$

where:

$y_{\max}$ = maximum saturated depth over the liner

L = maximum distance of flow

r = rate of vertical inflow to the drainage layer per unit horizontal area

K = hydraulic conductivity of the drainage layer

S = dimensionless slope of the liner.

This formula was first presented by Moore (1983) without derivation or explanation of its origin or limitations.

Other investigators have published solutions for closely related problems with different boundary conditions. Yates et al. (1985) presented a general analytical solution for steady drainage over an impervious sloping barrier with recharge, based on the standard Dupuit assumptions. McEnroe and Schroeder (1988) used numerical methods to investigate steady drainage over a slightly pervious sloping barrier. Childs (1971), Towner (1975), and McBean et al. (1980) all presented solutions for steady drainage over a sloping barrier with drains at both the upper and lower ends. The latter drain configuration is not typical for landfill drainage systems.

McEnroe (1993) presented a set of explicit formulas for the steady-state maximum saturated depth over an impervious sloping barrier. He derived these formulas analytically from the equation of continuity and an extended form of the Dupuit discharge formula for unconfined seepage.

$$y_{\max} = \begin{cases} \left(R - Y_L + Y_L^2\right)^{\frac{1}{2}} \left[\dfrac{(1-A-2R)(1+A-2Y_L)}{(1+A-2R)(1-A-2Y_L)}\right]^{\frac{1}{2}A} & \textit{for} \quad R < \dfrac{1}{4} \\ \dfrac{R(1-2Y_L)}{1-2R} \exp\left[\dfrac{2(Y_L-R)}{(1-2Y_L)(1-2R)}\right] & \textit{for} \quad R = \dfrac{1}{4} \\ \left(R - Y_L + Y_L^2\right)^{\frac{1}{2}} \exp\left[\dfrac{1}{B}\tan^{-1}\left(\dfrac{2Y_L-1}{B}\right) - \dfrac{1}{B}\left(\dfrac{2R-1}{B}\right)\right] & \textit{for} \quad R > \dfrac{1}{4} \end{cases} \qquad (3.13)$$

where:

y_{max} = maximum saturation depth (L)

Y_L = drainage distance, measured horizontal (L)

R = $r/(K \sin^2\alpha)$

K = hydraulic conductivity of drainage layer (L/T)

r = vertical inflow per unit horizontal area ($L^3/T/L^2$)

S = slope of liner (=tanα)

A = $(1\text{-}4R)^{1/2}$

B = $(4R\text{-}1)^{1/2}$

The above equations are useful for the analysis and design of landfill covers and leachate-collection systems. These equations yield an estimate of the maximum saturated depth over the liner for a constant rate of inflow. This maximum saturated depth is a spatial maximum for steady-state conditions. If the rate of inflow is an estimate of the long-term average inflow rate, then the resulting maximum saturated depth should be considered a long-term average. Over the short term, both the rate of inflow and the maximum saturated depth may differ considerably from their long-term averages.

3.6 Leachate Management

Leachate needs to be controlled in a landfill for the following four principal reasons:

1. To prevent liquid levels rising to such an extent that they can spill over and cause uncontrolled pollution to ditches, drains, watercourses etc.
2. To reduce the potential for seepage out of the landfill through the sides or the base either by exploiting weaknesses in the liner or by flow through its matrix.
3. To minimise the chemical interaction between the leachate and the liner.
4. To influence the processes leading to the formation of landfill gas and chemical and biological stabilisation of the landfill.

In cases where the generation of leachate forms part of the site design, it is equally important to find out amount of leachate production so that adequate provision can be made for collection, removal and treatment.

3.6.1 Factors Affecting Leachate Production

Leachate generation in landfill is complex and depends on several independent factors. Figure 3.5 summarises a number of these factors (Lu et al., 1985). The quantity and quality of leachate depend on many factors, namely, amount, composition and density of refuse, landfill age, hydrology of the site, climate and

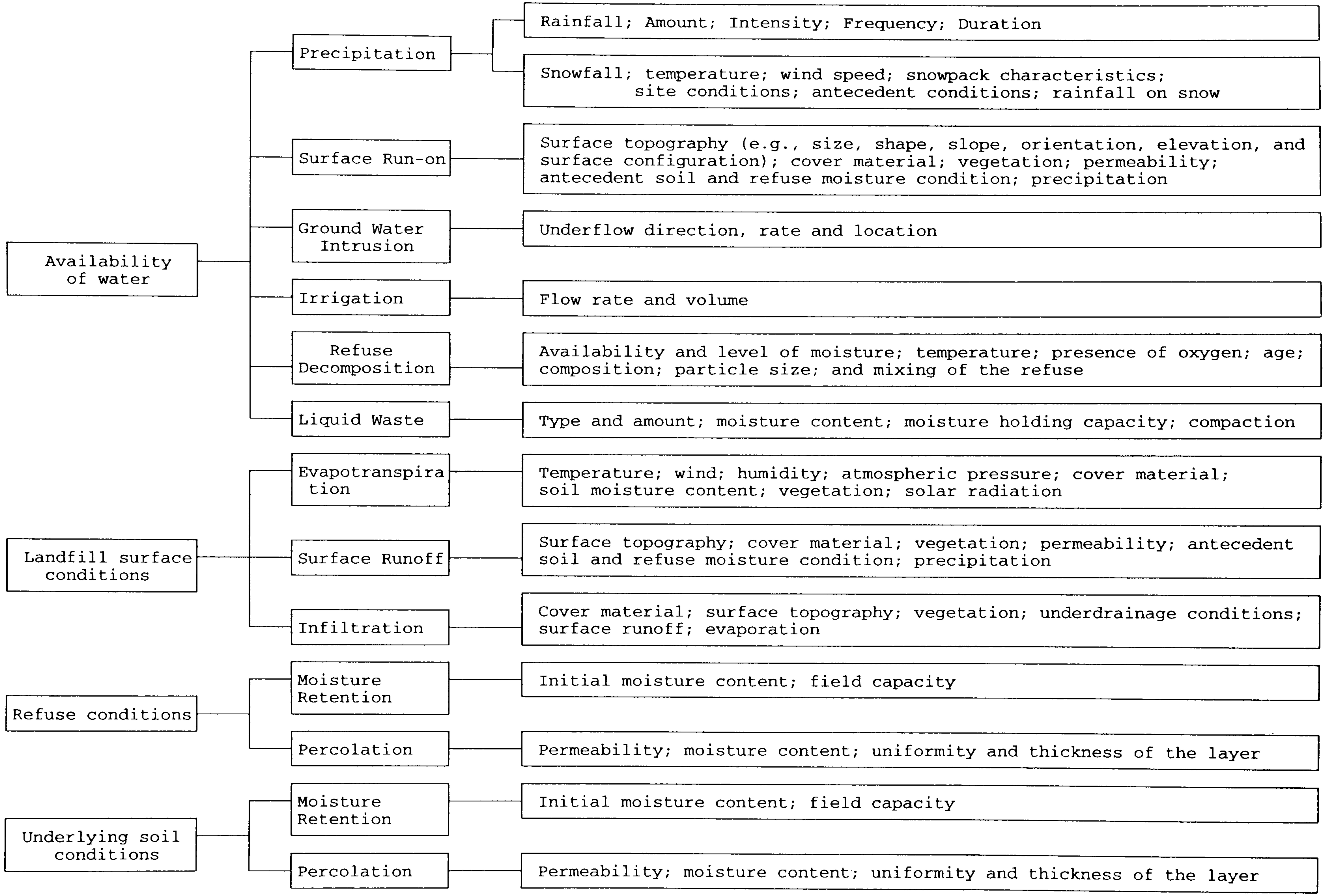


Figure 3.5. Factors affecting leachate volume generation (after Lu et al., 1985).

rainfall. The amount of leachate increases when sewage sludge is added to municipal solid waste (Navarro et al., 1988) or if wastes are baled (Kemper et al., 1984). This means that the way sanitary landfill is operated has an influence on the characteristics of leachate.

3.6.2 Time of First Appearance of Leachate

If no channelling effect occurs in the refuse, leachate will first appear when the soil cover and refuse reach field capacity. The time required for the first appearance of leachate can be obtained by using the moisture-routing calculation. The time of first appearance of leachate can also be estimated using graphics prepared by Fungaroli (1971).

The approximate time of leachate appearance can be estimated based on Oweis and Khera (1990):

$$t_1 = \frac{D\,(\theta_f - \theta_i)}{P} \tag{3.14}$$

where:

t_1 = the time of first appearance of leachate (months)

D = depth of refuse (L)

θ_f = the moisture content at field capacity (L^3/L^3)

θ_i = the placement moisture content (L^3/L^3)

P = the percolation (L)

As illustrated in the above equation, the leachate appearance time, t_1, is sensitive to the parameter (θ_f - θ_i). The composition of the refuse influences this parameter. If the refuse composition and its initial moisture content are known, the field capacity may be estimated.

Modern landfills are designed to be several feet above the groundwater. Surface run-on is prevented and the leachate produced by decomposition is usually relatively small (Lu et al., 1985). If the change in refuse storage volume is assumed to be zero, the leachate generated would be equal to the percolation in the soil cover. If this leachate is not collected and the landfill is founded on an impervious layer, then a leachate mound would develop.

Considering an effective drain only around the toe of the landfill and an impervious base, the leachate buildup h_l is estimated based on following equation (USEPA, 1983):

$$h_1 = \frac{L\ (\phi / K)^{0.5}}{2} \tag{3.15}$$

where:

L = the width of the landfill [L],

K = the hydraulic conductivity of refuse [L/T], and

ϕ = the porosity of refuse.

3.7 Landfill Settlement

Among the practical problems of utilizing landfill sites for development, settlement may be the most significant (Morris and Woods, 1990). Estimates of total settlement of a landfill range from 25% to 50% of the landfills initial thickness (Stearns, 1987). Settlement mechanisms in landfills are very complex and less understood than in coarse or fine-grained soils (Edil et al. 1990). This can be attributed in part to its inhomogeneous nature, large particle sizes, compression of refuse particles, and the loss of solids due to biodegradation. Settlement occurs in essentially three distinguishable stages: (1) initial compression; (2) primary compression; and (3) secondary compression (Morris and Woods, 1990).

Initial compression is settlement that occurs directly when an external load is applied to a landfill. Initial compression is generally associated with the immediate compaction of void space and particles due to a superimposed load (Tuma and Abdel-Hady, 1973). This type of settlement is analogous to the elastic compression that occurs in soils and is virtually instantaneous. Usual methods for calculation would require the measurement of a refuse modulus of elasticity and the settlement would be found using Bowles (1988) equation:

$$S_i = \frac{\Delta q \, H_o}{E_s} \tag{3.16}$$

where:

S_i = settlement due to initial compression (m)

H_o = initial height of refuse (m)

E_s = modulus of elasticity (kN/m^2)

Δq = stress increase in stratum (kN/m^2)

Primary compression is compaction due to the dissipation of gas from the void spaces (Gordon et al., 1986). In a completed landfill, settlement due to primary compression will occur rather quickly, usually within the first 30 days after load application (Gordon et al., 1986; Edil et al., 1990; Dodt et al., 1987).

Secondary compression is generally due to creep of the refuse skeleton and biological decay (Gordon et al., 1986). Settlement due to secondary compression can account for a major portion of the total landfill settlement and can take place over many years.

Additional settlement in landfill sites occurs because organic material decomposes and hollow containers collapse either as a result of subsequent degradation or simple mechanical loading. Settlement is most pronounced where the waste layer has been formed using a tracked machine and least where a steel-wheeled compactor has been used. Degrees of settlement have been recorded in a range from 10% to 50% (Edil et al., 1990). Settlement is only a problem where it is uneven. Uneven settlement tends to strain the cover material and may fracture it. This allows water, insects, vermin etc., to enter. If settlement is even no problems should arise, provided it is anticipated and incorporated in the design.

The settlement of a landfill stems from one or more of the following:

1. Settlement due to the reduction in void space and compression of loose

materials from self-weight of the waste and the weight of the cover materials.

2. Occasional movement of smaller particles in larger voids resulting from collapse of larger bodies, seepage, abrupt drop in the water table, shock wave or vibration. This type of movement may cause unexpected depressions on the surface.
3. Volume changes from biological decomposition and chemical reactions, which are accelerated at high moisture content, warmer temperature, poorer state of compaction and larger proportion of organic content.
4. Dissolution from percolating water and leachate.
5. Settlement of the soft compressible soils underlying the landfill.

3.7.1 Effect of Compaction

Compaction of waste materials increases their density and strength, and reduces their permeability. For heterogeneous materials, such as those found in a municipal landfill, reliable laboratory tests are difficult to design and conduct. Although field tests are expensive and time consuming, they yield more reliable data. Compaction has proved to be an effective means of reducing the volume of waste, increasing the life of disposal sites, and improving its engineering properties. For a given material there would be a range of values rather than a single curve.

Volume reductions of 2 - 17% have been reported from compaction. Excess pore pressures develop in saturated landfill materials from the weight of the roller, making it difficult to achieve any degree of compaction. Most of the reduction in volume occurs in five passes (Oweis and Khera, 1990).

If the refuse has an initial density between 0.3 and 0.6 tonnes per m^3, the settlement from physical causes can increase the density up to 0.8 tonnes per m^3. If, on compaction the initial density reaches 1.0 tonne per m^3, further settlement from physical causes is unlikely. However, settlements from 5 to 20% and even up to 30-35% can still be expected from biodegradation (Edil et al., 1990).

An increase in the compaction moisture content results in an increase in the waste permeability. This decrease is attributed to the material structure. Both the moisture content and the method of compaction affect the waste structure.

Charles et al. (1981) used dynamic compaction on a 15-year old and up to 6 m thick municipal landfill. A 15-tonne weight with a base area of 4 m^2 was dropped ten times at each location from heights up to 20 m. The primary grid spacing was 5 m. There were one or two additional tamping stages at grid points offset from the original grid with the maximum energy input of 2600 kNm/m^2. High excess pore pressures were observed in some instances of dynamic compaction. The average settlement was 0.5 m. Under identical embankment loads the immediate settlement of the untreated refuse was three times larger than that of the treated refuse. About 5 years later the long-term settlement of the treated section was about 35 mm.

Because of the substantial densification of refuse, dynamic compaction would be expected to reduce the rate of decomposition and secondary compression due to the reduction of the surface area. It appears that proper tamping could perhaps reduce the primary settlement by 70% and the secondary settlement by 5%. The dynamic compaction process introduces high excess pore water pressure.

At many landfill sites, waste densities of 0.7 to 0.8 t/m^3 are achieved, and at such densities it is likely that about 0.1 to 0.2 m^3 of added liquid per cubic metre can be absorbed before substantial leachate generation commences. However, at higher compaction densities, absorption values will fall. For example, at placement densities in excess of 1.0 tonne/m^3 the absorptive capacity may fall to as low as 0.02 to 0.03 m^3 liquid/m^3 (DoE, 1986).

The effect of overburden pressure will reduce the volume occupied by the waste, and hence settlement will occur. The decaying waste will also reduce in volume as leachate and gas is produced, therefore adding to the effect of settlement. The former may be easily calculated using the relationship between volume and density, or as a guide, the annual rate of settlement as described in the DoE Waste Management paper Number 26 (1986) indicates the rates as shown in Table 3.1.

Table 3.1. Annual Settlement Rate for Waste material (DoE, 1986).

Years after deposited	Annual settlement rate (%)	Example
1	10.0	when 2.00 m settles to 1.80 m
2	6.0	when 1.80 m settles to 1.69 m
3	4.0	when 1.69 m settles to 1.62 m
4	3.0	when 1.62 m settles to 1.57 m
5	2.0	when 1.57 m settles to 1.54 m

3.8 Summary

There are currently no definitive or widely accepted standards for leachate drainage or collection systems in the UK (North-West WDO, 1991). Moreover, there has been a notable lack of published data and information as to the efficacy and reliability of any particular system. This has resulted in a situation where current practice reveals widely different methods of approach. Therefore, the leachate drainage models mentioned in this chapter will not be adopted and a simple applied approach will be used based on the following EPA recommendations:

- a leachate collection system should extend over the entire base of a landfill.
- underdrainage with granular materials should be at least 300 mm thick and should have a hydraulic conductivity of at least 1×10^{-4} m/sec.
- the cell base should have a minimum slope of 2% to promote efficient drainage to the leachate collection point.
- a filter of granular material or a synthetic filter should be installed above the underdrainage layer.
- a network of perforated collection pipes should be laid within the drainage media with continuous (self cleansing) gradients towards the leachate collection point.

Chapter 4

REVIEW OF LANDFILL LEACHATE MODELS

The protection of water resources is a fundamental consideration in managing landfill operations. Landfill sites should be designed and operated so as to control leachate production and hence minimize the risk of surface and ground water pollution. A further important development is the use of computer models to estimate the production of leachate from landfill sites. These models allow different engineering schemes to be evaluated and are essential tools for design and operational management of modern landfills. A number of such models have been developed in recent years. This chapter describes such models mainly focused on their theory, practicability, data requirements, suitability to real situation and usefulness.

4.1 Estimating Leachate Volume

The amount of leachate generated is dependent on the available water, landfill constituents, its surface and foundation soils. The available water is affected by moisture in refuse itself, precipitation, surface runoff, irrigation, ground water moving through the landfill, ground water table rise, water originally present on site before the placement of refuse, and water generated from the decomposition process. The water reaching the landfill is affected by the surface runoff, evapotranspiration, and the field capacity of the soil cover. The field capacity is the maximum amount of water a soil or refuse can retain in a gravitational field without percolation.

In the last three decades, several empirical formulae have been established for calculating the volume of leachate generated in a landfill. The general approach used is a simple mass balance equation used to predict the approximate quantity of water that will percolate through the body of waste. This method assumes that the waste does not have a water holding capacity and all the water passing through the cover will eventually emanate from the base of the landfill as leachate. This method was first applied by Remson et al., (1968) to simulate leachate generation from solid waste. An alternative method applied later assumes no leachate will flow out of the landfill until the waste body approaches the field capacity for retaining water, then water in excess of this value is transformed into equal quantities of leachate leaving the landfill. However, experience has shown that the estimation of the water holding capacity may have significant variation depending on climate and depth of fill.

4.2 Physical Leachate Generation Models

Several laboratory and field models have been constructed in the past to study the relationship of water infiltration and leachate production in landfills. The results of all these physical models show the great importance of hydrologic conditions in the design, operation, and modelling of solid waste disposal facilities.

Fungaroli and Steiner (1971) constructed a laboratory lysimeter 6 feet square by 13 feet high, filled with compacted refuse waste. The lysimeter was monitored for approximately one and a half years while artificial rainfall was supplied on the top. They concluded that the leachate generation pattern is a function of the initial moisture content and the water input.

Rovers and Farquhar (1973), constructed three domestic waste leaching cells in Canada. Two of them were placed outside and were subjected to local precipitation and evapotranspiration, and the other was placed in the laboratory and was subjected to artificial rainfall. Their data shows that leachate production varied seasonally with changes in the amount of moisture infiltrating the refuse. Maximum leachate production occurred during the spring thaw, whereas in late spring and summer leachate production was drastically reduced due to evapotranspiration.

Results obtained by Raveh and Avnimelech (1979), from several small laboratory leaching columns, indicate that the most effective means to reduce leachate from sanitary landfills is to minimize the water flow through the refuse. Wigh and Brunner (1979) reported results from five municipal waste test cells installed in a Boone County, Kentucky field site. Two field scale and three small scale tests yielded inconclusive results.

Walsh and Kinman (1979) and Walsh et al. (1981) reported results from 19 municipal solid waste test cells. The cells were subjected to different artificial infiltration rates and were monitored for approximately six years. They noted that the cumulative amount of moisture leached is always less than the moisture supplied.

However, physical models are not, by nature, predictive tools since they are restricted by the physical characteristics of the particular refuse and mode of operation. Nevertheless, they can become useful when combined with a rigorous analysis of the mechanisms governing movement of moisture through the refuse.

4.3 Types of Leachate Production Models

Numerous mathematical methods have been proposed for a quantitative estimation of the volume of leachate generated from landfills and are usually based on a mass balance approach. Components of these models are relatively easy to obtain but other model variables such as the surface runoff coefficients, runoff curve number, and evapotranspiration from the landfill surface are more difficult to develop. Limited field data exists for verification for many of the leachate generation models. Therefore, the applicability, accuracy, and sensitivity of leachate generation models is largely unknown.

Different types of leachate models have been developed in the past by several researchers. These are of varying sophistication, ranging from simple water balance models to complex numerical models using Richard's equation for flow through porous media. The classification of such models is a difficult task because of variation in landfill practices. On the basis of model's theory they are grouped into two main classes as:

1. Water Balance Models.
2. Porous Media Models (based on Richard's equation).

The categorisation of leachate management models based on the mentioned criteria is given in Figure 4.1. The first column of this tree diagram shows the earliest water balance models doing calculations manually. More recent computer models using the same approach are shown in the second column. The porous media models are based on Richard's equation using complex numerical schemes such as finite difference, finite element and boundary integral.

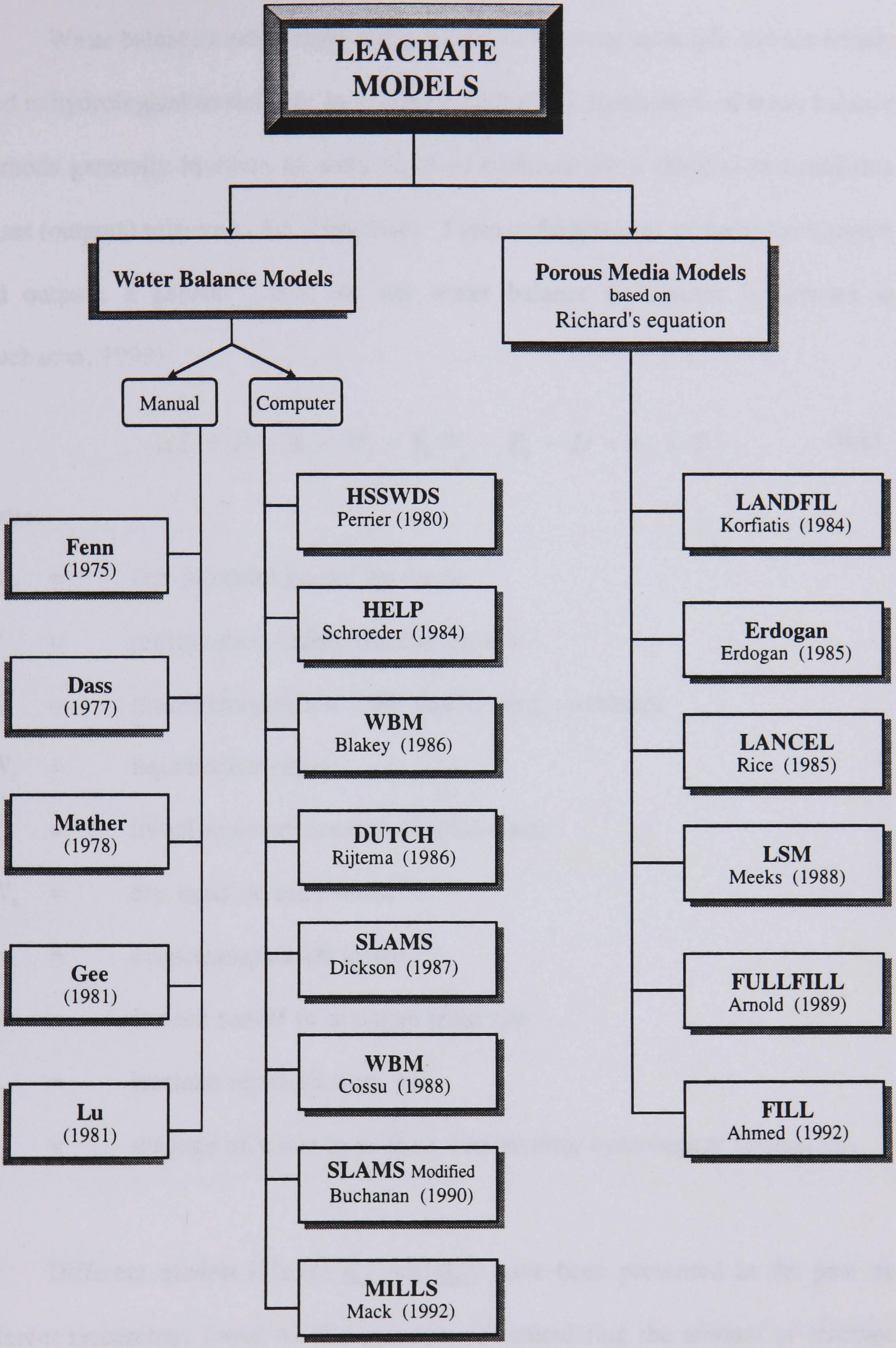


Figure 4.1. Categorisation of Leachate Management Models.

4.3.1 Water Balance Models

Water balance models apply the conservation of mass principle and are widely used in hydrological modelling. In dealing with landfill, application of water balance methods generally involves as assessment of moisture gains (inputs) and moisture losses (outputs) relative to the waste body. From considerations of the various inputs and outputs, a general model for site water balance assessment is derived as (Buchanan, 1993):

$$\Delta L = P + R + W_l + \theta_i W_s - E_t - D - L_r \pm S \tag{4.1}$$

where:

ΔL = nett moisture gained by waste

P = precipitation falling directly on site

R = runoff entering site from surrounding catchment

W_l = liquid waste inputs

θ_i = initial moisture content of solid waste

W_s = dry mass of solid waste

E_t = evapotranspiration losses

D = surface runoff or drainage from site

L_r = leachate removed from site

S = seepage of water to or from surrounding hydrological formations.

Different models (Tables 4.1 and 4.2) have been presented in the past by different researchers based on this principle for calculating the amount of leachate produced from a landfill side. Although the approaches employed in these methods vary, they are basically derived from a water balance or budget principle, the principal factors that control leachate production being:

- the monthly balance between the components of liquid input to the site that give rise to infiltration through the surface; and
- changes in the moisture retention and transmission characteristics of the waste as infiltration percolates through successive layers.

Table 4.1. Water Balance Models (Manual) used for Leachate Production.

Developed By	Evapotranspiration	Runoff
Fenn et al. (1975)	Thornthwaite Method	Rational Formula
Dass et al. (1977)	Thornthwaite Method	SCS Method
Mather (1978)	Thornthwaite Method	SCS Method
Gee (1981)	$PERC = 3.51\,(R-0.3)^{-0.126}\,S^{0.16}\,M^{0.619}\,D^{-2.143}$ **(4.2)** where PERC (percolation), R (rainfall), S (slope), M(soil moisture content), D (soil density) .	

Fenn Model

Fenn et al. (1975) used a water balance for the prediction of leachate volumes. The amount of water percolating the refuse was found by subtracting the surface runoff, change in soil moisture storage, and actual evapotranspiration, from the precipitation. The rational formula was used to compute the mean monthly runoff. The runoff coefficients are obtained from tables as functions of soil cover characteristics and surface slope, and the mean monthly rainfall from available data. The Thornthwaite method was used to obtain the actual evapotranspiration, and the Thornthwaite soil moisture retention tables for estimating the changes in soil moisture. The use of such empirical expressions and the introduction of various parameters that need to be approximated for each case study, render the prediction of leachate production very inaccurate. A flow chart illustrating the Fenn Model using water balance method is given in Figure 4.2.

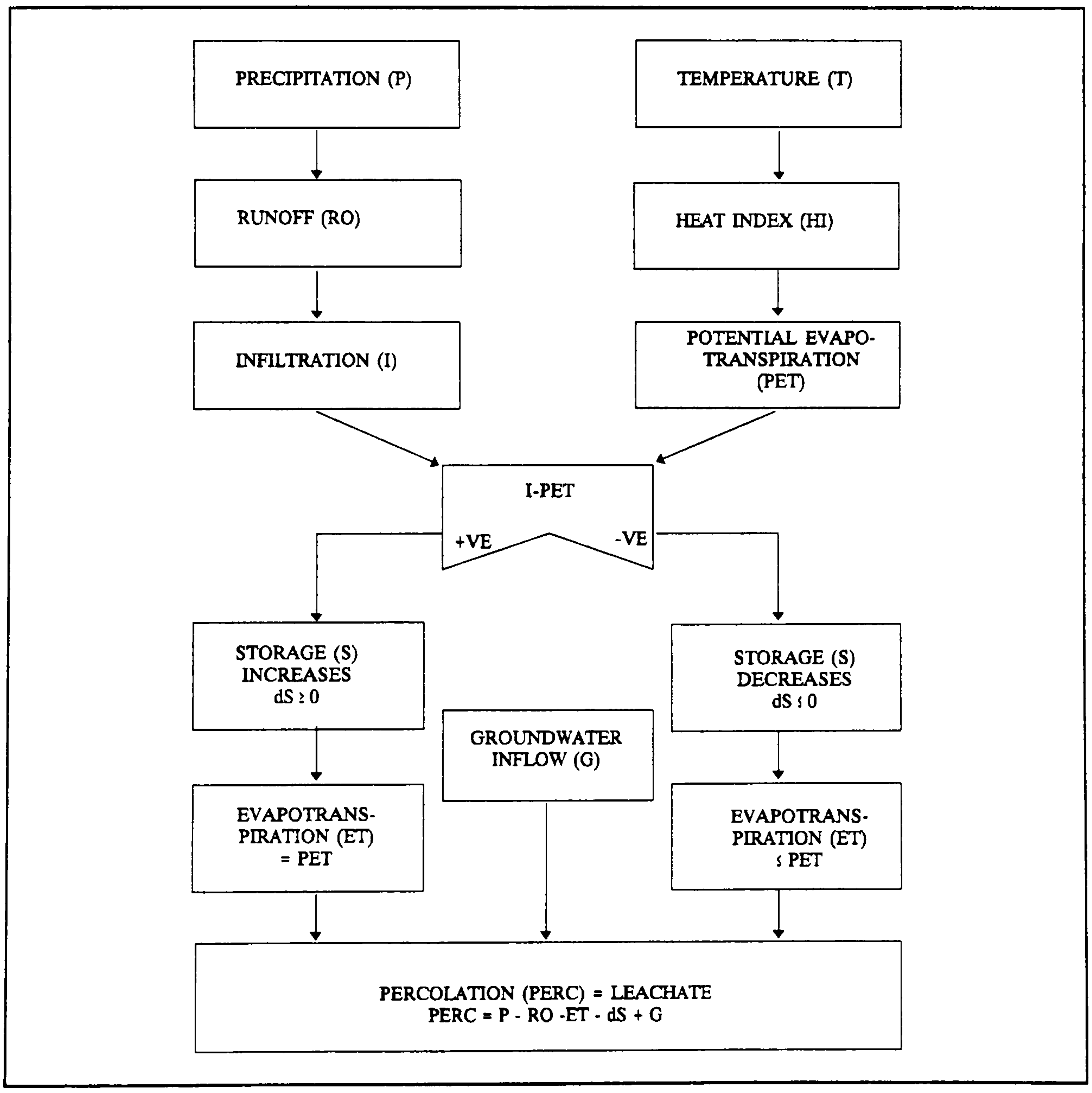


Figure 4.2. Flow Chart for the Water Balance Method (Fenn et al. 1975).

Dass et al. (1977) also used a water balance, and employed the Soil Conservation Service (SCS) procedure for surface runoff computations and the Thornthwaite method for evapotranspiration. Their model was applied to a Wisconsin site but no comparison was taken to actual field measurements.

Gee (1981), from laboratory simulations derived an empirical equation for percolation as a function of rainfall, cover slope, cover soil moisture content, and cover soil density. The derived expression was used to compute leachate production in a monitored landfill in Pennsylvania. He compared the results of his simulation with results obtained from the Fenn et al. (1975) and Perrier and Gibson (1980) models, and found that his model produced more accurate results.

Lu et al. (1981) presented a review of methods for estimation of the hydrologic components in the water balance equation, applied to landfill sites. A comparison was made between calculated and measured leachate quantities for five different landfill sites representing different geographical areas and site conditions. The simulated quantities were computed using twenty-five different methods or combinations of methods. Their study showed that the difference between simulated and measured quantities ranged from 1.32% to 5389%. The best that could be expected was possibly less than 100 % error. In 43% of the cases, the models underpredicted leachate generation, while in 57% of the cases, leachate generation was overpredicted. The study suggested that part of this error may be due to limited field data from existing landfills or to the fact that most of the methods used were originally developed for other purposes and may not be suitable for landfill conditions.

It is evident from the aforementioned studies that difficulties in the prediction of leachate discharges arise from uncertainties in the computation of the hydrologic processes of evapotranspiration, surface runoff and spatial variations. The use of empirical expressions for the components of the water balance poses certain problems in the prediction of leachate discharges. Furthermore, the actual process of moisture transport through the refuse is not taken into account. None of the aforementioned models includes the computation of leachate mound head generated due to leachate accumulation at the bottom of the landfill.

Later studies (Farquhar, 1989) showed the initial assumptions in the manual water balance models are partly inaccurate. The water balance method, however, is the basis for later developed computer models for predicting leachate generation, among others the Hydraulic Simulation of Solid Waste Disposal Sites (HSSWDS) model developed by Perrier and Gibson (1981), the Hydrologic Evaluation of Landfill Performance (HELP) model developed by Schroeder et al. (1984), and the Strathclyde Land Management System (SLAMS), developed by Buchanan (1990). More recent models have also used this approach with certain improvements as given in Table 4.2 and will be discussed in Section 4.4.

Table 4.2. Water Balance Models (Computer) used for Volumetric Leachate Production.

Model Name	Developed by	Model Features and method of Solution
HSSWDS Hydraulic Simulation of Solid Waste Disposal Sites	Perrier et al. (1980)	Deterministic SCS method for runoff Penman's equation for evapotranspiration CREAMS model for Infiltration and Percolation
HELP Hydrologic Evaluation of Landfill Performance	Schroeder et al. (1984)	Quasi 2-D Darcy's law Moisture accounting and water budget Modified from HSSWDS model
WBM	Blakey (1986)	Rational method for Runoff MORECS Model for evapotranspiration
DUTCH Model	Rijtema et al. (1986)	Water Balance
WBM Hydrologic Model	Cossu et al. (1988)	Water Balance monthly Curve number method for runoff Penman's formula for evapotranspiration Completed and uncompleted landfills
SLAMS Strathclyde LAnd Management System	Dickson (1987)	Water balance daily CREAMS for Land Surface Model Operational landfill Site Water Management Model Dynamic Waste Hydrology Model
SLAMS Modified	Buchanan (1990)	Water Balance Active landfill site Menu Driven
MILL Model Investigation of Landfill Leachate	Mack (1992)	Water Balance Modification in the Mather's Model Interactive mode

4.3.2 Porous Media Models

Richard's equation is one the most common fundamental mathematical expressions for unsaturated flow phenomena in porous media. It has been successfully used for the movement of water in the soil system. The same equation is implemented for the movement of leachate in an unsaturated zone of a landfill site in many models as listed in Table 4.3.

Table 4.3. Porous Media Models used for Volumetric Leachate Production.

Model Name	Developed by	Model Features and method of Solution
LANDFIL LANDFIL1	Korfiatis (1984)	Richard's equation using implicit finite-difference scheme
Erdogan and Neufeld's model	Erdogan et al. (1985)	Richard's equation using fully implicit finite-difference technique, method of lines and Runge-Kutta method of Integration
LANCEL LANdfill CELlular liquids model	Rice et al. (1985)	Richard's equation and Cell model using explicit finite difference approximation
LSM Landfill Source Model	Meeks et al. (1988)	Richard's equation (Ψ-based) using semi-analytical finite difference and water budget SCS method Part of MULTIMED
FULLFILL	Arnold (1989)	One dimensional, finite difference computer model based on the Richard's equation with appropriate constitutive laws and certain adjustable parameters
FILL Flow Investigation for Landfill Leachate	Ahmed et al. (1992)	Richard's equation using implicit finite-difference scheme Richard's equation using Boundary Integral Method

4.4 Water Balance Models

4.4.1 HSSWDS Model

A model which was designed especially for landfill sites is the HSSWDS (Hydrologic Simulation of Solid Waste Disposal Sites) model, developed by Perrier, et al. (1980). A water balance was used and the precipitation was separated to surface runoff, evapotranspiration and subsurface drainage. The model provides continued simulation and uses daily time steps. The SCS curve number method is used to estimate the surface runoff and a modified version of the Penman method to estimate evapotranspiration. In addition, a routing technique was employed to predict flow through the landfill soil cover. The moisture content of the solid waste material is assumed at field capacity; therefore, the volume of water entering the solid waste by percolation through the cover soil will immediately generate leachate. The flow chart of the HSSWDS Model is shown in Figure 4.3.

Clopper and Viste (1982) presented various modifications in the computation of the hydrologic parameters of the model. The model was applied to GROWS landfill site in USA and had a 107 % error. An updated version of the HSSWDS model, called HELP, has been prepared by EPA, USA.

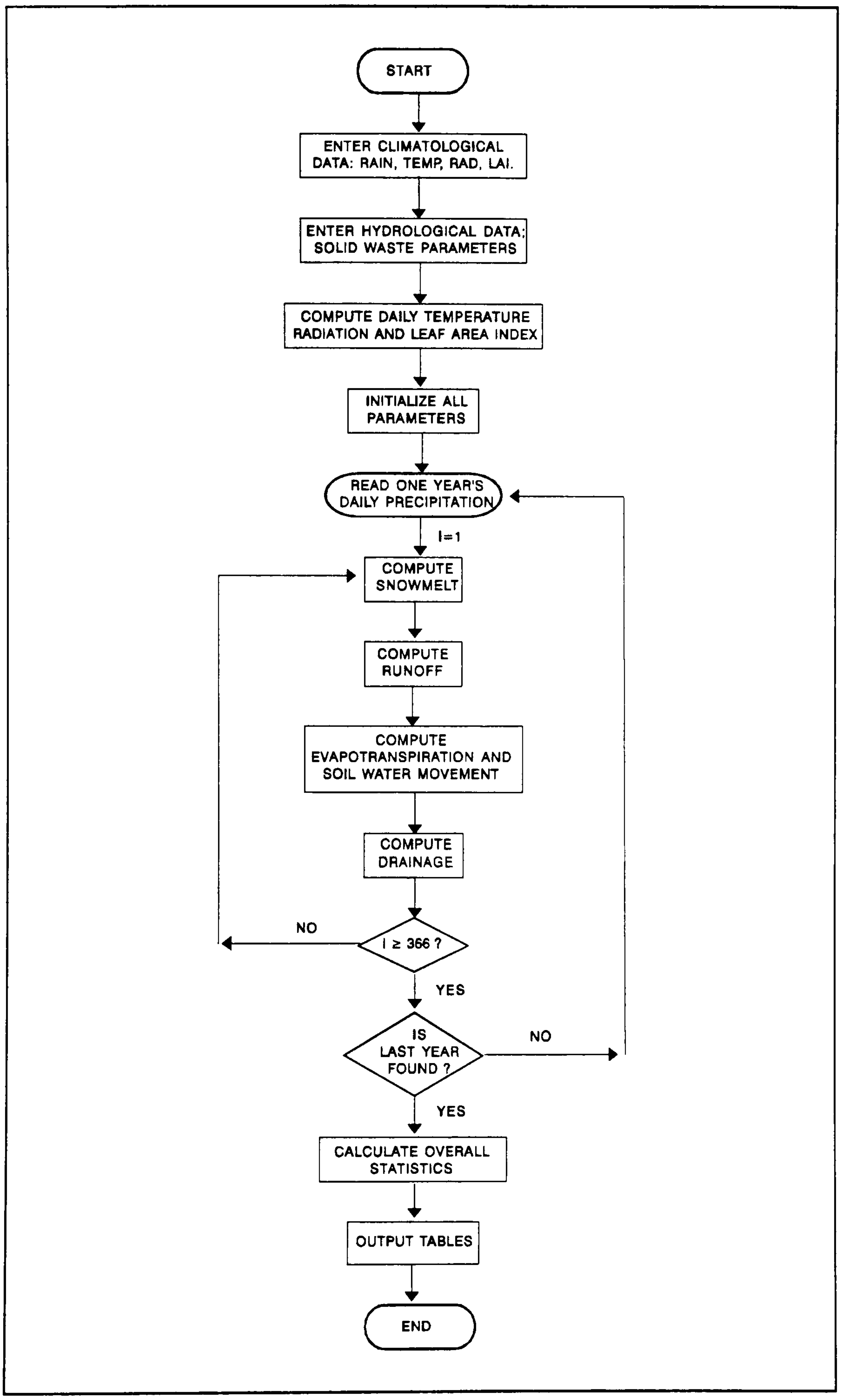


Figure 4.3. Generalised Flow chart for the HSSWDS Model (Perrier et al. 1980).

4.4.2 HELP Model

Schroeder et al. (1984) developed the Hydrologic Evaluation of Landfill Performance (HELP) model. The model simulates the effects of hydrologic processes on the water balance for landfills by performing daily sequential analysis using a quasi-two-dimensional, deterministic approach. The dominant hydrologic considerations include precipitation of any form, surface storage, interception, surface evaporation, runoff, snowmelt, infiltration, vegetation, rooting depth, plant transpiration, soil evaporation, soil moisture storage, soil moisture potential, unsaturated flow, and vertical and lateral saturated flow. The program handles each of these considerations, often in a simplified manner, to estimate runoff, evapotranspiration, vertical drainage to liners, percolation through liners, and lateral drainage from layers above liners.

The HELP model was adopted from the HSSWDS model of the USEPA (Perrier and Gibson, 1980). The infiltration, percolation and evapotranspiration routines were almost identical to those used in the CREAMS model, which was developed by Knisel (1980). The runoff and infiltration models are based on the USDA Soil Conservation Service (SCS) curve number method. Various modules of the SWRRB model (Arnold et al., 1989) were also used in the latest version of the HELP model.

The HELP model includes an optional default data base containing values that describe climate for 102 cities (precipitation, temperature, solar radiation, and growing season); seven types of vegetative cover; soil characteristics for 21 soil types (including municipal solid waste); and runoff curve numbers for the default soil and vegetation types. These default values, except precipitation and temperature, were used in the verification study unless measured soil characteristics were provided.

A simplified diagram showing the HELP model components and input-output data is shown in Figure 4.4. Version 1 of the model was compared with the DRAINFIL model, which was specially modified from DRAINMOD (Skaggs, 1982) for landfill sites. Version 3 of the model (latest version) released in 1994 is greatly enhanced over the earliest versions by increasing the number of modelling layers and using the interactive, full screen, menu-driven input techniques.

Field Verification of HELP Model

Peyton and Schroeder (1988) performed long-term simulations of 17 landfill cells from six sites in U.S.A. using the HELP model for simulation periods ranged from 2.5 to 8 years. They compared the results with the field data from a variety of landfills to verify the model and to identify shortcomings. They found that model predictions are generally bracketed by field measurements. Good agreement between the predictions and measurements was obtained by calibrating the hydraulic conductivity of the cover materials while staying within the range of hydraulic conductivity values reported in the literature for these materials. They concluded from the results that the model can be very useful tool for designing and evaluating landfills.

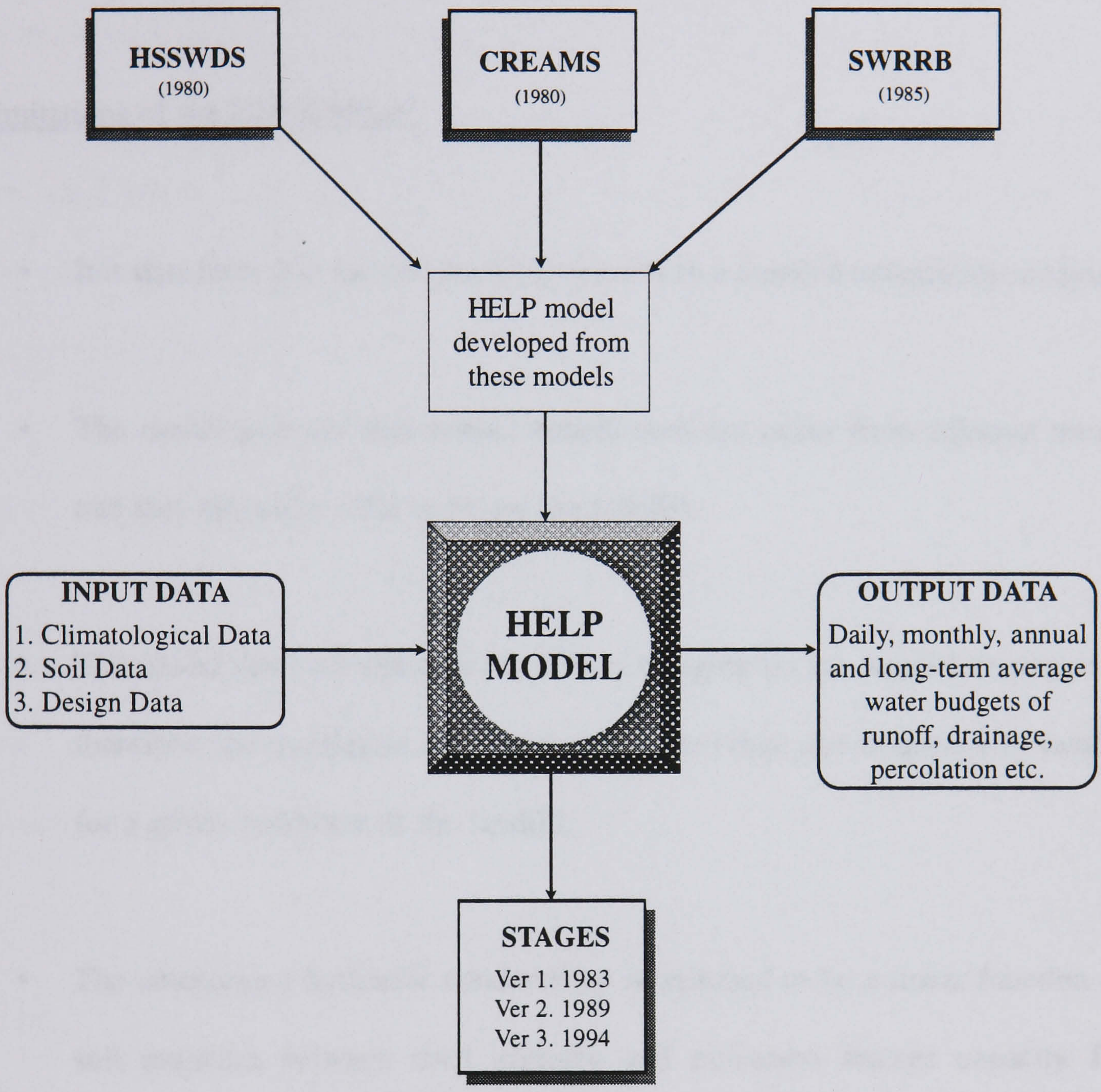


Figure 4.4. HELP Model Components.

Krantz and Bailey (1990) compared field data to the results of the HELP model. The comparison of the model's overall predictions to the field collection data showed that the HELP model predicted leachate collection and prediction relatively close for the actual size conditions.

Limitations of the HELP Model

- It is data intensive and not readily amenable to a detailed uncertainty analysis.
- The model assumes that surface runoff does not occur from adjacent areas, and that the water table is below the landfill.
- The model does not simulate the effects of aging on the landfill system and, therefore, the simulation run demonstrates the range and frequency of results for a given condition of the landfill.
- The unsaturated hydraulic conductivity is assumed to be a linear function of soil moisture between total porosity and minimum storage capacity for drainage.

4.4.3 SLAMS (Strathclyde LAnd Management System) Model

SLAMS, developed by Dickson (1987) and modified by Buchanan (1990), is a computer based design and management tool which allows the simulation of landfilling operations and hydrogeological processes, to enable prediction of moisture build-up within an active landfill site. Based on estimated waste characteristics and site hydrology, or as a real-time analysis tool, SLAMS can be used as a forecasting tool particularly in the design stage of a landfill site. Cell/section size, and configuration can be optimised in order to limit the amount of moisture build-up thus reducing leachate generation.

Modelling Approach:

The landfill site is considered as a series of user-defined cells, each of which receives inputs of waste and water over a period of time. The mass of waste and water in each cell is updated on a daily basis allowing moisture content to be evaluated at any point in time.

$$\alpha_k(t) = Mw_k(t)/Ms_k(t) \tag{4.3}$$

where:

$\alpha_k(t)$ = dry weight moisture content of cell k at time t.

$Ms_k(t)$ = mass of solids in cell k at time t.

$Mw_k(t)$ = mass of water (or liquid) in cell k at time t.

The mass of solids is a function of volumetric rate of waste placement, initial moisture content of the waste, and placement density achieved. Mean values of initial moisture content and placement density can be assumed, thus the mass of solids becomes a direct function of the rate of waste placement.

$$Ms_k(t) = \frac{\rho}{(1+\alpha_i)} \Sigma_{j=1,t} V_{k,j} \tag{4.4}$$

where:

ρ = placement density achieved.

α_1 = initial moisture content of waste (by dry weight).

$V_{k,j}$ = volume of waste placed in cell k at time j.

The mass of liquid is due to the inherent moisture in solid waste, liquid waste inputs and hydrological water entering the landfill. All moisture entering the site can be considered as absolute or conditional moisture inputs, where absolute inputs are due to the moisture initially present in the solid waste and liquid waste inputs, with the latter representing a gain due to actual infilling operations. Conditional inputs are due to effective precipitation falling directly onto the site or entering as runoff or net seepage from connected land areas and these can be considered as hydrological inputs. The mass of water present in a cell from these inputs is calculated as:

$$Mw_k(t) = \sum_{j=1,t} \left[\frac{V_{kj} \cdot \rho \cdot \alpha_i}{(1+\alpha_i)} + \rho_i \cdot L_{kj} + \rho_w \cdot H_{k,j} \right] \tag{4.5}$$

where:

ρ_i = density of liquid waste.

$L_{k,j}$ = volume of liquid waste placed in cell k at time j.

p_w = density of water.

$H_{k,j}$ = volume of hydrological water entering cell k at time j.

The volume of hydrological water entering a particular cell is dependant on the volume of available water, the permeability of the open surface and waste body, and the capacity of the waste to take up additional moisture. The latter is dependant, amongst other things, on the existing moisture content of the waste. The hydrological water available at any cell is assessed in the first instance as being due to direct precipitation on that cell together with any runoff from directly connected land areas. This is calculated by the following equation.

$$H_{k,j} = Pe_j (A_k + C_k \cdot Ac_k) \tag{4.6}$$

where:

Pe_j = effective precipitation occurring at time j.

A_k = plan area of cell k.

C_k = runoff coefficient applied to the connected land area (Ac_k) draining to cell k.

A containment approach is adopted and it is assumed that seepage, to or from ground water does not occur. Indirectly, an allowance for any net moisture gain from groundwater can be made by varying the runoff coefficient C_k. The available hydrological water arriving at each cell (Qi_k), is apportioned between infiltration (Fa_k) and runoff (Qo_k), based on the cell status at that time (Table 4.4), the existing moisture content of the cell, the saturated moisture content of the waste and the permeability of the cover material at the surface receiving precipitation.

The parameter e_k in Table 4.4 represents the efficiency of the cover material placed on cell k upon completion, which has a value between 0.0 and 1.0, representing infinite and zero permeability respectively. When e_k is set to zero, runoff from cell k only occurs when the waste has become saturated, whilst a value of 1.0 indicates that no further infiltration can take place irrespective of the current cell moisture content. Intermediate values are used to force a minimum proportion of the available water to drain from the cell.

Table 4.4. Cell Status used in SLAMS Model.

Status	$Fc_{k,j}$ (Infiltration capacity)	$Fa_{k,j}$ (Actual infiltration)	$Qo_{k,t}$ (Run-off)
Empty	0	0	$H_{k,j}$
Active	$(\alpha_s-\alpha_k(t))\ Ms_k(t)/\rho$	Minimum of $H_{k,j}$ and $Fc_{k,j}$	$H_{k,j}$ - $Fa_{k,j}$
Full	$(\alpha_s-\alpha_k(t))\ Ms_k(t)/\rho$	Minimum of $H_{k,j}(1-e_k)$ and $Fc_{k,j}$	$H_{k,j}$ - $Fa_{k,j}$
Closed	0	0	$H_{k,j}$

Excess water ($Qo_{k,j}$) drains to adjacent cells, supplementing available hydrological water. This process continues until the site boundary (or cut-off drain) is encountered, where the surplus is collected for treatment and disposal or redistribution over the landfill.

Data Requirements:

SLAMS requires data relating to description of site, hydraulic characteristics of waste material and cover material, and details of the site drainage system and meteorological data in the form of daily precipitation and daily or monthly potential evapotranspiration. Also required are design data, including rate of waste placement, placement density, and site filling procedure.

4.4.4 MILL (Model Investigation of Landfill Leachate) Model

The MILL model, based on water balance approach, is a interactive computer program to calculate the leachate production volume from a solid waste landfill is formulated and evaluated using a minimum of climatic and environmental data. The program is a standardisation and mathematical representation of methods which have previously required tedious calculations (from charts, graphs, tables, and separate computer programs), based on individual perceptions of landfill operations.

The model is based on current landfill building and operational techniques including the application of a daily soil cover and the optional incorporation of a "bathtub" level. Cell theory is introduced as the basis for the building phase, where each month's waste represents one building cell of the landfill. MILL employs "landfill sectioning" of the landfill into quarters to simulate a more continuous and real-life application of moisture. MILL can be used to evaluate leachate production during both the building and completed phases of the landfill operation.

The program is written in FORTRAN with options to allow easy access for future modifications and changes. There are four major divisions of the model. The MAIN section serves as a control centre to lead the user through the program. It initiates the major calls to the three other main subroutines. These programs are RUNPRE, WABAL, and LAND which are responsible for the evaluation of the direct overland runoff and the effective precipitation, the climatic water balance, and the leaching through the landfill, respectively. These main routines then call other subroutines as well.

MILL uses the Soil Conservation Service rainfall runoff curve number technique to calculate the direct overland runoff from the cap of a completed sanitary landfill. The Thornthwaite climatic water budget procedure is used to estimate the evapotranspiration and to calculate the surplus moisture which infiltrates into the landfill

MILL uses new techniques to estimate the percolation of moisture through the landfill for different landfill building and management assumptions. The model's two major assumptions are that moisture moves through the waste lifts as it would travel through a homogeneous soil layer of the same depth, and that the same water holding values can be used for both waste material and the cover material so that one water budget can be used for both.

4.4.5 Miscellaneous Models

Some models reported in the literature are not discussed separately because the concerned model documentation was not written in English. One of such models is the Dutch model developed by Rijtema et al. (1986). The model estimates values of monthly leachate production rates from both lined and partly unlined landfill sites.

4.5 Porous Media Models

4.5.1 LANDFIL Model

A real time flow model LANDFIL describing the movement of moisture in solid waste landfills was developed by Korfiatis (1984). The model is based on the principles of partially saturated flow and can be used to predict moisture transport through landfills with or without surface covers and/or bottom collection systems. A flow chart describing the basic functions of the model is shown in Figure 4.5.

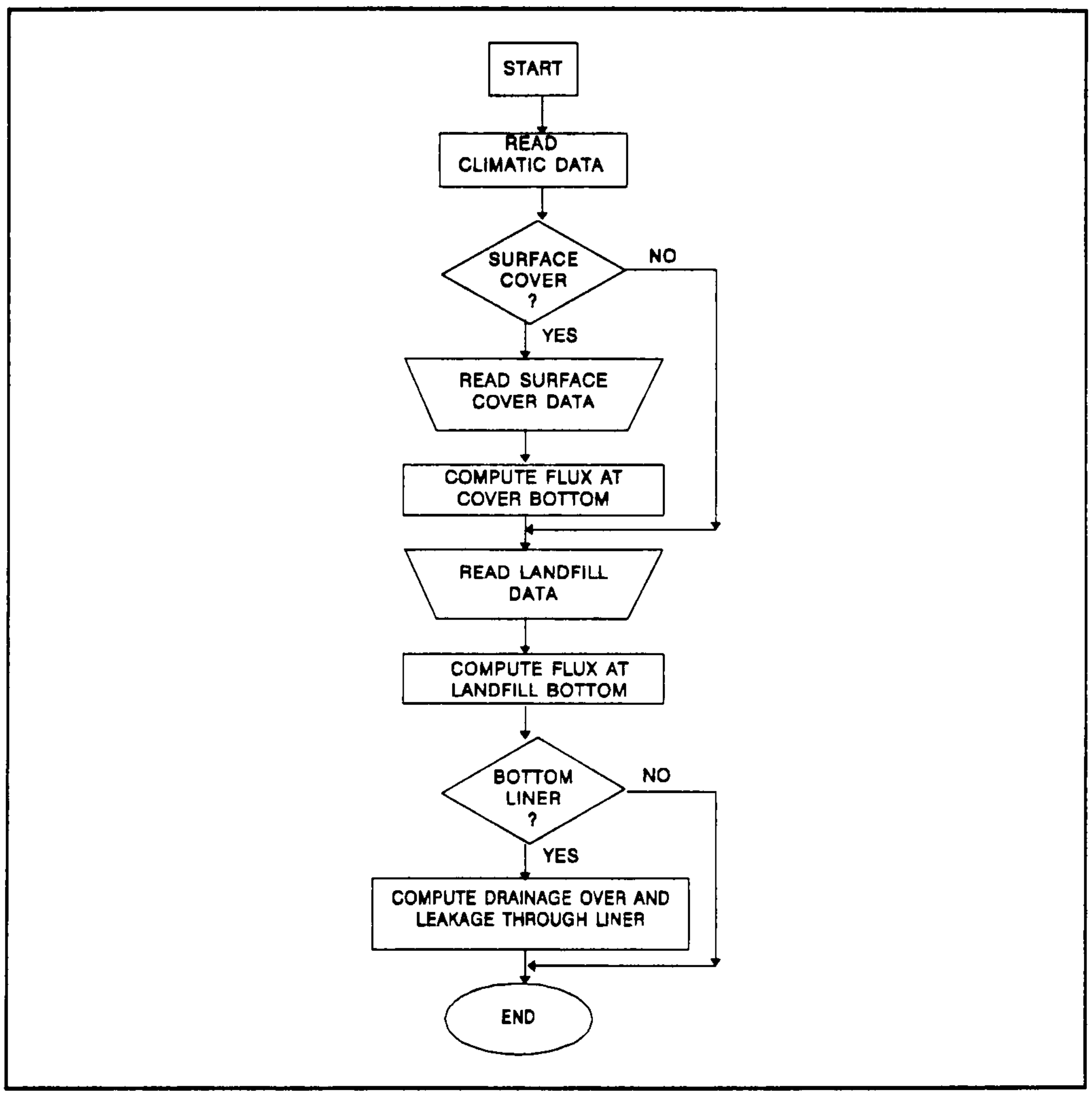


Figure 4.5. Simplified LANDFIL Model Flow Chart (Korfiatis, 1984).

The theory of unsaturated flow through porous media was used to develop the appropriate equations. Real time boundary conditions at the surface of the landfill were formulated accounting for the full precipitation-evapotranspiration cycle. The unsaturated flow equation through porous media is solved by a fully implicit finite-difference numerical scheme, in terms of the moisture content.

The discretisation of Richard's equation (Equation 2.5) for the j-th grid element and k-th time step yields:

$$\begin{aligned}&\left[-\frac{1}{\Delta z}D_{i-½}^{k+1}\right]\theta_{i-1}^{k+1}+\left[\frac{1}{\Delta z}D_{i+½}^{k+1}+\frac{1}{\Delta z}D_{i-½}^{k+1}+\frac{\Delta z}{\Delta t}\right]\theta_{i}^{k+1}\\&+\left[-\frac{1}{\Delta z}D_{i+½}^{k+1}\right]\theta_{i+1}^{k+1}=\frac{\Delta z}{\Delta t}\theta_{i}^{k}-K_{i+½}^{k+1}+K_{i-½}^{k+1}\end{aligned}\tag{4.7}$$

where θ = volumetric moisture content [vol/vol], $K(\theta)$ = unsaturated hydraulic conductivity [L/T], $D(\theta)$ = difffusity coefficient [L^2/T], z = vertical coordinates (L) and t = time (T).

The resulting system of algebraic equations has a tridiagonal coefficient matrix, which are solved by an iterative application of the Gaussian elimination method for the values of moisture content. Subsequently, the moisture flux through each layer interface is computed. In case of surface cover, the model first computes the flux through it and uses the output from the bottom of the cover as input on the refuse material. Real-time boundary conditions are applicable in both the cover and the refuse surfaces.

Demetracopoulos et al. (1986) described the governing equations, including the boundary conditions of the model, and presented results of sensitivity analyses to investigate the effect of different parameters related to leachate flow through a landfill. The model does not include the computation for runoff and evapotranspiration at the boundary of the landfill.

4.5.2 LANCEL Model

LANCEL (Landfill CELlular liquids model) dynamic landfill liquids simulation model was developed by Rice et al. (1985). It consists of approximately 1000 FORTRAN V statements and can be used to predict liquids movement, liquids placement and drainage at a landfill site. Both saturated and unsaturated flow conditions can be approximated by the model. The conceptual diagram of the unsaturated and saturated subsystems which compose a single cell is shown in Figure 4.6. The primary cell input is from cover percolation. These percolated liquids then cascade through a series of non-linear soil moisture reservoirs which represent the unsaturated zone (Figure 4.7). The outflow from the final non-linear soil moisture reservoir then serves as an input to the saturated subsystem. From here, liquids can follow many different flow paths, i.e., they can flow to caissons, or flow out through the base of the landfill. Figure 4.8 is a flow chart of the LANCEL model. LANCEL solves continuity equations for the unsaturated zone, as well as the saturated zone, at each simulation time and for the various flow mechanisms it is able to approximate.

The model's structure is consistent with the cell filling arrangement commonly used in landfills and hence allows for accurate geometric description of the landfill. Cell geometry is represented by coordinates of the cell nodes, are entered into the model, and the cell area is computed by the program. Other data required by the model is as per HELP model data in addition to the detailed description of the site.

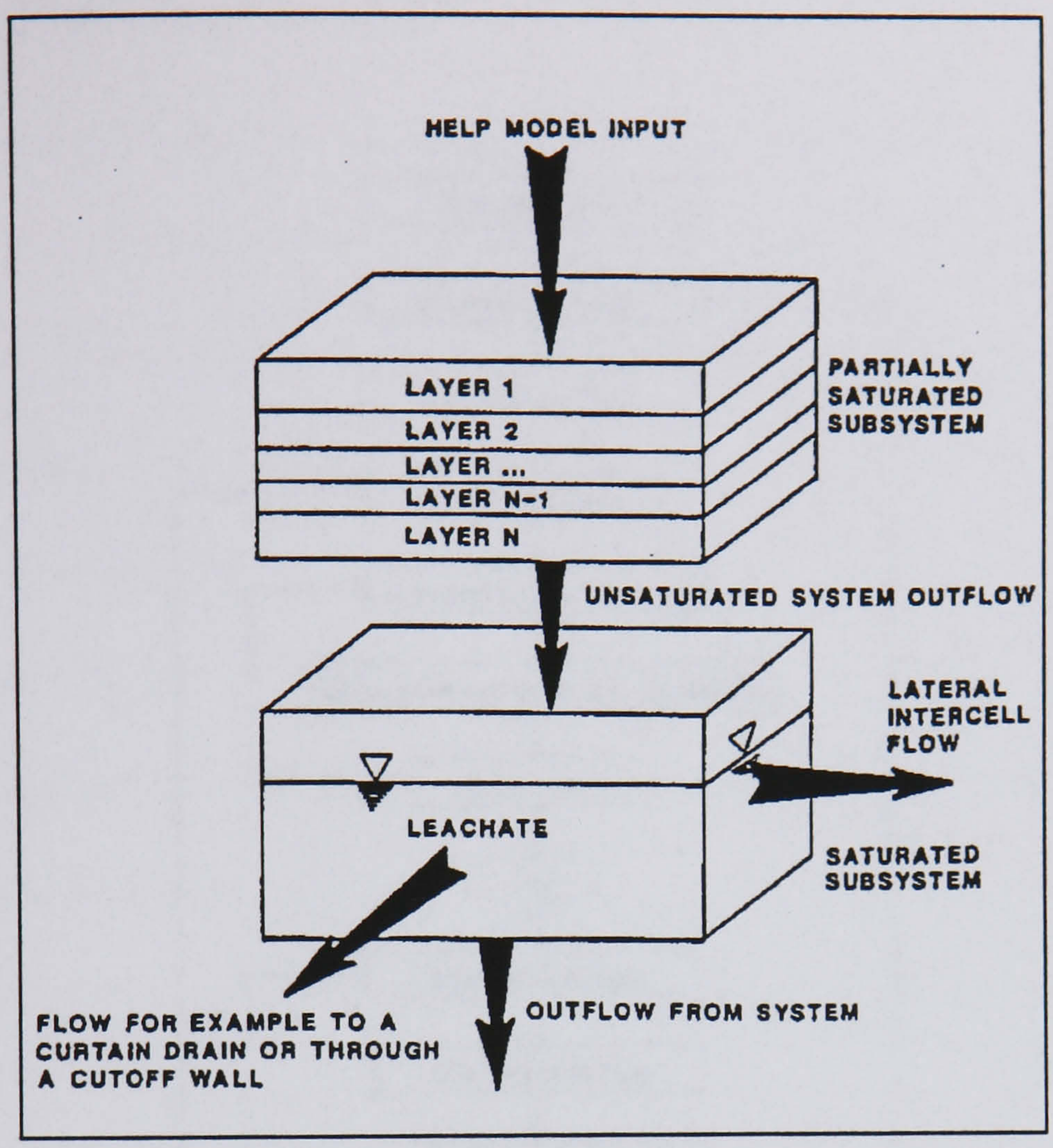


Figure 4.6. Schematic Diagram of LANCEL System Flows and Geometry.

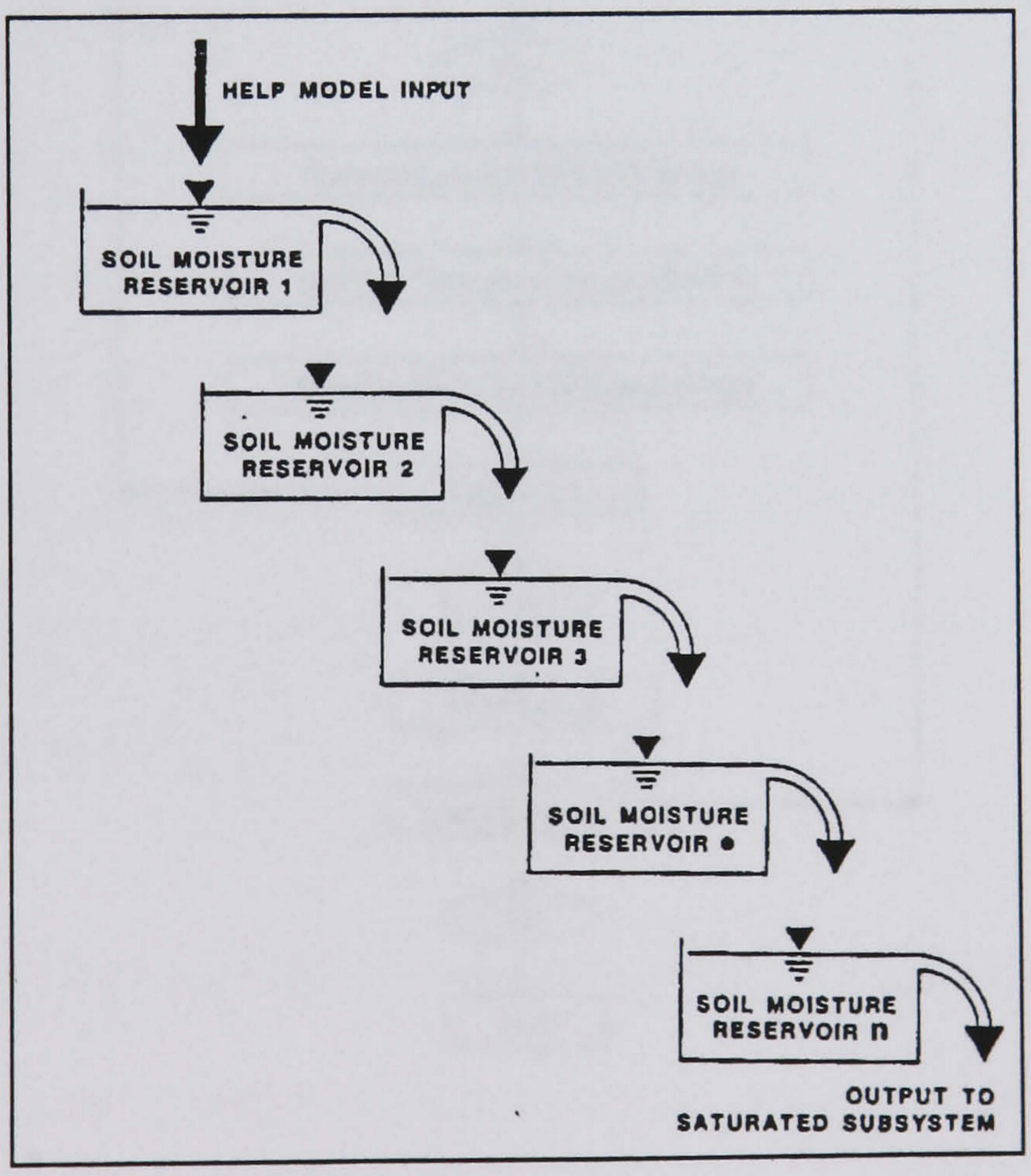


Figure 4.7. Unsaturated Sub-Model Throughout.

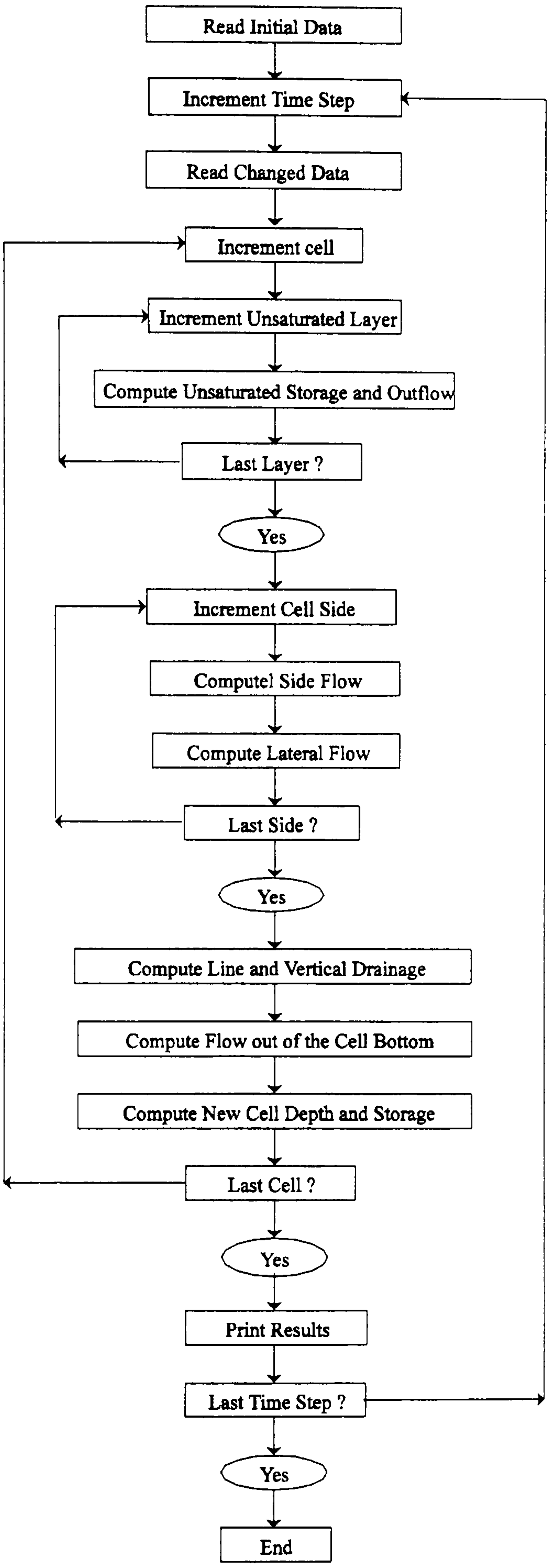


Figure 4.8. Flow Chart of LANCEL Model.

4.5.3 Erdogan and Neufeld Model

Erdogan and Neufeld (1983) have developed a mathematical model based on intrapartical and external film diffusion resistance between solid and liquid concentrations. Their model involves physico-chemical and biological processes responsible for generation and transport of contaminants in landfills. It is based upon the following assumptions:

1. Landfill is considered as a porous medium.
2. Moisture flow is unidirectional and moves vertically down through the landfill
3. Medium is unsaturated
4. Rate of generation of organic and inorganic containments in the solid phase is of the first order.

Later in 1985, Erdogan H. et al. presented an improved mathematical model describing generation and transport of leachate through a landfill. Their model is based on the theory of unsaturated flow through porous media. Numerical solutions of the mathematical models are obtained using finite difference implicit method, method of lines and Runge-Kutta method of integration. Their model can obtain moisture profiles through a landfill with or without presence of top, bottom and leachate collection system.

An attempt was made by Kastury et al. (1985) to apply HELP and Erdogan models to estimate the quantity of leachate expected in an existing landfill and a proposed conceptual landfill. They were trying to develop the correlation between the two models, but no firm conclusions were reported in their study.

4.5.4 LSM (Landfill Source Model) Model

The Landfill Source Model (LSM) developed by Meeks, Y. et al. (1988) is a physically-based, computationally efficient tool to estimate leachate emanating from landfills. It simulates steady-state flow through the landfill and the unsaturated zone. The effect of uncertainty or variability in the parameters can be quantified using the Monte Carlo simulation technique (Salhotra et al., 1988).

Under steady-state conditions percolation (Q) through each layer of the landfill and the unsaturated zone (plus any lateral drainage) is equal to the infiltration (I) at the surface. The two are coupled through their dependence on the near-surface soil moisture content. This necessitates an iterative solution technique.

First, Q is set equal to the smallest saturated hydraulic conductivity of the landfill layers and the soil moisture profile is calculated. Second, using the estimated near-surface moisture content and climatic data, surface infiltration (I) is calculated. If Q = I, the steady-state leaching rate has been found. If not, then Q is systematically modified and the two steps repeated until Q = I.

In step 1, with a known percolation (Q), Richard's Equation is used to estimate the water content profile in the soil. This solution requires either van Genuchten's or Brooks and Corey's effective saturation-hydraulic conductivity relationship. The semi-analytical solution is obtained by discretising the landfill and the unsaturated zone. A backwards, difference approximation for the spatial derivative is used and the equation solved using the Newton-Raphson technique. If this fails to converge, the bisection method is used.

The effect of synthetic liners is included by using the harmonic mean of the hydraulic conductivities of the liner and underlying soil layer. The user may specify partial failure of the liner. The effects of lateral drainage are included by using an algorithm based on the assumption that the drains do not allow any water ponding above them.

Having estimated the soil water content profile, in particular the near-surface water content, a water balance approach is used to calculate the infiltration (I) from precipitation (P), runoff and evapotranspiration (ET). The water balance is evaluated for a typical hydrological event, defined as the interval between the beginning of one precipitation event and the onset of the next precipitation. Sensitivity to the event interval is presented.

Precipitation rates are specified by the user. Evapotranspiration is estimated using potential evapotranspiration values corrected for available soil moisture, defined as the soil moisture (estimated in Step 1) less the wilting point moisture content in the uppermost layer. Water that can be removed by evapotranspiration is assumed to decrease downward in this layer because (i) the evaporative demand decreases with depth and (ii) the transpirative demand decreases as root density decreases. The Soil Conservation Service (SCS) curve number method, modified to account for the variation in soil moisture in the upper soil layers, is used to estimate runoff. Finally, infiltration is calculated as precipitation less the sum of evapotranspiration and runoff.

A comparison between the HELP model and the LSM is presented in Table 4.5. The HELP model is transient and can be used to simulate short-term leaching rates or variable leaching rates. The LSM is a steady-state model appropriate for estimating long-term, leachate rates; it is based on physical laws governing unsaturated flow; has considerable flexibility in specifying the landfill design; is easy to implement; and has fewer data requirements. Further, the model includes a Monte Carlo shell which can be used to propagate uncertainty in the input parameters through the model and estimate uncertainty in the leachate rate.

The LSM model is now incorporated in the U.S. EPA's Multimedia Exposure Assessment Model (MULTIMED) Version 2.0 (Salhotra et al., 1993), which simulates the fate and transport of contaminants released from a waste disposal facility or contaminated soils into the multimedia environment. MULTIMED utilizes analytical, semi-analytical and numerical solution techniques to solve the mathematical equations describing flow and transport. The simplifying assumptions required to obtain the analytical solutions limit the complexity of the systems which can be represented by MULTIMED. The model does not account for site-specific boundary conditions, multiple aquifers, or pumping wells.

To enhance the user-friendly nature of the model, separate interactive pre- and postprocessing software have been developed, using the ANNIE Interaction Development Environment (AIDE) (Kittle et al., 1989), for use in creating and editing input and in plotting model output. The pre- and postprocessors have not been integrated with the MULTIMED because of the size limitations of PC computers.

Table 4.5. Comparison of the HELP and LSM Models.

Model Feature	HELP Model	LSM Model
Dimensions	Quasi 2-D	1-D
Stochastic Capabilities	None (deterministic)	Monte Carlo
Method of Solution	Moisture accounting and water budget	Semi-analytical finite difference and water budget
Time Step	Daily	Steady-state
Processes		
Lateral Drains	Steady flow, fit piecewise functions	Complete drainage of ponded water
Infiltration	Water balance	Water balance
Runoff	SCS method	SCS method
Evapotranspiration	Modified Penman adjusted for limiting soil moisture	PET adjusted for limiting soil moisture
Surface storage (snow)	Water balance	None
Percolation	Modified Darcy's law with free drainage	Richard's equation
Water content profile	Moisture balance	Richard's equation
Landfill Design		
Layer Constraints	Maximum of 9, specified types with ordering restrictions	Maximum of 1 drainage layer
Layer Properties	Homogeneous user specified or default	Homogeneous user specified
Depth to water table	Not considered	Boundary condition
Unsaturated hydraulic conductivity	Linear function of soil moisture	van Genuchten or Brooks and Corey relationship
Results	Transient leachate rate Soil moisture profile Deterministic	Steady-state leachate rate Soil moisture profile Deterministic or cumulative probability distribution

4.5.5 FILL (Flow Investigation for Landfill Leachate) Model

The FILL numerical model was developed by Ahmed et al. (1992) to compute the time variation of leachate flow in landfills using Richard's equation. The two-dimensional moisture-transport equation, along with the boundary conditions, was solved using an implicit finite difference scheme in a vertical plane. The kinematic wave equation is used to compute runoff by taking the effect of the slope and the roughness of the landfill surface into account. Infiltration is a function of moisture content, hydraulic conductivity and depth of water at the soil surface. The infiltration equation, developed by Haverkamp et al. (1987) based on Philip's (1969) equation, takes the effect of aforementioned parameters into account, and is used in the FILL model. The model developed by Demetracopoulos et al. (1984) based on mass-conservation principle, to predict the movement of the leachate mound head and to compute the variation of leachate flow rate from the landfill is incorporated in the FILL model.

Landfill leachate flow in the unsaturated zone in a vertical section can be described by the two-dimensional moisture flow equation in an unsteady-state condition as (Willis and Yeh, 1987)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right] + \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial \theta}{\partial z}\right] - \frac{\partial K(\theta)}{\partial z} \tag{4.8}$$

where:

θ = volumetric moisture content [vol/vol]

$K(\theta)$ = unsaturated hydraulic conductivity [L/T]

$D(\theta)$ = difffusity coefficient [L^2/T]

x and z = lateral and vertical coordinates (L)

t = time (T)

The discretisation of Equation 4.8 for the i-, j-th grid point yields

$$\begin{aligned}\frac{\theta_{i,j}^{k+1} - \theta_{i,j}^{k}}{\Delta t} &= \frac{1}{(\Delta x)^2}\left[D_{i+\frac{1}{2},j}^{k+1}(\theta_{i+1,j}^{k+1} - \theta_{i,j}^{k+1}) - D_{i-\frac{1}{2},j}^{k+1}(\theta_{i,j}^{k+1} - \theta_{i-1,j}^{k+1})\right] \\ &- \frac{1}{(\Delta z)^2}\left[D_{i,j+\frac{1}{2}}^{k+1}(\theta_{i,j+1}^{k+1} - \theta_{i,j}^{k+1}) - D_{i,j-\frac{1}{2}}^{k+1}(\theta_{i,j}^{k+1} - \theta_{i,j-1}^{k+1})\right] \qquad (4.9) \\ &- \frac{1}{\Delta z}(K_{i,j+\frac{1}{2}}^{k+1} - K_{i,j-\frac{1}{2}}^{k+1})\end{aligned}$$

where:

k = previous time level; and k+1 = forward time level.

This system of algebraic equations is solved by the successive application of the Gauss-Seidel iteration method. The coefficients are first computed using the moisture values of the previous time step. The system solved for one iteration uses the new moisture values to update the coefficients. This iteration procedure is continued until two consecutive sets of moisture values agree within a prescribed tolerance criterion.

The FILL model was used to simulate the leachate flow rates in section 6/7 of Fresh Kills landfill, situated in New York (Khanbilvardi et al., 1995). The model results were compared with the results from HELP model, which was also applied to the same site. The simulated leachate flow rates by the FILL model were found to be less than those obtained by the HELP model. No firm conclusion was drawn by the authors, but they concluded that the computation of surface runoff and evapotranspiration are extremely important to get the real picture of landfill leachate.

4.5.6 Conclusions about Porous Media Models

The application of Richard's equation for the movement of leachate in a landfill was first initiated by Korfiatis (1984). He considered refuse as a porous homogeneous material and developed his model solving the equation mentioned. He tested his model on column experiments receiving percolation under varying conditions. The results were very encouraging and this approach was later used by many other researchers in the development of their models. This technique originally developed for soil being translated for waste is seem to be a better option than traditional methods, especially on a limited data base.

A numerical scheme for the approximation of Richard's equation should be stable and convergent. This is only achieved if one uses a small time and spatial steps, which means very expensive computer runs for simulations over long time periods. If the coherent conditions are violated, physically unrealistic results could emerge (Korfiatis, 1984).

The usefulness and validity of these models can be enhanced with calibration of these models with field data before their use. These models require a large number of parameters which are only available for a few sites. In addition, several of these parameters influence the models in a highly nonlinear manner, and results can be very sensitive to parameter changes. It is extremely difficult to assess these parameters at unsampled locations. Therefore, the application of these models to the real sites is presently limited. Some of those models are compared with the HELP model, which is not based on Richard's equation, adding further restriction to these models. As a conclusion this can lead to the justification of the HELP model approach, which is simple and most applied model for simulating leachate production.

4.6 Limitations of Existing Models

There are a number of limitations in the existing leachate production models, some of which are reported and discussed here.

1 Intermediate soil cover

Intermediate soil cover can provide a barrier sufficiently impermeable to cause water to accumulate above the cover producing water tables within the landfill or zones of saturated waste. Existing models ignore this aspect and model waste and intermediate soil layers as a combined waste layer. This assumption can lead to over estimation of the leachate mound at the bottom of landfill.

2 Drainage from waste layer

Many of the existing models are based on the soil drainage function relationships. This is mainly because no drainage function relationship has been developed or verified for the waste material. Most of the existing water balance models simplify the drainage from waste layers by considering that unsaturated hydraulic conductivity varies linearly with moisture content. This is a very generalized assumption, whereas in reality hydraulic conductivity varies nonlinearly with the addition of moisture content. Furthermore, it also depends on the type of waste material, emplacement density and age of the material.

3 Changing conditions

Physical properties describing the retention and movement of water in waste material are assumed constant in time, although these properties change with time as waste decomposes. It is difficult to find the behaviour of these properties as a function of time, but a density approach can be successfully utilized for this purpose. As waste is compacted and placed in the landfill, it starts settlement as a result of overburden pressure and decomposition of waste material itself, which results in a change in density of material. So the density will have a significant effect on these physical properties of material. Presently, no model allows for changing conditions during the analysis period.

4 Leachate recirculation

Leachate recirculation is now practiced at many landfills sites to promote methanogenesis, by utilizing unused absorptive capacity of waste material and to produce a more uniform quality of leachate throughout the landfill. The process includes the irrigation of leachate collected at the bottom on the surface of landfill (mostly below the landfill cover). This phenomena is not included in the existing landfill leachate production models.

5 Ground water table

Normally landfills are designed and build above the level of ground water table, in order to prevent water ingress to the landfill site. This assumption seams to be valid from the practical point of view. There is no consideration given in the existing models to the ground water table. In cases, when there is a possibility of leachate seepage from the landfill boundary, the height of water table should be taken into account.

6 Software capability

Most of the existing models work in a batch mode which besides being time consuming are less informative. None of the models has an user interactive interface facility and has no option for drawing the landfill and its components. The user interactive interface facility increases the effectiveness of the model utilization and offers more options for the user to design different alternatives. Model software capabilities can be improved by developing a menu driven system.

Chapter 5

HYDRAULIC PROPERTIES OF WASTE MATERIALS

This chapter discusses hydraulic properties such as: moisture capacities, hydraulic conductivity and density for waste materials, and the factors affecting these properties. Particular consideration is given to municipal solid waste (MSW) because of increasing concern over the longer term sustainability of landfill operations within the UK. MSW is a heterogeneous mixture of wastes which are primarily of residential and commercial origin, and typically consists of food and garden wastes, paper products, plastics and rubber, textiles, wood and fines.

The literature reveals that limited information is available on hydraulic properties of waste. Although some information is available this is not categorised relating to type of waste material or any other relevant property (for example density). Furthermore, there is a discrepancy in defining some of these properties. The main concern here is to summarise all information available from the literature and put it together in order to make it more conclusive. Some of these individual physical properties will then be used in situations where actual observations are not available.

5.1 Moisture Retention Parameters

Prior to considering the physical properties of waste material, it is necessary to understand the existence and behaviour of water in a soil system. A soil profile comprises a conglomeration of solid particles together with the void space between these particles. This void space may be filled with gas, liquid, or a combination of both. On the basis of three constituents of soil (solids, water and air), the relative quantity of liquid can be defined using a range of parameters. The most common of these are; the wet weight moisture content, the dry weight moisture content, the volumetric moisture content, and the degree of saturation. These parameters are also applicable to waste matrix and are briefly explained in the next paragraphs.

Wet weight moisture content (θ_w)

This relates the mass of water in a soil (M_w) to the total mass (M_t) (Equation 5.1). It has a lower limit of 0 (dry soil) with a theoretical upper limit approaching 1.0.

$$\theta_w = M_w / M_t \tag{5.1}$$

Dry weight moisture content (θ_d)

This relates the mass of water in a soil (M_w) to the mass of solid particles (M_s) (Equation 5.2). It has a lower limit of 0 (dry soil) with a theoretical upper limit approaching infinity.

$$\theta_d = M_w / M_s \tag{5.2}$$

Volumetric moisture content (θ)

This is the ratio of the volume of water in a soil (V_w) to the total volume of the soil (V_t),

$$\theta = V_w / V_t \tag{5.3}$$

It has a lower limit of 0 (dry soil) with a theoretical upper limit approaching

1.0; for a given soil system, the upper limit of θ equals the porosity of the soil. This measure of moisture content is particularly useful in hydrology since it can be used to evaluate the equivalent depth of soil moisture storage.

Degree of saturation (S)

The degree of saturation is the ratio of the volume of water (V_w) to the total volume of voids (V_v) in a sample (Equation 5.4). It has a lower limit of 0 (dry soil) and an upper limit of 1.0 (saturated soil).

$$S = V_w / V_v \tag{5.4}$$

There is a direct relationship between wet weight moisture content and dry weight moisture content, between volumetric moisture content and degree of saturation, and between volumetric moisture content and wet weight moisture content. These relationships are often of practical use and are given below.

$$\theta_w = \theta_d / (1+\theta_d) \tag{5.5}$$

$$\theta_d = \theta_w / (1-\theta_w) \tag{5.6}$$

$$S = \theta/\alpha \tag{5.7}$$

$$\theta = \theta_d (\rho_{db} / \rho_w) \tag{5.8}$$

where:

α = is called void ratio, and is the ratio of the volume of voids (V_v) to the volume of solids (V_s).

ρ_{db} = is dry bulk density of the sample, and is defined as the ratio of mass of dry solids (M_s) to total volume (V_t).

ρ_w = is density of water equal to 1000 kg/m^3

5.2 Physical Properties of Waste

A body of waste material is generally considered as being hydraulically similar to a soil system. The parameters used to define the hydraulic characteristics of a soil can therefore be used in describing waste bodies. Theses include; initial capacity, field capacity, saturation capacity and hydraulic conductivity. A further parameter is introduced which is specific to waste bodies, termed the absorptive capacity (Campbell, 1982). So the waste in a site has four significant moisture capacities, which in ascending order are; the initial moisture, the absorptive capacity, the field capacity and the saturation capacity. These capacities are defined below.

Initial moisture capacity

It is the moisture held by capillary action within the micro-pores of the waste itself and within voids in the waste.

Absorptive Capacity

It represents the lower limit of moisture content at which the waste body will produce leachate.

Field Capacity

It is the moisture content that previously saturated waste will drain down to.

Saturation Capacity

It is the moisture content at which all the void space of waste matrix is used for liquid retention.

The assumption that the initial moisture is less than the absorptive capacity is normally true; but each of the initial moisture and the absorptive capacity will only be attained once in the lifetime of a landfill.

As percolation or rainfall enters the site, the moisture content will rise from the initial level towards the absorptive capacity. Once the absorptive capacity is reached, during rising moisture conditions, leachate production will commence. At this moisture content the principal flow mechanism is pipeflow, or channelling, and the moisture content of the material surrounding the channels will be higher than absorptive capacity; but away from the channels it will be lower. Thus, the material itself still has the ability to absorb more liquid.

Before field capacity the overall moisture content will rise further, at the same time as continuing leachate generation. Field capacity is the moisture content at which free drainage, beginning from saturation and following the drainage curve, just stops. After the field capacity is reached, the moisture content of waste is more in equilibrium; there would not be as much variation throughout the waste. At field capacity, the moisture content will not fall below this level under gravity alone, a similar definition to a soil. Normally, just above field capacity the waste will absorb and release liquid slowly, but at higher levels the pipeflow phenomenon will begin to dominate. At higher moisture contents the flow will be relatively rapid, but nearer field capacity the flow will be low and sustained.

A waste body which has reached field capacity is capable of taking up additional liquid up to the point of saturation, if the infiltration continued. This upper limit of moisture content is termed as saturation capacity. The liquid which is in excess of the absorptive capacity of the waste material is termed free leachate. This free leachate is able to move, under the forces of gravity, through the landfill site; and, if allowed, to drain from the site.

Typical values of initial capacity, absorptive capacity, field capacity and saturation capacity are given in DoE, Waste Management Paper No. 26; and are shown in Figure 5.1. The data given in Table 5.1 is extrapolated from Figure 5.1, and relates the initial dry density of waste to the amount of water which must be added in order to achieve various levels of wetness. Initial moisture content will typically be 0.20 - 0.30 on wet weight basis.

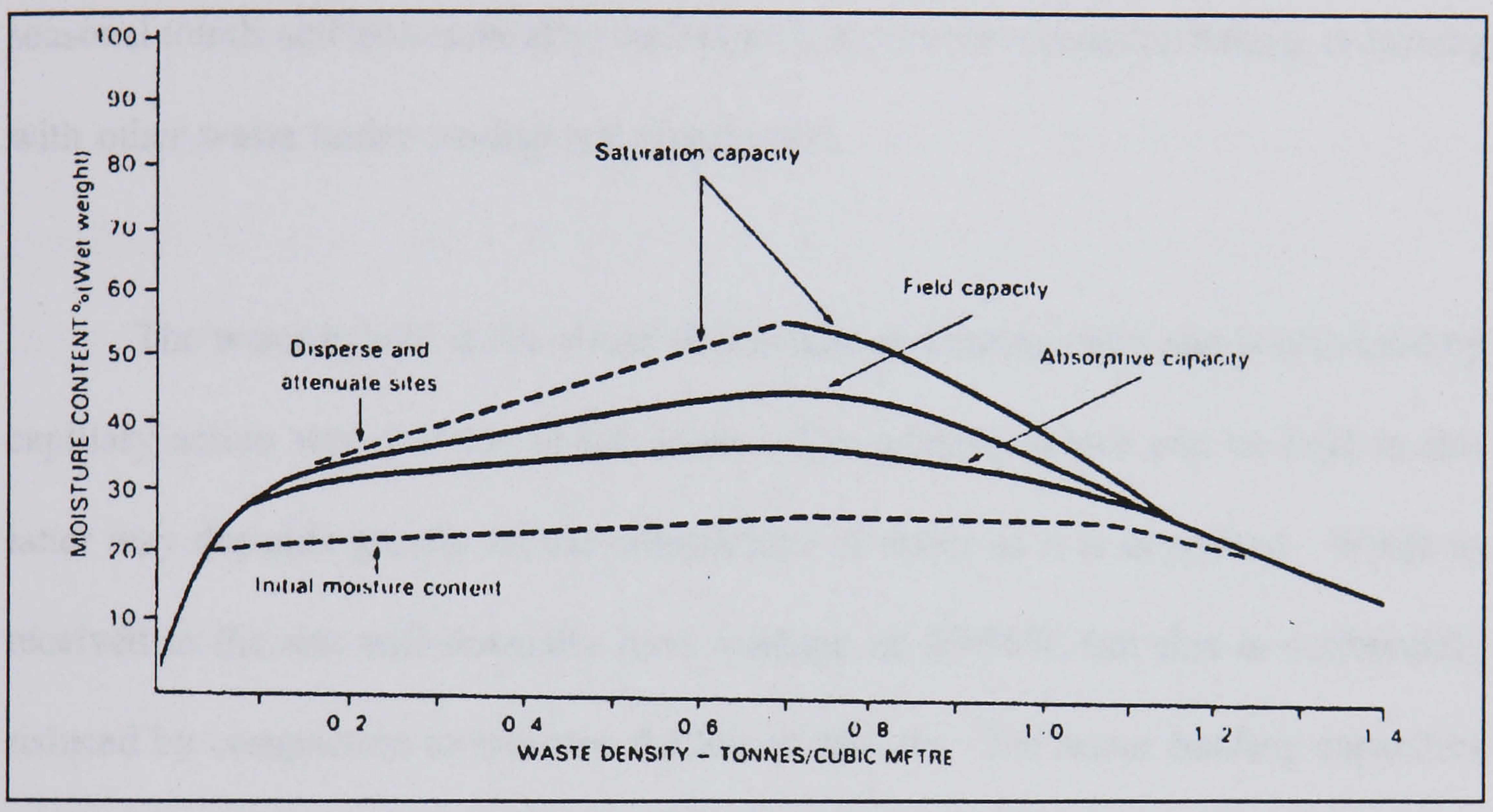


Figure 5.1. Relationship between waste moisture capacities and densities (DoE, 1986)

Table 5.1. Values of moisture capacities (DoE, 1986).

Waste density (Tonnes/m^3)	Wet weight basis		
	θ_{abc}	θ_{fc}	θ_{sat}
0.6	0.36	0.43	0.50
0.7	0.36	0.45	0.55
0.8	0.36	0.43	0.50
0.9	0.33	0.40	0.45
1.0	0.31	0.36	0.40
1.1	0.27	0.30	0.33
1.2	0.23	0.23	0.23

5.2.1 Initial Moisture Content

The initial moisture content of waste is one of the most important in-situ factors affecting the quantity and quality of leachate produced. Its value is practically taken as the average moisture content that waste contains when first received at the site for disposal. The value of initial moisture content is dependent on waste type, seasonal trends and treatment after collection (i.e. wet pulverisation, baling, or mixing with other waste under co-disposal conditions).

The water is held in the waste chemically and biologically and is also held by capillary action within voids in the waste. The quantity which can be held in this latter way depends greatly on the compaction of waste as it is deposited. Waste as received at the site will normally have voidage of 20-35%, but this is deliberately reduced by compaction to increase the life of the site. The water holding capacities of waste as reported by Fenn et al. (1975) are given in Table 5.2., which shows initial moisture content of 10 - 20 % on volume basis. A typical value of 35 % of dry weight (26 % on wet basis) is often used for general purpose.

Table 5.2. Water Holding Capacity of Waste (Fenn et al., 1975).

Point in time	% by volume	Equivalent mm of water per m of waste	Equivalent gallons of water per yd^3 of waste
At placement time	10 - 20	150	30
At field capacity	20 - 35	300	60
At saturation (porosity=0.4)		550	110

5.2.2 Absorptive Capacity

As water infiltrates through the waste, the moisture content will rise from the initial level towards the absorptive capacity. As this capacity is exceeded by further infiltration, leachate emissions commence. This may be attributed to channelling or pipeflow, due to the heterogeneity of the waste mass, or to high-intensity, short duration precipitation which exceeds the maximum rate at which waste can absorb rainfall. The absorptive capacity of the waste controls the magnitude of water flowing through the waste and, consequently, controls the amount of leachate produced. Waste is capable of retaining a certain quantity of water in addition to its initial moisture content. This retention quantity can be determined when the initial waste moisture plus the added moisture just causes gravity drainage.

The absorptive capacity of waste is not a fixed variable, but differs as a result of:

1. Waste pretreatment practices such as baling and pulverization, affect absorptive capacity. Pulverisation of waste leads to particle size reduction, which results up to a threefold increase in the absorptive capacity of waste, by provision of additional void spaces, while baling has an opposite effect.

2. *Emplaced waste density:* The amount of liquid which can be retained in waste is inversely proportional to its density. In one experiment when emplacement waste density was increased from 0.7 to 1.0 tonne/m^3 this resulted in a reduction from 100 to 24 litres of leachate/tonne (w/w) and is also accompanied by a much slower rate of percolation (Campbell, 1982).

3. The method of collection, the method of storage, and the amount of precipitation are important. It has been shown that publicly collected domestic waste has an average moisture content approximately double that of privately collected waste (Senior, 1990). The effect of a high rainfall event would be to encourage short-circuiting.

4. Waste composition is another factor which affects absorptive capacity, for example paper may absorb water in excess of 250 % of its own weight.

5. Site and operational methods result in a variation in the value of absorptive capacity. If waste is deposited in layers instead of single layer, it will normally result in reduction in absorptive capacity. It has been shown that in highly compacted landfills, leachate production rates correspond to 15 to 20% of annual precipitation, whereas in those with lower compaction leachate production was between 25 and 50% of annual precipitation (Senior, 1990).

The relationship between absorptive capacity and the in-situ density of waste has been discussed by a number of workers. When waste density was increased over the range 250 to 500 kg/m^3, the absorptive capacity expressed as weight of moisture per unit weight of waste changed slightly, decreasing from about 63 to 57% (Stegmann, 1982).

Empirical figures for absorptive capacity as reported by Campbell (1982), are in the range of 0.1 m^3/tonne at densities of about 0.7 tonnes/m^3 falling to between

0.02 to 0.03 m^3/tonne at densities of 1.0 tonne/m^3. Such figures ignore the effects of short circuiting by preferential pathways through waste and the effects of high rainfall intensity. Greater absorption may be achieved by leachate recirculation.

5.2.3 Field Capacity

The moisture content at which free drainage, beginning from saturation and following the drainage curve, just stops, is the field capacity. The field capacity of waste is affected by its composition, age, and the density to which it has been compressed.

It is obvious that as decomposition and compaction of waste occurs in a landfill, the field capacity will progressively decrease. The literature records values for the field capacity of waste that vary from 80% for fresh waste (Campbell, 1983) to between 63% and 74% for waste more than four years old (Holmes, 1980). These figures obviously depend both on the composition of the waste and the method of determining the dry mass.

The results of two independent studies by Roper & Fongoqa (1988) and by the second author are summarised in Figure 5.2. The waste contained on a dry weight basis 54% organic, 23% paper, 9% glass, 8% plastic and 6% metal. The figure shows field capacities that range from 225% for fresh waste predominantly of paper and cardboard, to around 55% for 1-5 year old wastes after compression to high densities. The other reason in wider variation of field capacity is composition of waste itself.

Since field capacity is not a constant, but a function of the waste composition, processing, and climate, therefore reasonable approximation of its value cannot be ascertained. As a rule of thumb, however, moisture contents of the waste at field capacity have been found to range between 30% and 45% of the volume.

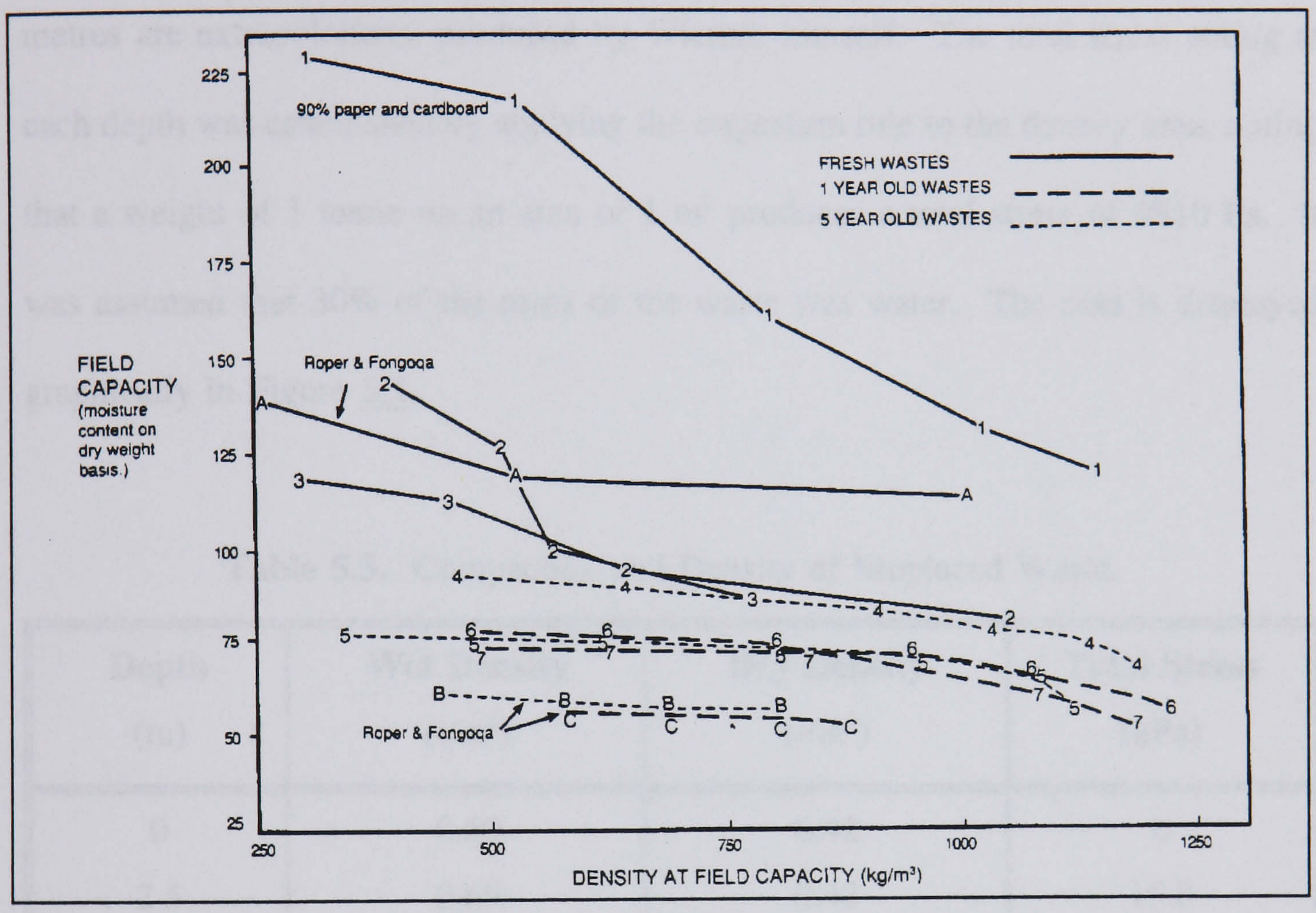


Figure 5.2. Measurements of the field capacity of waste (Roper & Fongoqa, 1988).

5.2.4 Saturation Moisture Content

The saturation capacity is the moisture content at which all the void space is occupied by the liquid. Such a level would only occur in practice if the landfill site is fully contained and no leachate is allowed to drain. The saturation capacity of waste is affected by its type, age, and emplaced density. Saturation capacity is expected to decrease with higher compaction and with time due to settlement and biodegradation.

5.3 Compaction and Density of Emplaced Waste

Table 5.3 is the data of Wiemer (1982) for the densities of samples extracted from a selection of West German Landfill Sites. The values for depths below 25 metres are extrapolations, produced by Wiemer himself. The total stress acting at each depth was established by applying the trapezium rule to the density area, noting that a weight of 1 tonne on an area of 1 m^2 produces a total stress of 9810 Pa. It was assumed that 30% of the mass of the waste was water. The data is displayed graphically in Figure 5.3.

Table 5.3. Compaction and Density of Emplaced Waste.

Depth (m)	**Wet Density** (t/m^3)	**Dry Density** (t/m^3)	**Total Stress** (kPa)
0	0.60	0.42	0
2.5	0.69	0.48	15.8
5	0.76	0.53	33.6
7.5	0.82	0.57	53
10	0.86	0.60	73.6
15	0.90	0.63	117
20	0.94	0.65	162
25	0.96	0.67	208
30	0.98	0.69	256
35	0.99	0.69	304
40	1.00	0.70	353

N.B. The author of this data describes the stresses as effective stresses instead of total stresses which they are using in data.

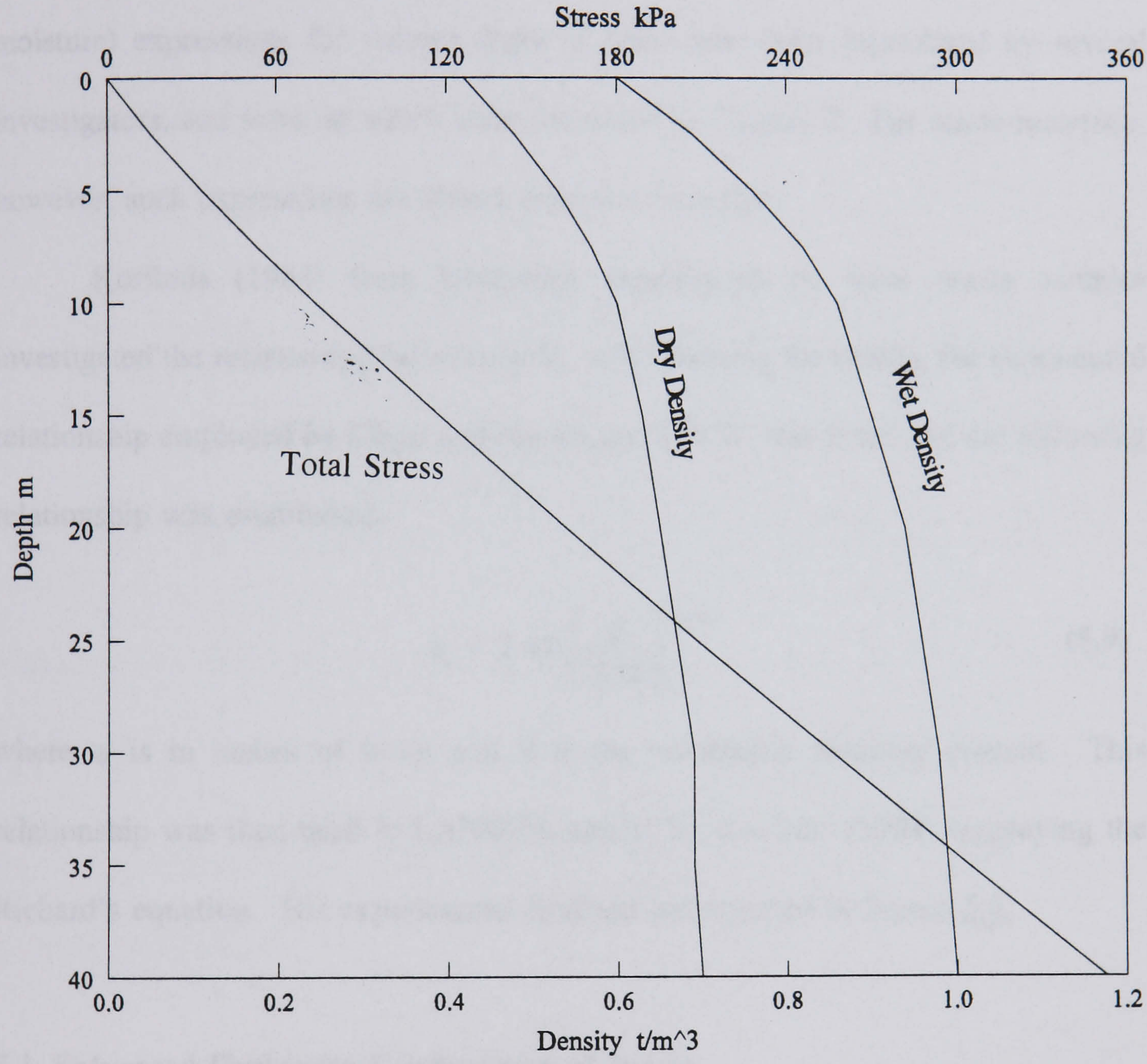


Figure 5.3. Landfill Density and Compaction.

5.4 Moisture content versus suction

Moisture suction is a measure of the energy required to extract water from the porous material in which it is held. It is extremely difficult to measure this parameter for waste material. Moisture suction information is used in the porous media models used for leachate production, as discussed in Chapter 4. Empirical ψ-θ (suction-moisture) expressions for various types of soils have been formulated by several investigators, and some of which were discussed in Chapter 2. For waste materials, however, such expressions are absent from the literature.

Korfiatis (1984) from laboratory experiments on three waste samples investigated the relationship between ψ-θ. After plotting the results, the exponential relationship employed by Clapp and Hornberger (1978) was fitted and the following relationship was established.

$$\psi = 2.45\left(\frac{\theta}{0.55}\right)^{-1.50} \tag{5.9}$$

where ψ is in inches of water and θ is the volumetric moisture content. This relationship was then used in LANDFIL model by Korfiatis (1984) employing the Richard's equation. His experimental findings are reported in Figure 5.4.

5.4 Saturated Hydraulic Conductivity of Waste

Saturated hydraulic conductivity is the rate at which water drains through a saturated waste body under a unit pressure gradient. Its value is affected by type, age and density of waste. The data regarding the saturated hydraulic conductivity of waste has been reviewed and a summary is presented in Table 5.4. Inspection of this table reveals a range of K_s values for a variety of waste types, states of compaction

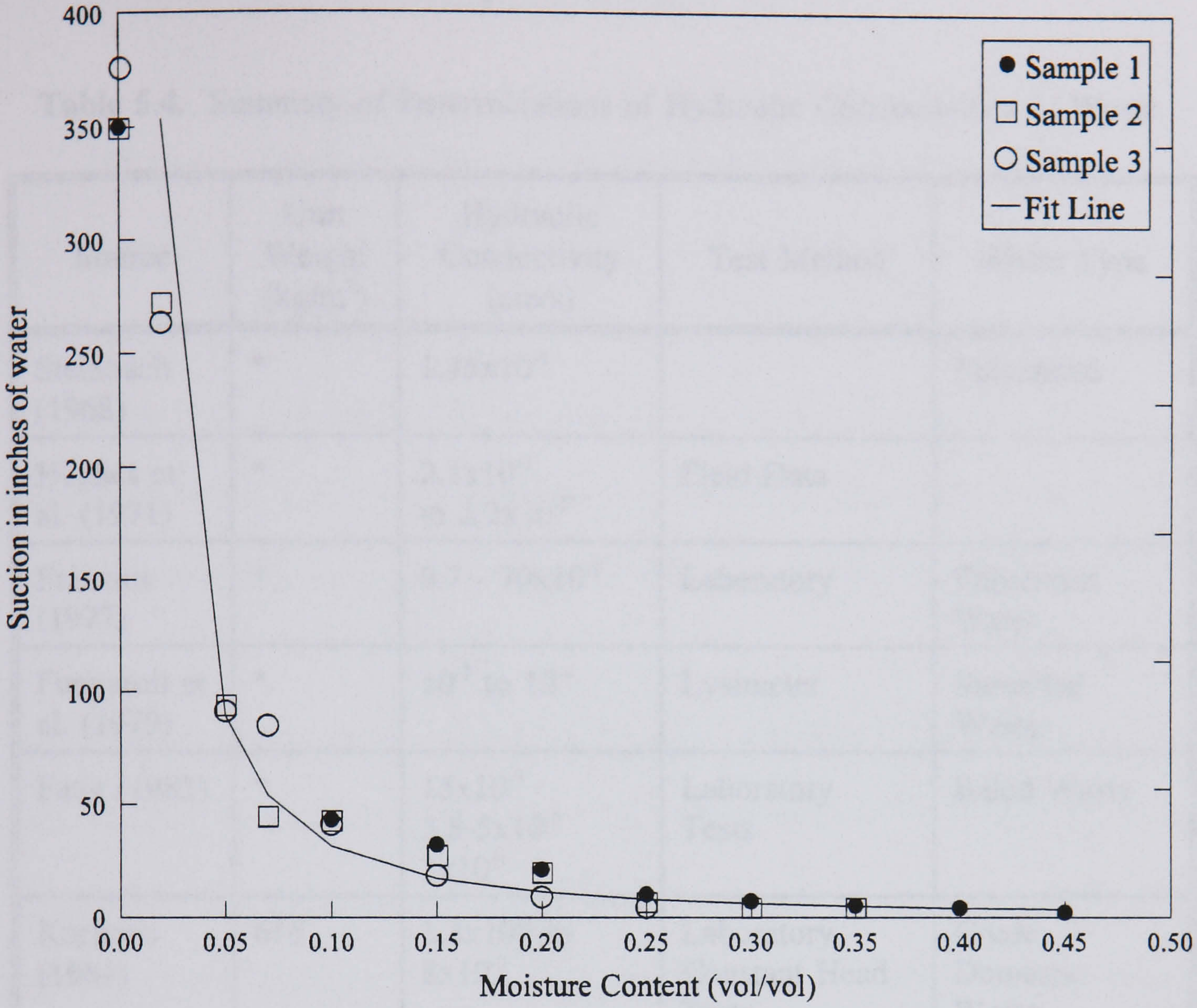


Figure 5.4. Relationship of Suction and Moisture content for waste (Korfiatis, 1984).

and testing methodologies. Therefore, cross correlation between the results reported is made very difficult.

Ahmed et al. (1993) performed field scale investigation on leachate flow in Fresh Kills landfill at Staten Island, New York. They found an estimated value for hydraulic conductivity to be 0.00176 cm/sec. For the same site a value of 0.0036 cm/sec was determined in year 1983. The reason for decrease in hydraulic conductivity value has not been given by the authors. However, it appears to be due to the effect of compaction and decomposition which occurred over ten years.

Table 5.4. Summary of Determinations of Hydraulic Conductivities of Waste.

Source	Unit Weight (kg/m^3)	Hydraulic Conductivity (cm/s)	Test Method	Waste Type
Steinbach (1968)	*	$1.45x10^{-1}$		Pulverised
Hughes et al. (1971)	*	$2.1x10^{-2}$ to $2.2x10^{-5}$	Field Data	
Franzius (1977)	*	$0.7 - 70x10^{-3}$	Laboratory	Pulverised Waste
Fungaroli et al. (1979)	*	10^{-2} to 10^{-4}	Lysimeter	Shredded Waste
Fang (1983)	*	$15x10^{-3}$ $3.5\text{-}5x10^{-3}$ $7x10^{-4}$	Laboratory Tests	Baled Waste
Korfiatis (1984)	616	$1.3x10^{-2}$ to $8x10^{-3}$	Laboratory Constant Head Tests	Crude Domestic Waste
Oweis and Khera (1986)	*	$1x10^{-3}$ $2.6x10^{-3}$	Pumping Test Water Budget	Crude Domestic Waste
Ettala (1987)	Dense Loose	$2.5x10^{-2}$ to $5.9x10^{-3}$ 2.1 to $2.5x10^{-1}$	Pumping Test	Crude Domestic Waste
Oweis et al. (1990)	*	$1x10^{-3}$ $1.1x10^{-3}$ $1.5x10^{-4}$	Pumping Test Falling Head in Field Test Pit	Crude Domestic Waste
Ahmed et al. (1993)	*	$1.17x10^{-3}$ (1993) $3.6\ x10^{-3}$ (1983)	Pumping Test	Fresh Kills Landfill NY

* - not mentioned

5.6 Models of Unsaturated Hydraulic Conductivity

Different models, describing unsaturated hydraulic conductivity (K) are used in the leachate production models discussed in Chapter 4. Most of them use K-θ functional relationships to describe the movement of water and leachate in the unsaturated zone of landfill. The models based on Richard's equation utilize K-θ relationship except LSM model as reported in Table 5.5. The LSM model required the K-ψ relationship because it is based on Richard's equation (ψ-based).

Using porous media equations for the unsaturated zone increases the complexity of the problem in three ways. First the solution of Richard's equation is not simple. Second the K-θ or K-ψ models were primarily developed for soil systems, not yet being verified for the waste materials. Thirdly the parameters of those models are not commonly available and are difficult to measure in real situations.

The leachate production models based on the water balance approach have employed a linear relationship to model the unsaturated hydraulic conductivity of the form $K = K_s f(\theta)$. The reason for this approach being used is that as moisture of waste increases from field capacity to saturation capacity, the resulting unsaturated hydraulic conductivity increases from 0 to saturated hydraulic conductivity, respectively. Only two relationships of K used in the HELP and SLAMS models are discussed here and are given in Table 5.6.

Table 5.5. Different Hydraulic Conductivity Functions used in Porous Media Models.

Model	Unsaturated Hydraulic conductivity function	Coefficients
LANDFIL Korfiatis(1984)	Campbell (1974) $K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^B$ Clapp and Hornberger (1978) $\psi = \psi_s\left(\frac{\theta}{\theta_s}\right)^{-b}$	b = 7 B = 9 ψ_s/θ_s = 100 cm K_s = 1.83 cm/day
LANCEL Rice (1985)	Gardner and Mayhugh (1958) $K(\theta) = e^{a\theta - b}$	a = 33 b = 14.33067
LSM Meeks (1988)	van Genuchten (1980) $S_e = \begin{cases} [1+(\alpha\|\psi-\psi_a\|)^{\beta}]^{-\gamma} & \psi<\psi_a \\ 1 & \psi\geq\psi_a \end{cases}$ van Genuchten (1980) $k_{rw} = S_e^{½}\left[1 - (1 - S_e^{1/\gamma})^{\gamma}\right]^2$ or Brooks and Corey (1966) $k_{rw} = S_e^n$	$\gamma = 1 - \frac{1}{\beta}$ $k_{rw} = \frac{K}{K_w}$ $S_e = \frac{S_w - S_{wr}}{1 - S_{wr}}$
FILL Ahmed (1992)	Campbell (1974) $K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3}$ Bristow and Williams (1987) $\psi = \psi_e\left(\frac{\theta}{\theta_s}\right)^{-b}$	b = 4.0 θ_f = 0.046 θ_s = 0.417 ψ_e = 45.72 cm K_s = 0.02 cm/s

N.B. θ is on volumetric basis.

Table 5.6. Hydraulic Conductivity Models used in HELP and SLAMS Models.

Model	Unsaturated Hydraulic conductivity function	Coefficients
HELP Schroeder (1984)	Version-1 Linear function of soil moisture $K(\theta) = K_s \left(\frac{\theta - \theta_f}{\theta_s - \theta_f} \right)$	$K_s = 0.72$ cm/day $\theta_s = 0.520$ $\theta_f = 0.294$
	Version-2 Campbell (1974) equation $K(\theta) = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{3 + \frac{2}{\lambda}}$ Brooks and Corey (1964) $\left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) = \left(\frac{\psi_b}{\psi} \right)^{\lambda}$	$K_s = 2 \times 10^{-4}$ cm/sec $\theta_w = 0.140$ $\theta_f = 0.294$ $\theta_s = 0.520$ $\theta_r = 0.015$ $\lambda = 0.211$ θ is on volume basis
SLAMS Dickson (1987)	$K = K_s f(\theta)$ $f(\theta)$ is a twin power function of (θ_a, θ_f and θ_s).	$K_s = 8.00$ cm/day $\theta_a = 0.55$ $\theta_f = 0.80$ $\theta_s = 1.25$ θ on dry weight basis

In the HELP model (version-1), the unsaturated hydraulic conductivity is modelled as a function of soil moisture and varies from zero to K_s (Schroeder et al., 1983)

$$K(\theta) = K_s \left(\frac{\theta - \theta_f}{\theta_s - \theta_f} \right) \tag{5.10}$$

where θ is the initial moisture content of the soil.

Equation 5.10 is used for both the soil cover and waste material of the landfill corresponding to their moisture capacities and K_s values. The default physical properties for waste used in the HELP model are given in Table 5.6.

In version-2 of the same model, K(θ) is calculated by the Campbell (1974) equation which is based on the Brooks and Corey (1964) model given as.

$$K(\theta) = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{3 + \frac{2}{\lambda}} \qquad \textbf{(5.11)}$$

where λ is a pore index, imposing further parameter and is difficult to measure for waste.

The percolation from the bottom of a waste layer in the SLAMS model is calculated by the following relationship as reported by Dickson (1987).

$$K = K_s f(\theta) \qquad \textbf{(5.12)}$$

where

K = percolation from bottom of layer j [m/s]

K_s = saturated hydraulic conductivity [m/s]

f(θ) = function of moisture content in layer j [by dry weight]

The inhomogeneity of the material means that the definition of the function could not be exact, but would be a rule of thumb solution following guidelines based on observation (Dickson, 1987). The author established two types of relationships between moisture contents (i,e., absorptive, field and saturation capacity) and saturated hydraulic conductivity of waste as:

1. A twin linear relationship
2. A twin power relationship

The latter relationship of f(θ) which is a twin power function of (θ_a, θ_f and θ_s) was then employed in the SLAMS model. This formulation is logically correct but it appears to be mathematically incorrect.

The three K-θ models are compared as shown in Figure 5.5 using the default data of the HELP model given in Table 5.6. The linear model simplified the process between the two limits i.e., field and saturation capacities. The other two functions relate that hydraulic conductivity increases slowly upto moisture content of 0.40 vol/vol and then increases rapidly. But there is no consideration given for the type and density of waste material, and also the parameters are not well defined.

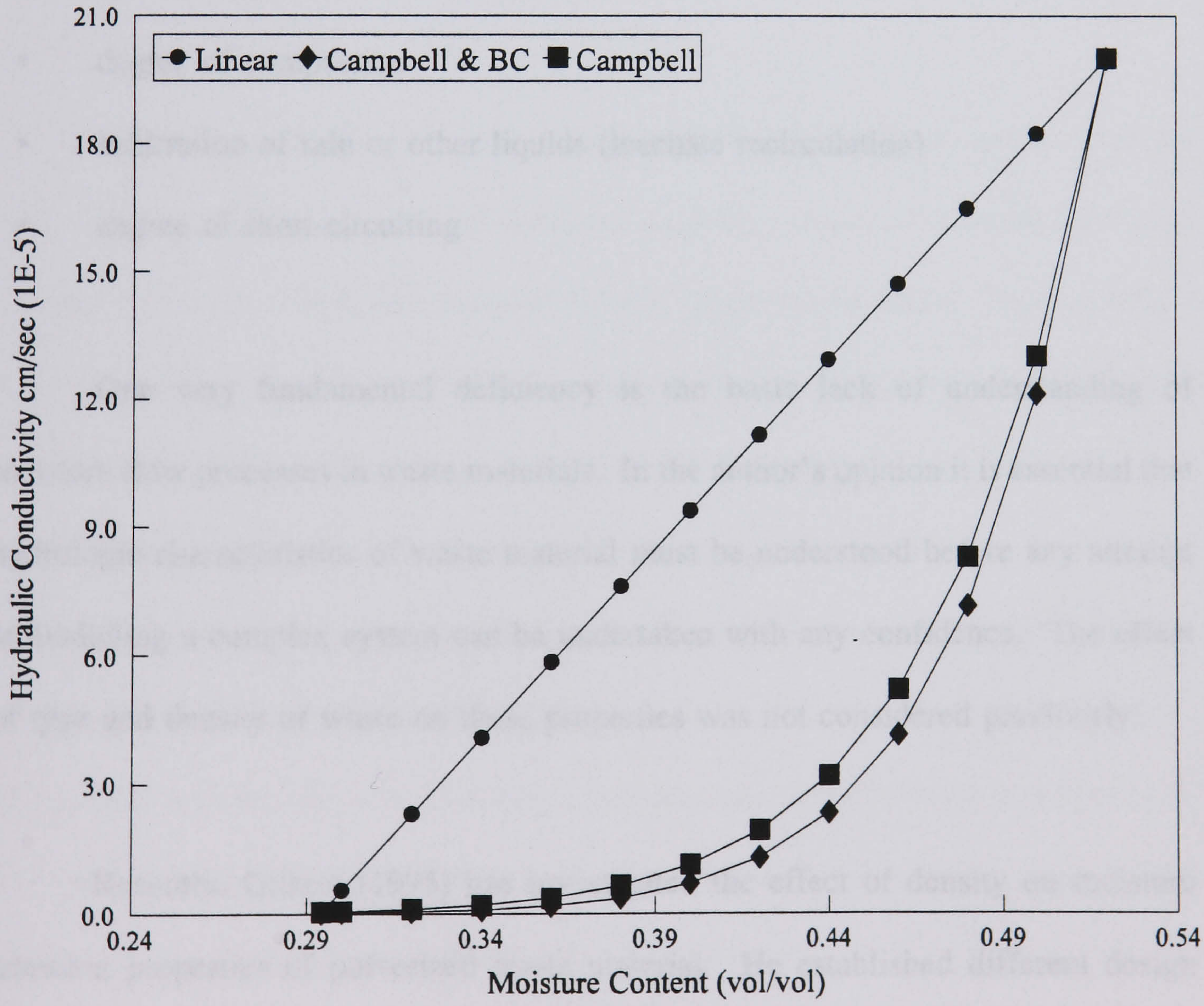


Figure 5.5. Comparison of three K-θ Models.

5.7 Concluding Remarks

Various hydraulic properties of waste material are reviewed in this chapter, showing wide discrepancy in their values. These include moisture retention properties (such as initial, field, absorptive and saturation capacities) and movement of water within the waste matrix (such as drainage and permeability). A great deal of uncertainty exists regarding these properties, particularly since this depends on a variety of factors, for example:

- type and age of waste material
- initial moisture content (taken as on arrival at the site)
- degree of compaction
- infiltration of rain or other liquids (leachate recirculation)
- degree of short-circuiting

One very fundamental deficiency is the basic lack of understanding of moisture flow processes in waste materials. In the author's opinion it is essential that hydrologic characteristics of waste material must be understood before any attempt at modelling a complex system can be undertaken with any confidence. The effect of type and density of waste on these properties was not considered previously.

Recently, Gilbert (1995) has investigated the effect of density on moisture retention properties of pulverized waste material. He established different design curves for field and saturation capacities in relation to the density of waste material.

He also investigated the effect of density on the internal drainage characteristics of pulverized waste. He recommended that Irmay's (1950) model can be used to determine the drainage rate from the waste layer.

Another important parameter of the waste matrix is its permeability to allow movement of water. Since the waste permeability affects the rate of water percolation, such information is essential for the estimation of leachate production. It is obvious that as decomposition and compaction of refuse occur with time, the aforementioned parameters will also change. The movement of water through waste has not been thoroughly investigated, so a correlation between permeability and density can be not established.

It is obvious that the hetroegenity of waste material leads to significant errors in the leachate estimation. Further the continuous degradation of material itself may change the density which affects other physical properties of waste. There is thus a need to establish a relationship for the vertical and horizontal saturated hydraulic conductivities of the waste material, in terms of waste type and dry density. It is obvious that a high degree of variability will be associated with any such a relationship as a consequence of the other influential factors; heterogeneous nature of material, measurement precision, precision of density control, experimental system, etc., which will be difficult to take into account. A research study is proposed to investigate the effect of compaction on the permeability of waste material, the methodology of which is presented in the next chapter.

Chapter 6

EXPERIMENTAL INVESTIGATION

One of the main objectives of this research was to investigate the effect of compaction on both vertical and horizontal hydraulic conductivities of waste. A series of laboratory experiments were undertaken in order to determine the relationship between waste density and saturated hydraulic conductivity. It is expected that the development of such a relationship will be beneficial in more accurately modelling the movement of leachate through landfill waste. In this chapter, the details of the experimentation and statistical analysis of the data are reported.

6.1 Theoretical Considerations

Hydraulic conductivity expresses the ease with which a fluid can be conveyed through a porous medium and is a function of the properties of both the porous medium and the fluid (Mills et al., 1985b). Measurements of hydraulic conductivity can be made in the field and in the laboratory. Field measurements are generally perceived to provide more accurate and reliable data, but are both costly and time consuming, and therefore less frequently used. Laboratory tests are generally easier to perform but there are certain difficulties associated with them. The size of the sample may not be large enough to be representative of field conditions, the sample may be disturbed during sampling presenting difficulties with reconstruction within the laboratory, or in certain circumstances it may not be feasible to obtain an appropriate sample. In cases where the hydraulic conductivity is to be determined for a compacted sample, and the specimen is prepared by laboratory compaction, this may not be truly representative of the material in the field. Anisotropy in the material's hydraulic conductivity will yield erroneous values if the direction of the flow in the laboratory does not correspond to the field flow direction.

Due to time constraints and also practical considerations, it was decided that the experimental investigation should be restricted to a series of bench scale tests in the laboratory. A number of factors influenced this decision:

- The need to adopt a procedure whereby the vertical and horizontal hydraulic conductivity could be isolated and measured directly with the necessary accuracy;
- The requirement that all variables such as density could be accurately controlled; and
- The need to obtain a large database of information to cover the range of material variability and for statistical analysis of the results.

Although standard methods are available for determining the hydraulic conductivity of soils, there is no agreed standard method for waste materials. Hydraulic conductivity is usually measured in laboratory tests using a constant head permeameter, for soils with relatively large permeability, or a falling head permeameter for soils with relatively low permeability. In both the cases water flows through a soil sample and the rates of flow and the hydraulic gradients are measured.

In the constant head test as illustrated in Figure 6.1 a, water from a constant head tank flows through the cylindrical soil sample and is collected in a measuring jar. The flow is steady state and, from the observations and using Darcy's law, the value of the coefficient of permeability (K) is determined as,

$$K = \frac{V\ L}{A\ t\ \Delta h} \tag{6.1}$$

where

t = time (sec)

V = the volume of water transmitted through the sample in time t (cm^3)

L = length of the sample between manometers (cm)

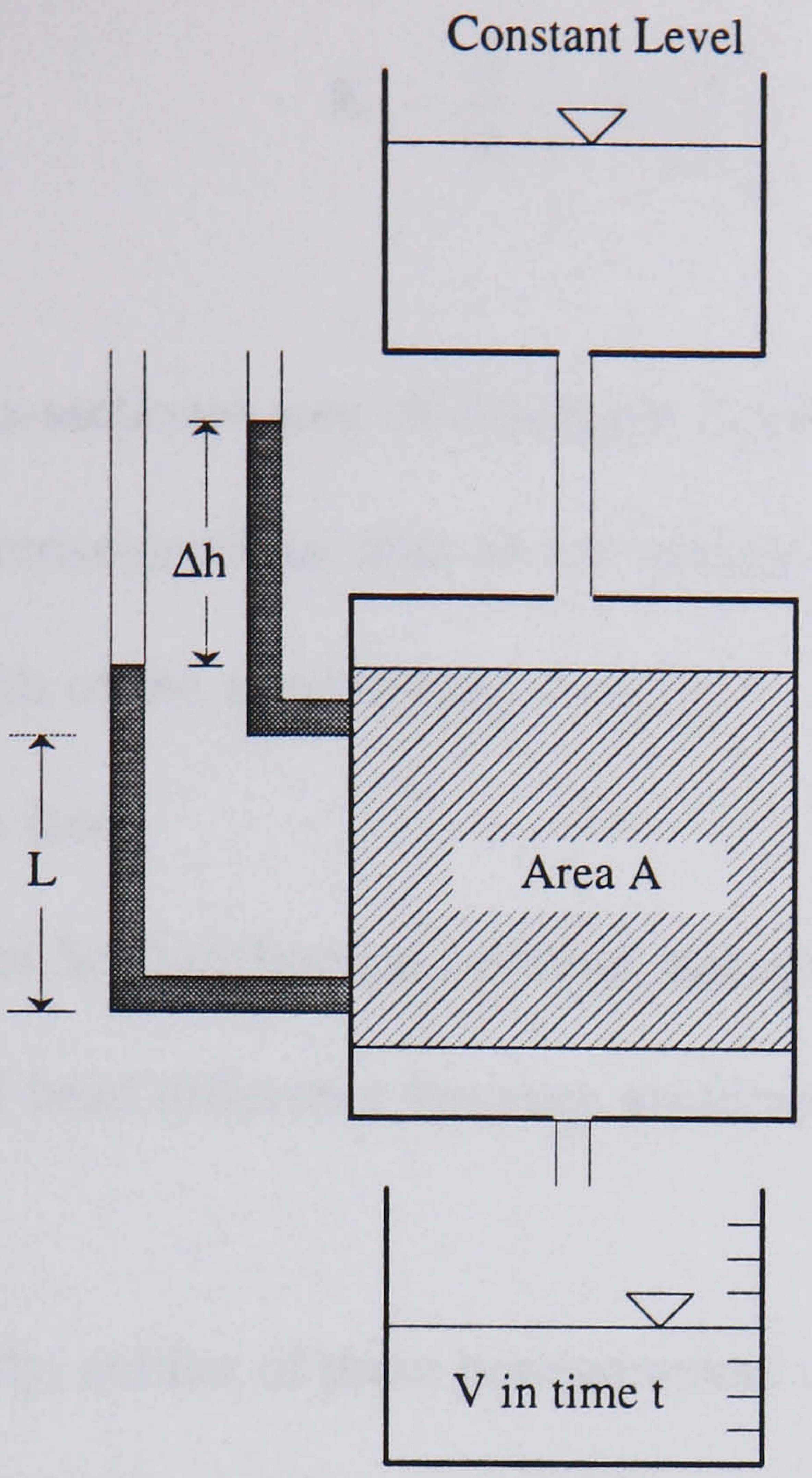
A = the cross-sectional area of the sample (cm^2)

Δh = difference of head in two manometers across the sample (cm)

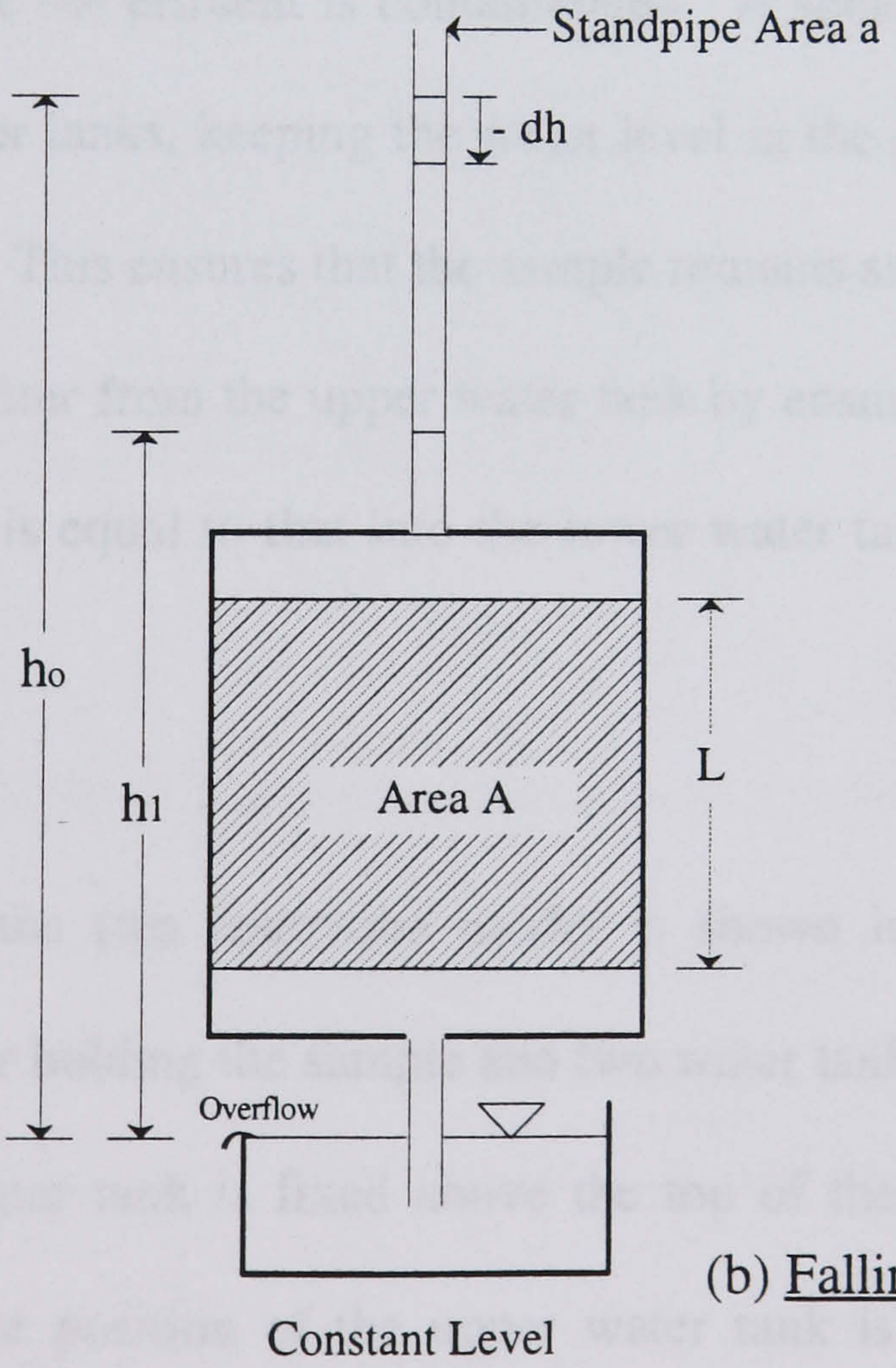
The arrangement for the falling head permeameter is illustrated in Figure 6.1 b. Water flows through the sample under an initial head difference of h_o, with this water level in the vertical standpipe reducing as flow progresses. After a period of time (t) the head difference is h_1. At any intermediate time interval the difference in total head between the top and bottom of the sample is given by h and its rate of change by -dh/dt. Since the head varies throughout the duration of the test, the rate of flow (q) during this time interval, using Darcy's law is:

$$q = -a \frac{dh}{dt} = K \frac{h}{L} A \tag{6.2}$$

A value of the coefficient of permeability (K) (cm/sec) is determined by integrating the above equation between limits of h_o and h_l for h and for time t,



(a) Constant Head Test



(b) Falling Head Test

Figure 6.1. Permeameters for determining Hydraulic Conductivtiy.

$$K = \frac{a}{A}\frac{L}{t}\ln\left(\frac{h_o}{h_1}\right) \tag{6.3}$$

where

a = cross-sectional area of standpipe (cm^2)

A = the cross-sectional area of the sample (cm^2)

L = length of the sample (cm)

t = time (sec)

h_o = initial head difference between standpipe and overflow tank (cm)

h_1 = final head difference between standpipe and overflow tank (cm)

For this study, neither of these permeameters were used because it is difficult to maintain the test under saturated conditions and practical issues relating to drainage of the test since the effluent is contaminated. A special permeameter was developed with two water tanks, keeping the water level in the lower tank above the top of the waste sample. This ensures that the sample remains saturated and provides a check on the loss of water from the upper water tank by ensuring the volume flow from the top water tank is equal to that into the lower water tank.

Two Reservoirs Model

A schematic of the two reservoirs model is shown in Figure 6.2, which consists of a container for holding the sample and two water tanks of equal size. The position of the lower water tank is fixed above the top of the container to ensure saturated flow, whilst the position of the upper water tank is variable to achieve hydraulic gradients ranging from 0 to 4.

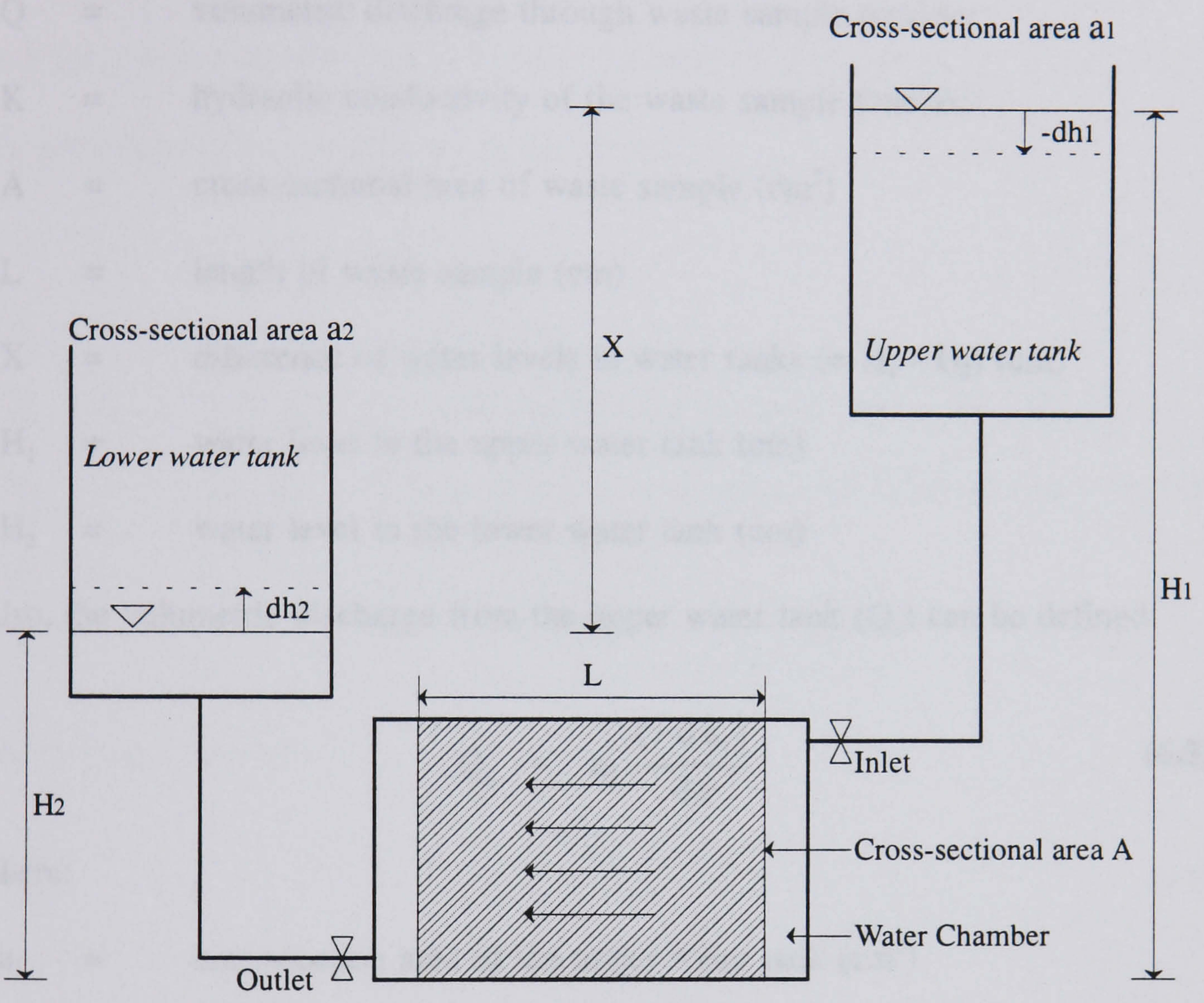


Figure 6.2. Schematic representation of two reservoirs model.

The flow through the sample in time dt is given by Darcy's law:

$$Q = K \frac{X}{L} A \tag{6.4}$$

where:

Q = volumetric discharge through waste sample (cm^3/sec)

K = hydraulic conductivity of the waste sample (cm/sec)

A = cross-sectional area of waste sample (cm^2)

L = length of waste sample (cm)

X = difference of water levels in water tanks ($= H_1 - H_2$) (cm)

H_1 = water level in the upper water tank (cm)

H_2 = water level in the lower water tank (cm)

Also, the volumetric discharge from the upper water tank (Q_1) can be defined:

$$Q_1 = a_1 \frac{(-dh_1)}{dt} \tag{6.5}$$

where:

a_1 = cross-section area of the upper water tank (cm^2)

dt = time increment (sec)

dh_1 = drop in water level in the upper water tank in time dt (cm)

The volumetric increase in discharge to the lower water tank in time dt will be equal to

$$Q_2 = a_2 \frac{dh_2}{dt} = -Q_1 \tag{6.6}$$

where:

a_2 = cross-section area of the lower water tank (cm^2)

dh_2 = increase in water depth in the lower water tank in time dt (cm)

Given that the cross-sectional area of the upper and lower water tanks is the same i.e., $a_1 = a_2 = a$, it can be concluded that the loss of head from the upper water tank (dh_1) will equal the gain of head in the lower water tank (dh_2) i.e., $dh_2 = dh_1 = dh$, provided there is no leakage in the system.

Let:

X_1 = initial difference of water levels in water tanks = $H_1 - H_2$

X_2 = difference of water levels in water tanks after time dt = $H_1 - H_2 - 2dh$

dX = $X_1 - X_2 = 2\,dh$

Equation 6.5 becomes

$$Q = -a\,\frac{dX}{2\,dt} \qquad (6.7)$$

Equating equations 6.4 and 6.7, and integrating from X_1 to X_2 for time period t,

$$K = \frac{aL}{2At}\ln\left(\frac{X_1}{X_2}\right) \qquad (6.8)$$

The above derived equation is only valid when X_2 is greater than 0.

6.2 Experimental Setup

To conduct both vertical and horizontal hydraulic conductivity tests a two reservoirs permeameter was designed and constructed. The instrumentation consisted of a container for holding waste, two water tanks, one for supplying water to the container and the other for collecting water from the container, two water depth gauges to measure changes in water levels in the water tanks and the necessary pipe connections. Two grids were designed in order to provide water to the chamber and to facilitate the water flow through a sample both in vertical and horizontal directions depending on their placement. A schematic of the permeameter and the details of instrumentation is shown in Figure 6.3.

The container was made of 1 cm thick PVC sheet, which had enough strength to withstand compaction, having inside cubic dimensions of 45 cm, provided with a top lid which was tightened by means of nuts and screws. Two grids of the same size were placed inside the container to provide water chambers at the ends to ensure a sufficient water supply to the sample. The grids were fabricated from hollow rectangular beam (2.5 x 5 cm cross-section) made of steel and provided with holes for connectivity as shown in Figure 6.4. These were placed at the bottom and on the top of the sample for vertical flow and at inlet and outlet faces for horizontal flow. A 45 cm square PVC sheet of 0.6 cm thickness was mounted on the top of the grids having 100 holes of 0.5 cm diameter for water flow, which provides a flow area of 19.63 cm^2 (Figure 6.5). The purposes of the PVC sheets were:

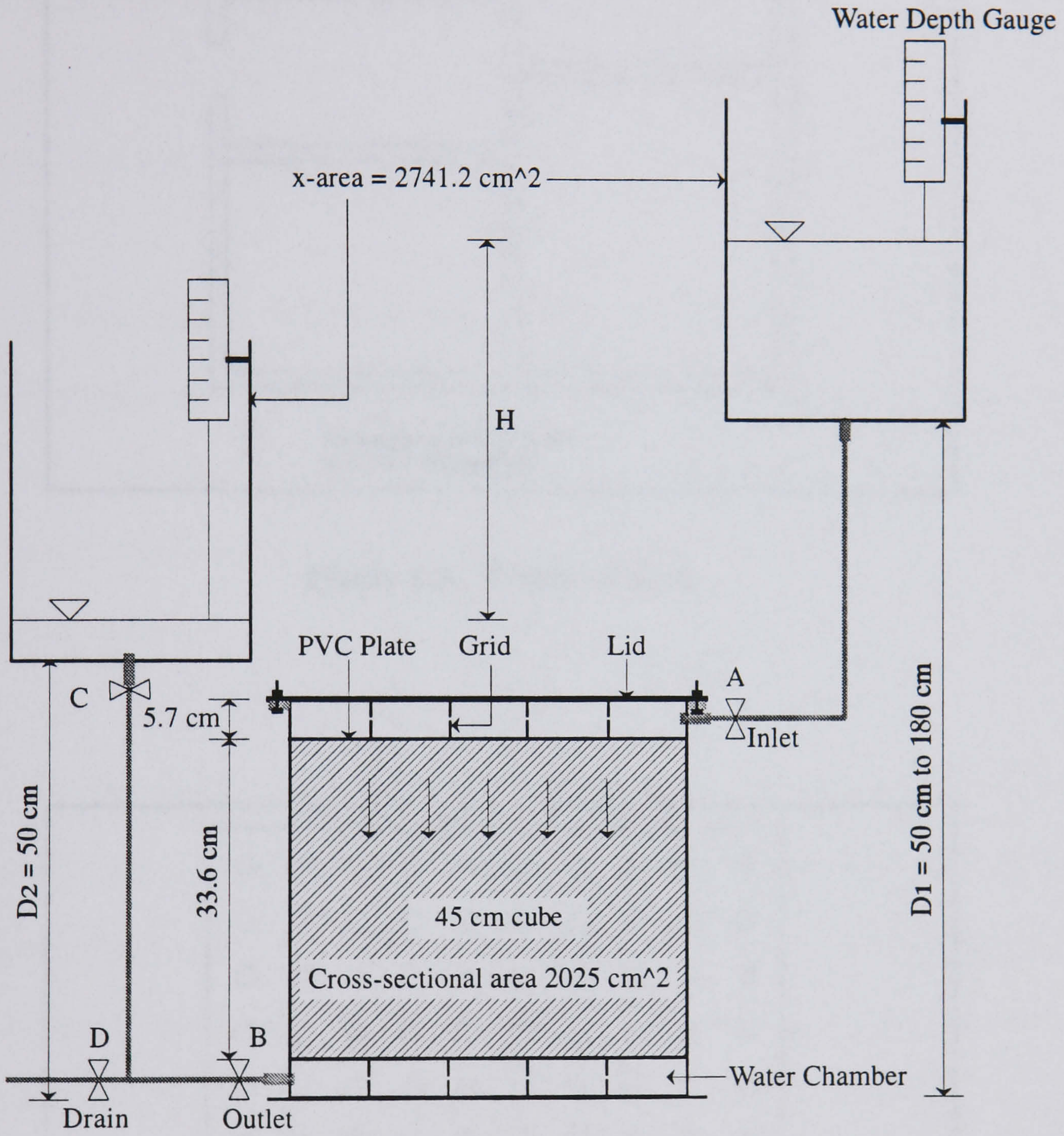


Figure 6.3. Details of two reservoirs model.

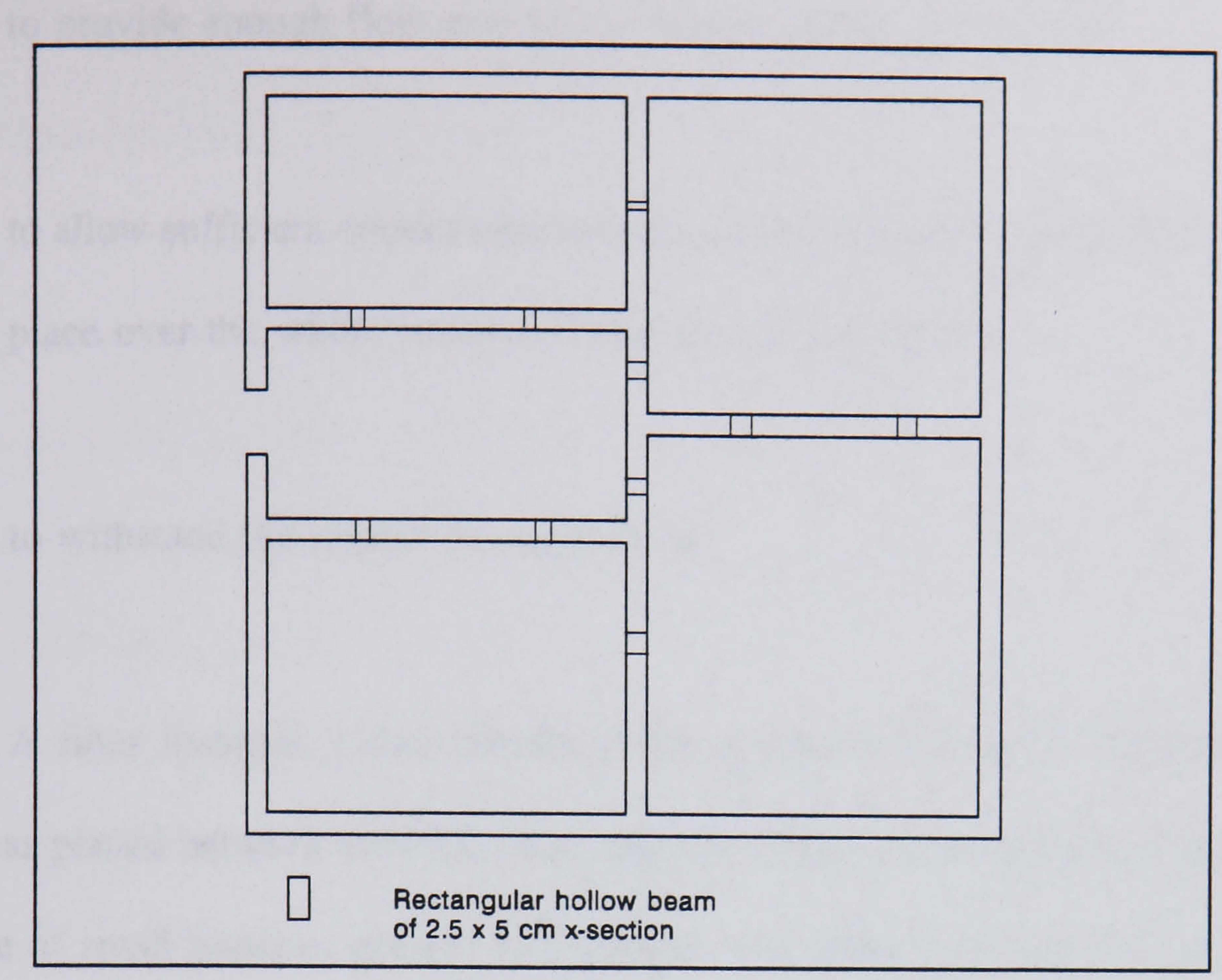


Figure 6.4. Details of Grid.

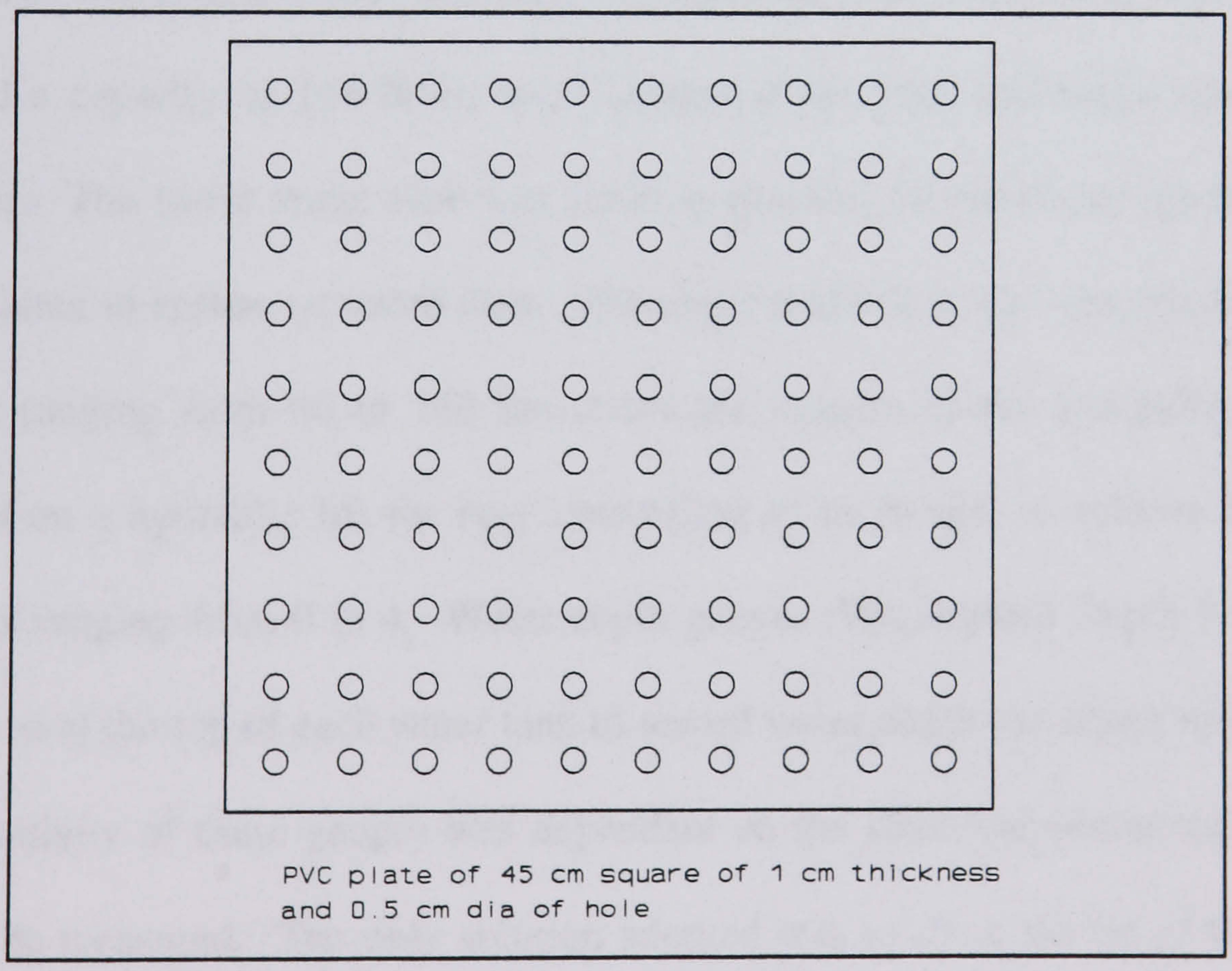


Figure 6.5. Details of PVC sheet.

1. to provide enough flow area to meet the samples requirement.

2. to allow sufficient contact area of water with the sample so that flow will take place over the whole cross-sectional area of the sample.

3. to withstand the impact of compaction.

A filter material, pidum needle punch polyester (having a thickness of 0.1 cm), was placed between the PVC sheet and the sample on both grids to prevent the passage of small particles present in a sample. It further increased the contact area of water with the sample to allow water to flow evenly over the full cross-sectional area of the sample.

The two plastic water tanks each having an internal size of 61.6 x 44.5 x 58.4 cms and a capacity of 154 litres, were located at the inlet and outlet sides of the container. The lower water tank was fixed in position 50 cm above the bottom of the container to ensure saturated flow. The upper water tank was variable in vertical position ranging from 50 to 180 cm above the bottom of the container. It was mounted on a hydraulic lift for easy controlling of its height, to achieve hydraulic gradients ranging from 0 to 4. Water depth gauges (Wallingford Depth Recorders) were fixed at the top of each water tank to record water depth variations upto 20 cm. The sensitivity of these gauges was dependent on the electrical conductivity of the fluid to be measured. The only solution adopted was to clean the tip of the needle of the water depth gauge at the start of each experiment.

A chart recorder having six channels was linked to these water depth gauges which recorded the signals transmitted by these gauges showing changes in water depths in the water tanks. The signals were plotted on a continuous chart with different colours to show the water depth variations in the two water tanks with time. The graph produced was in two dimensions, representing horizontally water depth variation and vertically the distance covered by the chart recorder after the test started. On the control panel of the chart recorder, its speed was selected before starting the test. The time was calculated by dividing the distance covered by chart recorder between any two positions with speed of the chart recorder.

The container and the two water tanks were connected by a plastic pipe having an internal diameter of 1.5 cm and four control valves were placed in the arrangement as shown in Figure 6.3. The purpose of the inlet and outlet valves was to control the flow of water into and out of the container. The drain valve D was placed to drain the leachate collected in the lower water tank. This was important from the safety point of view to avoid any contamination of the surrounding place. Although the connection system had some minor head losses due to pipe friction, joints, valves etc., these were not taken into consideration.

6.2.1 Calibration of Apparatus

A detailed calibration of the equipment was carried out before starting the experiments. The two water depth gauges which were connected to the chart recorder, have a working range to measure a water depth upto 20 cm. With the variation of water depths in the water tank the needle of the water depth gauge was also changing its position and transmitting corresponding electric signals to the chart recorder to plot on the chart. A continuous chart was loaded on the chart recorder drum, which has a width of 20 cm. Each water depth gauge was calibrated individually in respect to the specified chart recorder pen. For the zero position i.e., no water in the tank, the chart recorder pen was set on the zero scale. After that water tank was filled with water to a mark of exactly 20 cm, the water depth gauge needle also changed its position and a chart recorder pen was adjusted on 20 cm scale manually. The water tank was emptied, as a result a chart recorder pen will come to the zero mark. If the chart recorder pen was not exactly positioned on the zero scale, then the same procedure was again repeated and with a few trials exact calibration was achieved by removing the adjustment error.

Before starting the actual experimentation with the waste samples, a number of trials were carried out using 'Leighton Buzzard' medium sand with more than 95% particles in the range of 0.6 to 2 mm. The procedure consisted of placing a bottom grid, PVC sheet and filter material inside the container. The container was filled with sand and its top surface was levelled with hands, without any compaction. A filter material, PVC sheet and top grid were placed on the top of the sand, and the container lid was tightened by means of nuts and screws. The sample was allowed to saturate from the bottom of the container, by connecting outlet valve (B) to the lower water tank, with valve C opened and drain valve D closed. When continuous flow of water was appeared from the top inlet valve A, the outlet valve (B) was closed and the upper water tank was connected to the container through inlet valve (A). After filling the upper water tank to a 20 cm depth, valves A and B were opened and valve C was closed.

The chart recorder was switched on and its speed was selected from the control panel. When the chart recorder pens came to rest, this was logged on the paper and valve C was opened to run the test. The test was continued until the pens reached their end positions, which means that a 20 cm depth of water had flowed to the lower water tank. The pen representing the upper water tank reached the 0 cm mark, while the pen representing the lower water tank reached the 20 cm mark.

The information from the marked chart was read out for each increment of 0.5 cm water drop in the upper water tank. The time was calculated by knowing the speed and the distance covered by chart recorder for each 0.5 cm increment. By substituting the required values, value of K was calculated by using Equation 6.8.

Many trials were carried out and the data were read out from the charts to determine the vertical saturated hydraulic conductivity of sand. The vertical saturated hydraulic conductivity for the sand was found to range from 0.024 cm/sec to 0.10 cm/sec. For the same sand, a mean value of 0.05 cm/sec was determined by using a small falling head permeameter 8 cm in diameter and 20 cm in length. The permeameter was available in the Geotechnical Laboratory, having a free out flow at the bottom, so it was submerged in a water container in order to test the sample under saturated conditions.

The scatter in the results of the two reservoirs model was very high using standard soil samples, indicating many flaws in the experimental setup and procedure. There were many possible reasons for this variation in the results, some of which are discussed below:

1. The density of the material was not taken into consideration, which is one of the most significant factors affecting the permeability of porous material.
2. It was always observed from the water of the lower water tank that some fine particles were washed away. Many times the outflow was stopped suddenly and by inspecting the filter material by opening the permeameter, small sand particles were found in it, causing chocking of the filter.
3. The permeability tests are based on the assumption that the water will flow over the whole cross-sectional area of the material. With the existing setup, it was possible that the water flow was concentrated in the regions of the holes in the PVC sheet. If this situation occurred, it may cause errors in the results.
4. The water depth gauges were found to be ineffective in measuring accurately particularly at small changes in the water depths. The interpretation of the data from the chart was time consuming and approximate which contributed towards error in the results.

Keeping in view the above problems, the permeameter was discarded and it was concluded that the tests should be carried out separately for vertical and horizontal hydraulic conductivities. It was also decided that the container should be reduced to a minimum acceptable size in order to better control and operate the experimentation. The setup for the new experimentation is described in the next section.

6.3 Modified Experimental Set-up

As explained earlier the first experimental setup had a number of problems mainly related to the accuracy of the results and operating the equipment. The following points were considered in the modified experimental setup.

1. to reduce the size of the container in order to better control and operate the equipment.
2. to replace the water depth gauges with new pressure transducers, using a computer to record and manipulate the data more accurately and efficiently.
3. to provide a mechanism for removing and collecting gas generating during the test run as preliminary tests with waste in the initial apparatus had shown that gas was released during tests in the permeameter affecting the flow.

Two different permeameters were designed to determine separately the vertical and horizontal hydraulic conductivities of pulverized waste. Each permeameter consisted of a container for holding waste and two water cylinders, each 23.3 cm diameter and 120 cm long. In each case, the cylinders were placed above the top level of waste container. One cylinder was used for supplying water to the container and the other one for collecting water from the container. A pressure transducer was attached near the bottom through the side of the supplying water cylinder, which measures the water depths in the water cylinder. The analogue signals transmitted by the pressure transducer were received by Analogue-Digital Convertor and converted into digital signals. A computer was connected to Analogue-Digital Convertor through a data acquisition system, which captures the digital signals representing water depths in the supplying water tank with time and saves the data on a computer hard disk. A gas collector made of plastic was attached in the inlet way which collected all the gas which was generated during the test run.

The pressure transducers (type PTX-21-series) used in the experimentation were purchased from Caledonia Instrumentation Ltd, Clydebank. These have a stainless steel body, pressure and vacuum protected, and have a working range to measure 1 metre depth of water, which gives a hydraulic gradient of up to 4 in the case of both permeameters. The Analogue-Digital (A-D) converter was used to convert the analogue signals coming from the pressure transducer and sending them to the computer. The IOCALC (Input Output Calculator) data acquisition software was used to capture those digital signals coming from the A-D converter, which represent the water depths in the supplying water cylinder.

The container and the two water cylinders were connected by a pipe of 1.2 cm internal diameter and three control valves were placed in the arrangement as shown in Figures 6.6 and 6.7. The functions of the valves were;

Valve A	to control the flow of water into container
Valve B	to control the leachate flow out of container
Valve C	to drain out the leachate from the lower water cylinder.

The vertical cylinder permeameter was constructed from 5 mm thick polyethylene pipe having a diameter of 20 cm, as shown in Figure 6.6. Extra strength to resist the compactive effort was provided at the bottom of the

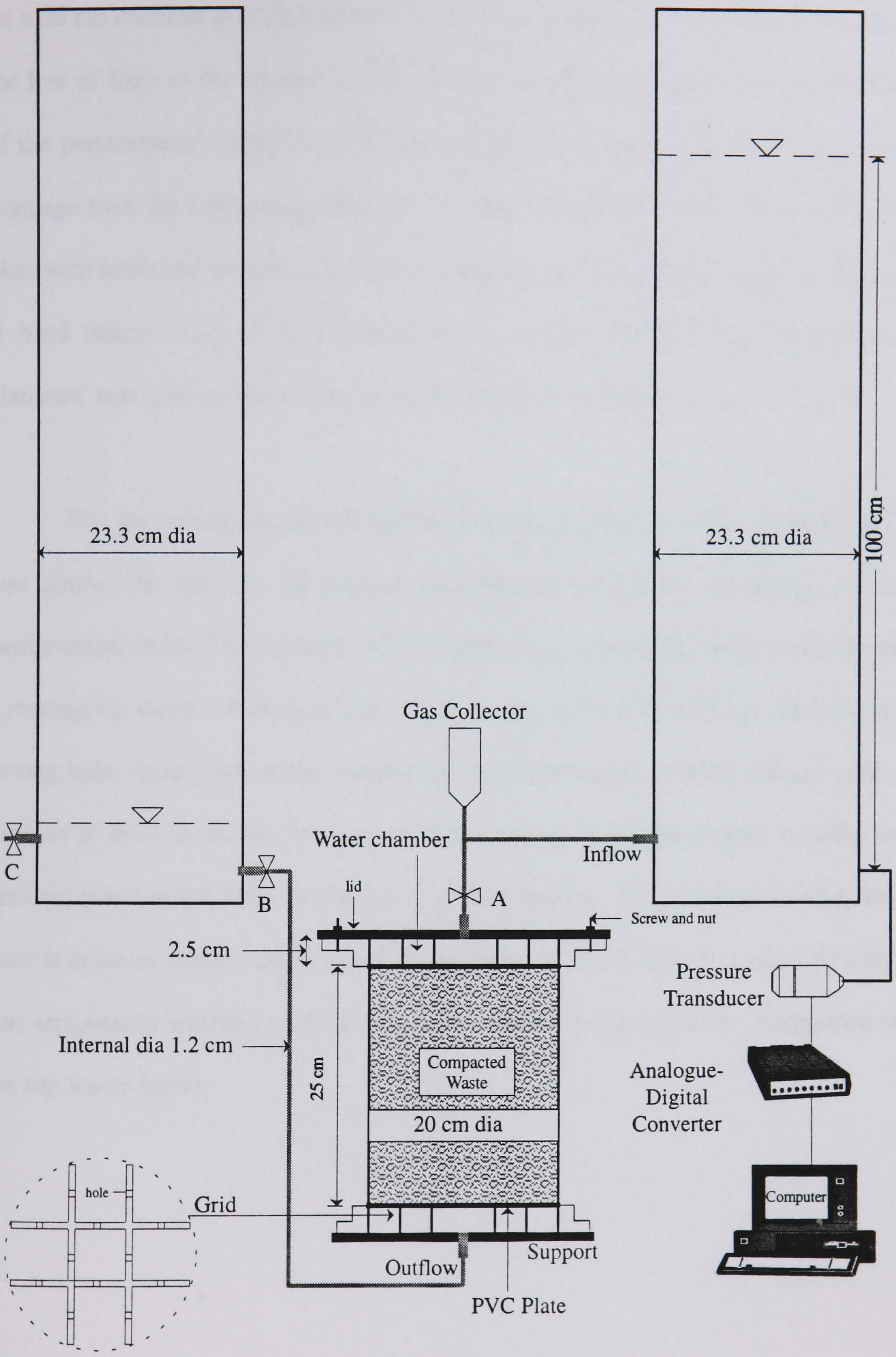


Figure 6.6. A schematic view of the vertical permeameter.

permeameter by a deep sleeve and a strong wooden base. A wire mesh, supported on a 20 cm diameter polyethylene plate with holes drilled into it, was used to reduce the loss of fines in the outflow system. This plate itself was supported on the base of the permeameter via a 2.5 cm deep steel grid with drainage holes allowing free drainage from the compacted sample. The same arrangement of the mesh wire, the plate with holes and the grid were also provided on the top to make a water chamber. A hand tamper made of steel having 19 cm diameter smaller than permeameter diameter, was used in order to achieve the required compaction.

The instrumentation of the horizontal permeameter (as shown in Figure 6.7) was almost the same as for vertical permeameter except for the design of the permeameter itself. The horizontal permeameter was constructed from wood having a rectangular shape. A layer of wire mesh, glued on the side of 20 cm square plate having holes drilled into it was used in the vertical position on both sides to reduce the loss of fines in the outflow system. These plates were held in their position by grooves made in the sides of the box. A hand tamper, 20 cm square in size, was used in order to achieve the required compaction. A 20 cm cube box made of wood was temporarily attached to the top of the container, to facilitate the compaction of the top waste layers.

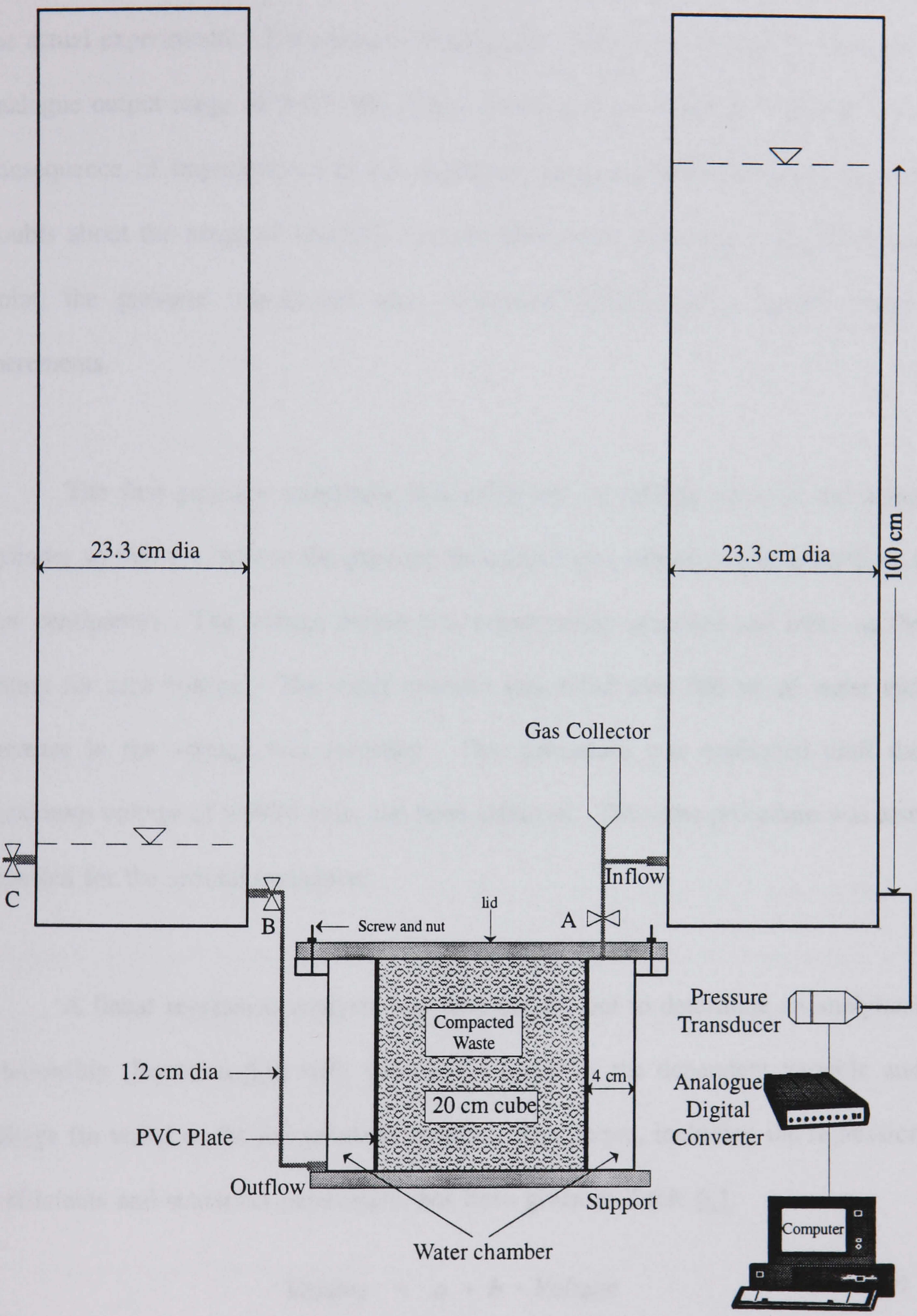


Figure 6.7. A schematic view of the horizontal permeameter.

6.3.1 Calibration of Apparatus

A detailed calibration of the new equipment was carried out before starting the actual experiments. The pressure transducers used were specified as having an analogue output range of 0-10 volts over a working water depth of 1 metre. As a consequence of imperfections in the miniature electro-inductive pressure sensors, doubts about the range of linearity, and the difficulties in setting a standard zero point, the pressure transducers were calibrated individually in small volume increments.

The first pressure transducer was calibrated by adding water to the water cylinder so that the inlet to the pressure transducer was submerged to a depth of a few centimetres. The voltage output was consequently recorded and taken as the datum for zero volume. The water cylinder was filled with 500 ml of water and increase in the voltage was recorded. This procedure was continued until the maximum voltage of 9.9976 volts had been achieved. The same procedure was also repeated for the second transducer.

A linear regression analysis was then carried out to determine an analytical relationship (Equation 6.9) with volume (in litres) as the dependent variable and voltage (in volts) as the independent variable. The output, including the regression coefficients and statistical parameters, has been given in Table 6.1.

$$\mathit{Volume} = a + b \cdot \mathit{Voltage} \tag{6.9}$$

For pressure transducer # 1 $\quad 2.034 < \text{Voltage} < 10.0$

For pressure transducer # 2 $\quad 1.978 < \text{Voltage} < 10.0$

Table 6.1. Linear Regression Output (calibration data for pressure transducers).

Regression Output	Pressure Transducer	
	# 1	# 2
Slope coefficient (lit/volt) [b]	5.6849	5.6864
Intercept (lit) [a]	-11.5640	-11.2487
R-Squared	0.999960	0.999991
S.E. Slope	0.0037	0.0022
S.E. Regression	0.0846	0.0405
Mean Absolute Deviation	0.0655	0.0318

Before starting the actual experimentation with the pulverized waste samples, four trials were carried out using 'Leighton Buzzard' medium sand, with more than 95% particles in the range of 0.6 to 2 mm. An individual value of K for the sand was determined for time interval of 10 sec for each trial using Equation 6.8, to ensure linearity over the full range of hydraulic gradient. One test for each case is shown in Figures 6.8 and 6.9, which shows the value of K for the time interval of 10 sec, from the start of the test over hydraulic gradients decreasing from 4 to 0. It is evident from these graphs that there is no significant variation of K with respect to hydraulic gradient. So it is deduced that the water flow is laminar upto a hydraulic gradient of 4 and that Darcy's law is therefore applicable. Thereafter, average values of the hydraulic conductivity were determined from a simple arithmetical averaging procedure using these individual values and are given below.

K	Trial 1	Trial 2	Trial 3	Trial 4	Average
Vertical (cm/sec)	0.045	0.061	0.056	0.048	0.053
Horizontal (cm/sec)	0.053	0.085	0.076	0.059	0.068

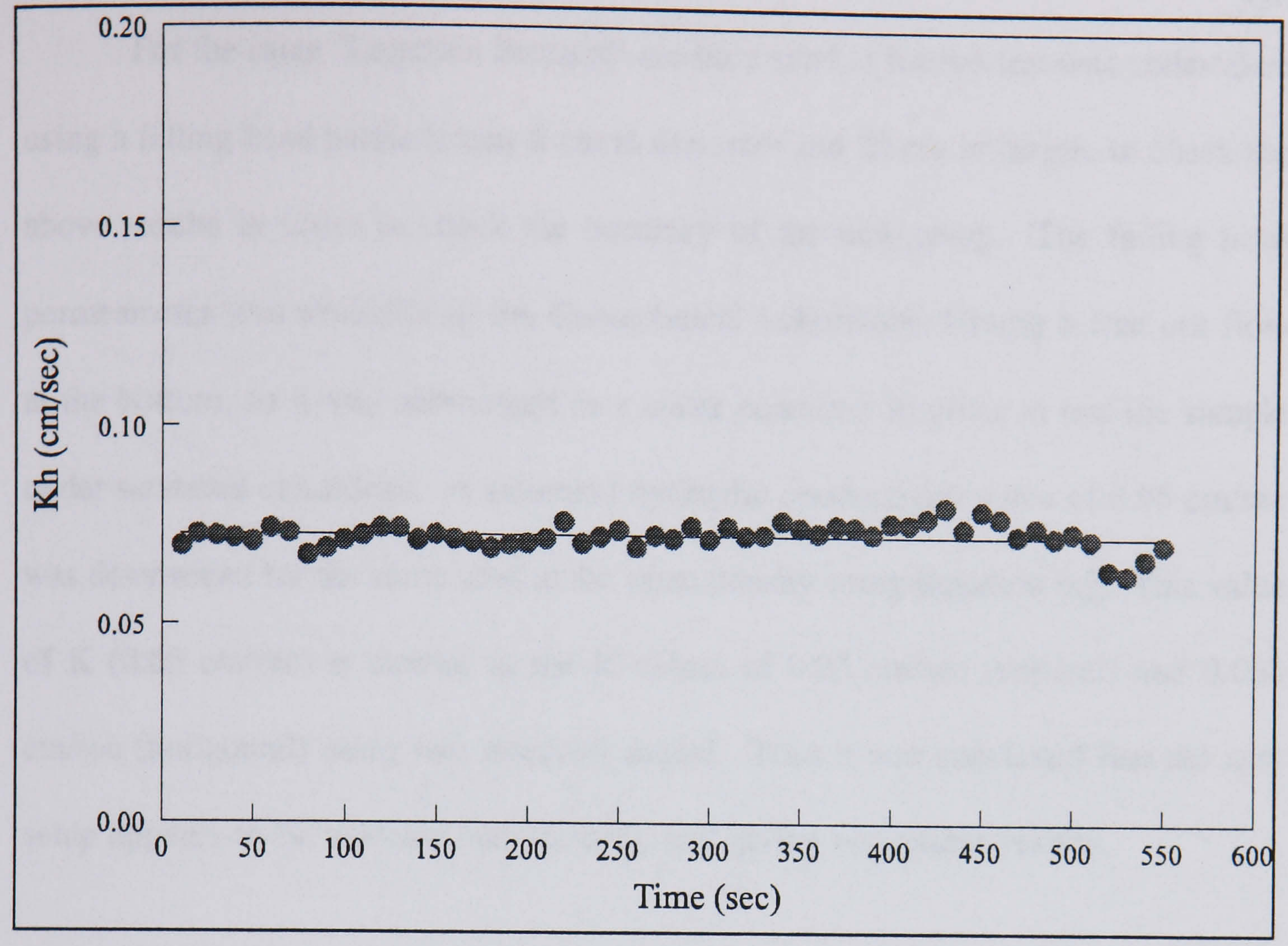


Figure 6.8. Time versus vertical hydraulic conductivity for sand.

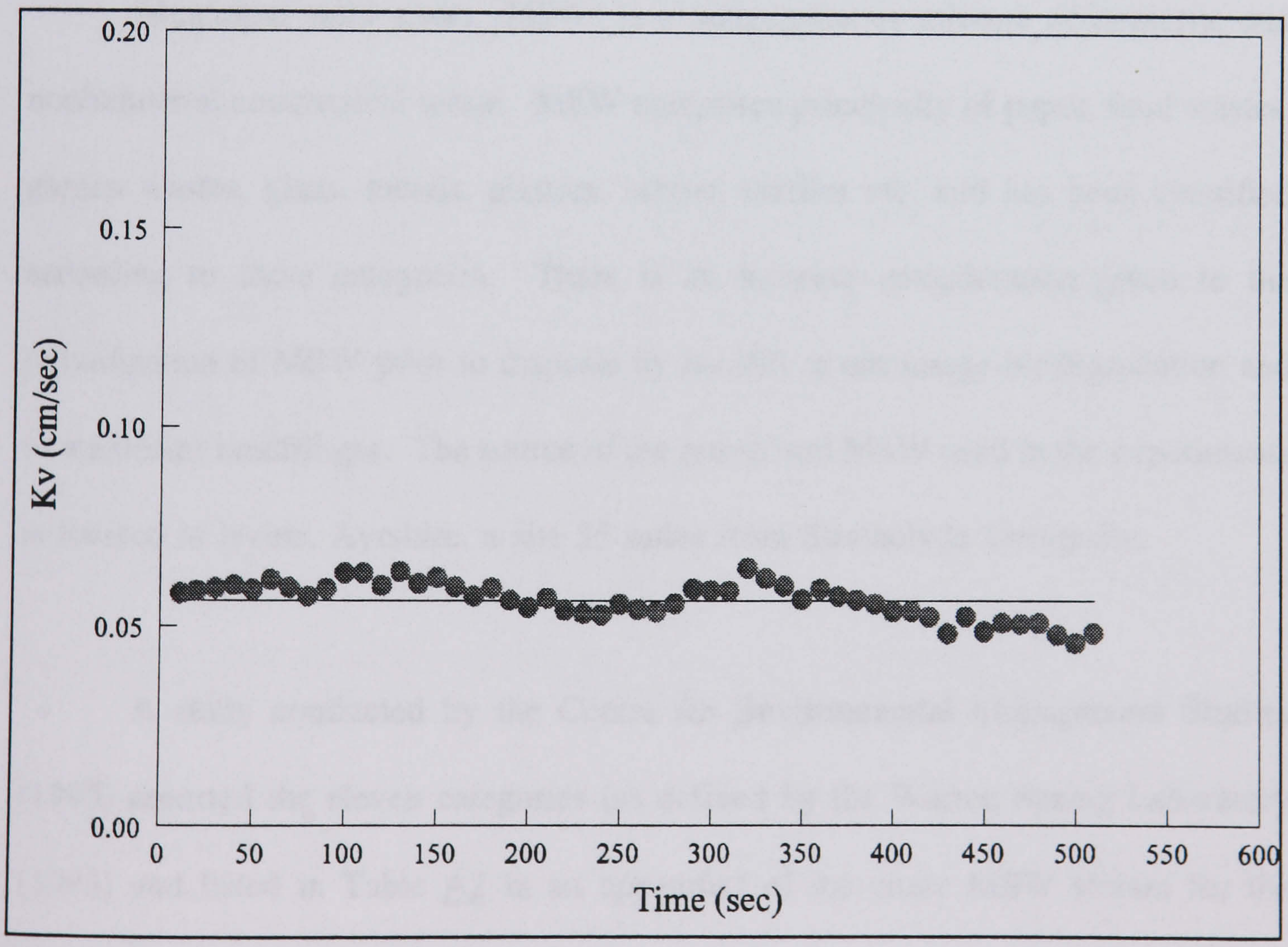


Figure 6.9. Time versus horizontal hydraulic conductivity for sand.

For the same 'Leighton Buzzard' medium sand, a further test was undertaken using a falling head permeameter 8 cm in diameter and 20 cm in length, to check the above results in order to check the accuracy of the new setup. The falling head permeameter was available in the Geotechnical Laboratory, having a free out flow at the bottom, so it was submerged in a water container in order to test the sample under saturated conditions. A saturated hydraulic conductivity value of 0.05 cm/sec was determined for the same sand at the same density using Equation 6.3. This value of K (0.05 cm/sec) is similar to the K values of 0.05 cm/sec (vertical) and 0.068 cm/sec (horizontal) using two reservoir model. Thus it was concluded that the new setup appears to be working satisfactorily and giving acceptable results.

Type and source of waste material

Municipal solid waste (MSW) is a heterogeneous mixture of domestic and nonindustrial commercial waste. MSW comprises principally of paper, food wastes, garden wastes, glass, metals, plastics, rubber, textiles etc. and has been classified according to these categories. There is an increase consideration given to the pulverization of MSW prior to disposal by landfill to encourage biodegradation and to maximize landfill gas. The source of the pulverised MSW used in the experiments is located in Irvine, Ayrshire, a site 35 miles from Strathclyde University.

A study conducted by the Centre for Environmental Management Studies (1995) reported the eleven categories (as defined by the Warren Spring Laboratory (1993) and listed in Table A2 in an appendix) of the crude MSW stream for the above plant on a weight basis are as:

Category of Waste	Before Pulverization	After Pulverization
1. Paper/card	(25 %)	(30.3 %)
2. Plastic film	(5.6 %)	(1.2 %)
3. Dense plastic	(4.8 %)	(0.6 %)
4. Textiles	(3.9 %)	(0.6 %)
5. Miscellaneous combustibles	(3.2 %)	(3.6 %)
6. Miscellaneous non-combustibles	(0.6 %)	(0.7 %)
7. Glass	(4.0 %)	(4.8 %)
8. Putrescibles	(44.4 %)	(53.8 %)
9. Ferrous metal	(4.4 %)	-
10. Non-ferrous metal	(0.7 %)	-
11. Fines	(3.5 %)	(4.2 %)

These compositions are typical for this type of waste, however, it is recognised that the actual compositions of a sample will vary due to seasonal and short-term factors (e.g. collection policy). During this research, a total of 20 samples were taken over a period of 8 months in order to take account of such variability.

The categorisation of a MSW (crude form) is simpler than that of pulverized MSW, because pulverization makes it difficult to sort out the waste into eleven categories. The values of waste categories after pulverization of MSW listed above are estimated from a knowledge of the waste stream and by inspection of the pulverized waste. During pulverization process ferrous metals are removed by over drum magnet and non-ferrous metals are sorted out for recycling. Some bigger size materials of plastic, rubber, textiles etc. are retained by the screens.

Pulverization Process

The MSW (crude form) is treated in the plant by a Dano Wet Drum Pulveriser prior to disposal by landfill. The Dano Silo is an 82 ft long, 12 ft in diameter cylinder which rests horizontally on a set of rollers. The cylinder is rotated by an external gear ring and pinions with power supplied via three electrically driven hydraulic pumps supplying oil at the rate of 1050 litres per minute to the four hydraulic motors. Speed of rotation of the pulveriser with three electric motors running is 3.65 r.p.m. which is the normal operating speed.

The refuse is loaded into the silo by an articulated wheel shovel. Projecting steel spears are fitted through the Silo and also at the inner screen to improve the tumbling action and assist in breaking up any accumulation of waste textile materials. Water is added to the refuse at the rate of 45 gallons per tonne to assist in the breakdown of the crude refuse. At the outlet end of the silo, the material passes to the screen section (having 38 mm circular aperture) which separates the finely pulverised material (as was used for this study) from the coarser material and each is taken by conveyor to the storage hopper for collection.

As specified in BS 1377: Part 5: 1990 for soil systems, for constant-head permeameter tests the internal diameter of the cell body shall be at least 12 times the maximum particle size of the sample to be tested. However, there is no agreed standardization for waste materials. The structure of the pulverized MSW material will differ from that of a soil and the waste material will tend to compact more readily. The problems of scale are therefore likely to be less significant than with a soil sample. The maximum size of the waste material was 38 mm diameter and the diameter of the permeameter was 200 mm. This provides a scaling ratio of 1 to 5.3 which although less than that required by BS 1377 for soils, was considered to be acceptable for the waste material due to its structural form.

The pulverised waste samples were collected in plastic bins and carried to the laboratory. Initial trials were carried out to determine the most efficient equipment for waste compaction and the range of the densities achievable with the available laboratory equipment. Initially a vibrating hammer was tested to compact the pulverised waste. However, the vibratory action, which is so effective in granular material, was found to have little effect on the waste material. It was then concluded that a dynamic compaction method imparting a crushing effect would be far more effective in waste materials as well as being more representative of field compaction procedures. After preliminary trials, a hand held tamper was found being the most effective equipment for laboratory compaction.

6.3.2 Experimental Procedure

The experimental procedure was relatively simple as the problems regarding the permeameter had been overcome. First, initial moisture content of the pulverized waste was measured using an electric oven (at 50 °C for 10 hours), which was used for the determination of the dry density of the waste. The details of the amount of the pulverized waste required for different densities are given in Tables 6.2 and 6.3 for vertical and horizontal permeameters respectively. For each density, 20 different samples were used. Also for the statistical analysis such a number of replicates should result in high confidence in the results.

A known weight of pulverized waste was placed in the vertical and horizontal permeameters by compacting it to a known density. Four dry densities of 400, 450, 500 and 550 kg/m^3 were used in the trials. The waste was compacted in layers and as a result the bottom layers were more dense compared to the top layers. From the practical point of view, it was assumed that all the layers had the same density. However, it is not practically possible to get an exact value of density for each layer, so overall rounded values were used which equal the pre-assumed densities. A lid was placed on the top of each permeameter and was tightened up by means of screws. In case of the horizontal permeameter, a plastic sheet was placed below the lid in order to seal any gap. The containers were then connected to the upper and lower water tanks.

Table 6.2. Weight of pulverized MSW for different densities for Kv.

Dry densities (kg/m^3)	Bulk Densities (kg/m^3)	Total weight (kg)	No of layers
400	800	6.28	4
450	900	7.07	4
500	1000	7.85	4
550	1100	8.64	4

Table 6.3. Weight of pulverized MSW for different densities for Kh.

Dry densities (kg/m^3)	Bulk Densities (kg/m^3)	Total weight (kg)	No of layers
400	800	6.40	4
450	900	7.20	4
500	1000	8.00	4
550	1100	8.80	4

The software IOCALC was run on the computer, which records the digital signals coming from the pressure transducers. Each time before staring the experiment, the software was logged in with a given time interval for updating the information and a filename to store the data. The software was limited to update the information with a minimum time interval of 10 sec. So in the case of lower density (i.e., 400 kg/m^3), a time interval of 10 sec was used. For the other densities, the flow rate through waste material was very slow, this minimum time interval of 10 sec was not adopted. Therefore, time intervals of 60, 120, and 300 sec were used for the dry densities of 450, 500 and 550 kg/m^3 respectively.

The information stored by PC (Personal Computer) from the pressure transducers was in ASCII data file format. The software used for the data acquisition was not good, so all the data were in a voltage format, which shows the time dependant drop in the water head in the upper water tank. The file was then imported in an ASEASY spreadsheet where voltage readings were transformed into corresponding values of volume of water using Equation 6.9, which were then changed into water depth values for calculating flow rates and corresponding hydraulic gradients.

Many problems were encountered during this experimental study and were remedied within the existing frame work of the apparatus. Some assumptions were also made which are discussed below.

1. The water collected in the lower water tank was normally of a black colour

with a higher density than clean water. This may affect the flow through waste sample, as we assumed a constant density for water in both water tanks.

2. The gas generation from the waste material commenced immediately after water was added. A gas collector was mounted in the inlet way to collect any gas which was generated during the test run. However, it is possible that some gas will not escape from the container and is entrapped inside the material, which might restrict the flow to some extent.

3. It was also observed that waste material expands, when it becomes saturated. As, the sample is confined this may create some pressure in the sample affecting flow.

4. The pressure transducers were not effective in measuring a small change in water levels. This was more significant when running the test at small hydraulic gradients, because very slow flow takes place at that stage.

5. Although the temperature affects the permeability to some extent this was not taken into consideration. The standard temperature of 20 °C should be used while conducting permeability tests. Permeability tests conducted in a laboratory having a temperature of 15 °C is to be corrected by multiplying with a correction factor of 1.15 as specified in BS 1377: Part 5: 1990.

6.4 Results and Discussions

Each experimental data set collected from the laboratory experiments consists of time of drop in water levels from the upper tank water over a hydraulic gradient ranging from 4 to 0. The time intervals were fixed having a values of 10, 60, 120, and 300 sec for the dry densities of 400, 450, 500 and 550 kg/m^3 respectively, as mentioned earlier. The hydraulic gradient and the corresponding flow rate for a given time increment were calculated. The flow rates (cm^3/sec) were plotted against hydraulic gradients, for a given time interval. Most of the plots show a linear relationship with the line passing through the origin. An individual value of K was determined for each time interval for each experiment using Equation 6.8, to ensure linearity over the full range of hydraulic gradient. It was checked from these values of K whether the hydraulic conductivity value for the waste sample under consideration was constant or changed as the hydraulic gradient decreased from 4 to 0. It was observed that there is a little variation in the value of K, which was expected and is within the accepted range. Thereafter, an average value of the hydraulic conductivity was determined from a simple arithmetical averaging procedure using these individual values.

Values of K calculated for each time interval were plotted against time, to observe the behaviour of the permeameter to see whether the value of K is constant within the range or not. Representative graphs for four densities for vertical and horizontal permeability are shown in Figures 6.10 and 6.11. It is evident from these graphs that for the samples K is approximately constant with time, although there is evidence of long time trends which might be associated with changes in the waste. The apparatus appears to be working satisfactorily.

In some cases, at very low hydraulic gradient, the value of K substantially decreased. This is probably because at low head the pressure transducer was not accurately measuring the small changes in water level. The same pattern was also observed many times working at the higher density of 550 kg/m^3. Another important factor was the temperature of the waste sample, which was not taken into consideration.

The values of saturated hydraulic conductivity in both vertical and horizontal directions are given in Tables 6.4, 6.5, 6.6 and 6.7 for the dry densities of 400, 450, 500 and 550 kg/m^3 respectively. For each experiment, the coefficient of correlation (R^2) was calculated using Equation A-7 as given in appendix. The high values of R^2 indicate that a strong relationship exists between flow rates and hydraulic gradients for the zero intercept model (Darcy's equation). So it is deduced that the water flow in the pulverized waste under an existing compacting conditions is laminar up to a hydraulic gradient of 4 and follows the Darcy's law.

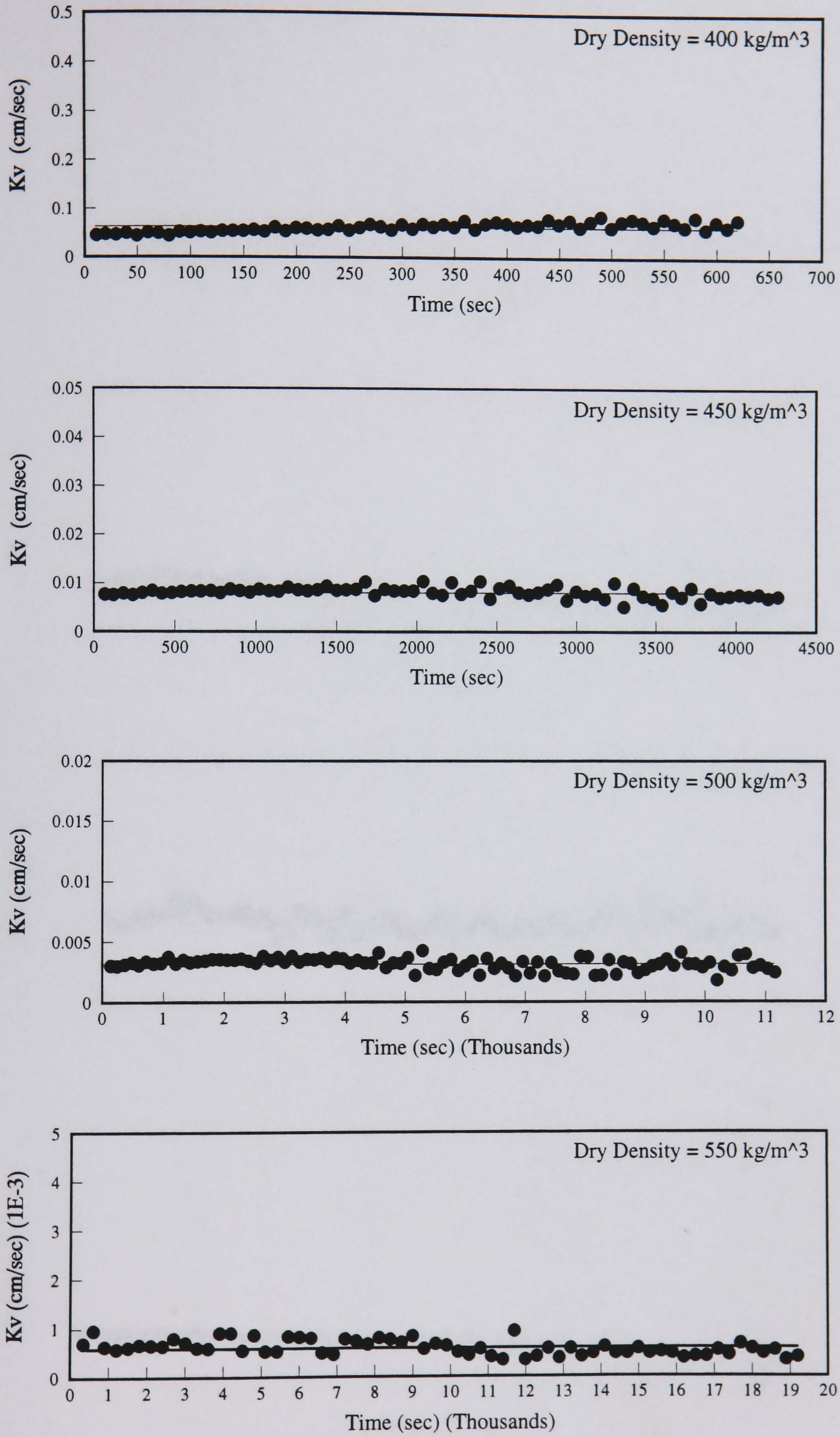


Figure 6.10. Time versus vertical hydraulic conductivity for waste.

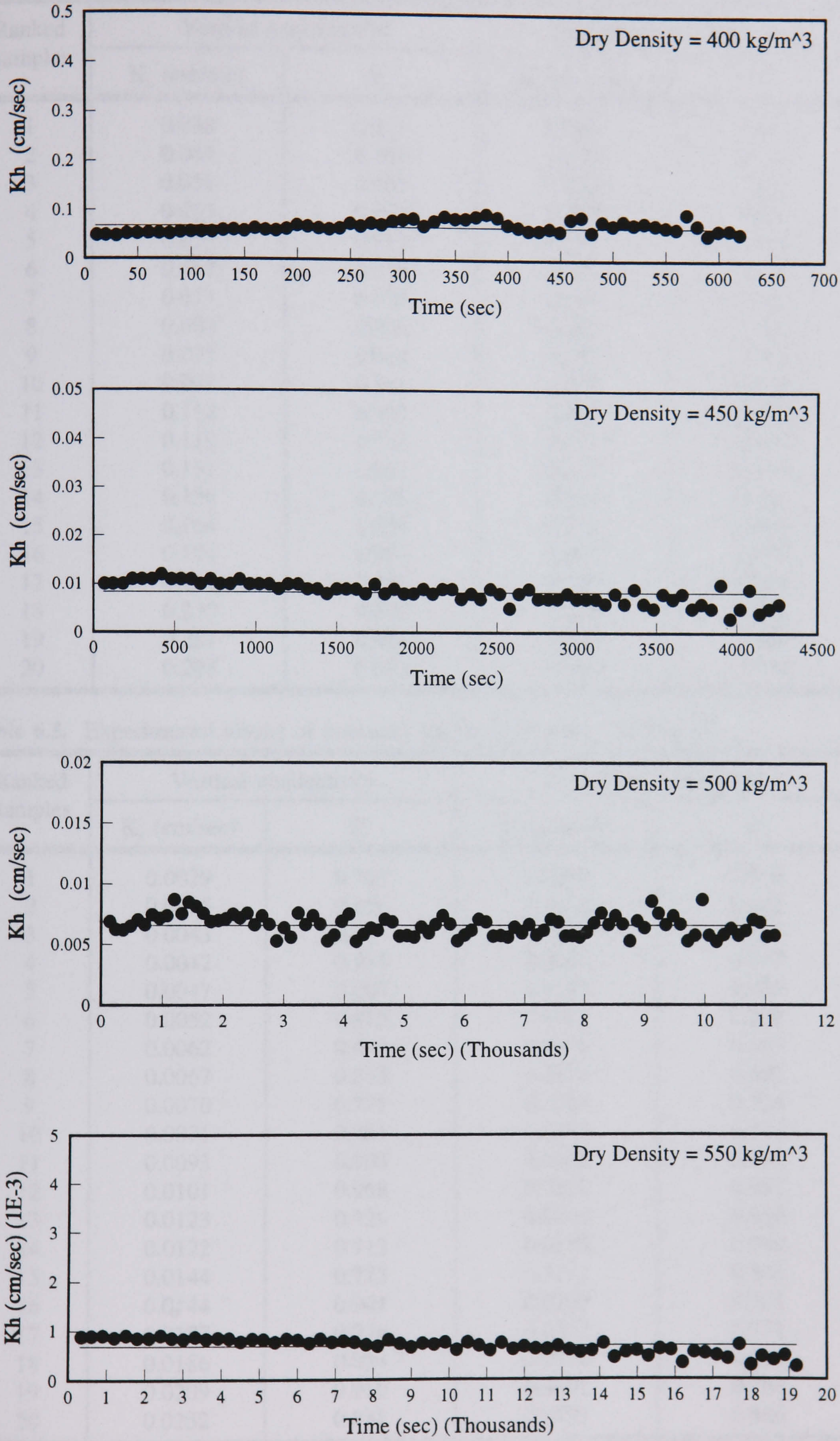


Figure 6.11. Time versus horizontal hydraulic conductivity for waste.

Table 6.4. Experimental results of saturated conductivity at $\rho_d = 400$ kg/m^3.

Ranked Samples	Vertical conductivity		Horizontal conductivity	
	K_v (cm/sec)	R^2	K_h (cm/sec)	R^2
1	0.038	0.911	0.049	0.872
2	0.043	0.863	0.055	0.918
3	0.051	0.901	0.081	0.845
4	0.053	0.893	0.098	0.913
5	0.059	0.913	0.117	0.881
6	0.065	0.935	0.151	0.879
7	0.071	0.921	0.155	0.981
8	0.080	0.916	0.164	0.760
9	0.091	0.986	0.192	0.858
10	0.091	0.941	0.219	0.872
11	0.112	0.967	0.271	0.872
12	0.119	0.971	0.313	0.868
13	0.131	0.931	0.347	0.976
14	0.138	0.801	0.360	0.993
15	0.164	0.824	0.376	0.907
16	0.174	0.856	0.405	0.970
17	0.196	0.988	0.477	0.956
18	0.235	0.876	0.518	0.876
19	0.281	0.981	0.535	0.969
20	0.298	0.943	0.602	0.975

Table 6.5. Experimental results of saturated conductivity at $\rho_d = 450$ kg/m^3.

Ranked Samples	Vertical conductivity		Horizontal conductivity	
	K_v (cm/sec)	R^2	K_h (cm/sec)	R^2
1	0.0029	0.788	0.0050	0.850
2	0.0035	0.856	0.0058	0.902
3	0.0043	0.907	0.0066	0.915
4	0.0042	0.980	0.0073	0.867
5	0.0047	0.867	0.0085	0.968
6	0.0052	0.913	0.0088	0.792
7	0.0062	0.845	0.0090	0.895
8	0.0067	0.853	0.0118	0.892
9	0.0070	0.771	0.0144	0.756
10	0.0071	0.861	0.0213	0.916
11	0.0093	0.903	0.0208	0.792
12	0.0101	0.968	0.0212	0.992
13	0.0123	0.929	0.0245	0.986
14	0.0122	0.912	0.0259	0.900
15	0.0144	0.775	0.0272	0.806
16	0.0144	0.941	0.0299	0.901
17	0.0177	0.918	0.0347	0.971
18	0.0186	0.924	0.0378	0.869
19	0.0209	0.910	0.0401	0.768
20	0.0252	0.831	0.0437	0.886

Table 6.6. Experimental results of saturated conductivity at $\rho_d = 500$ kg/m^3.

Ranked Samples	Vertical conductivity		Horizontal conductivity	
	K_v (cm/sec)	R^2	K_h (cm/sec)	R^2
1	0.0010	0.954	0.0015	0.941
2	0.0012	0.976	0.0017	0.960
3	0.0013	0.969	0.0018	0.975
4	0.0015	0.981	0.0019	0.971
5	0.0016	0.985	0.0019	0.969
6	0.0018	0.983	0.0021	0.981
7	0.0018	0.900	0.0021	0.997
8	0.0020	0.967	0.0023	0.984
9	0.0020	0.969	0.0024	0.983
10	0.0022	0.981	0.0030	0.985
11	0.0022	0.979	0.0034	0.902
12	0.0024	0.984	0.0039	0.963
13	0.0026	0.934	0.0041	0.968
14	0.0027	0.987	0.0049	0.969
15	0.0028	0.960	0.0050	0.976
16	0.0034	0.970	0.0050	0.987
17	0.0040	0.983	0.0067	0.984
18	0.0043	0.982	0.0070	0.983
19	0.0051	0.978	0.0078	0982
20	0.0062	0.985	0.0085	0.979

Table 6.7. Experimental results of saturated conductivity at $\rho_d = 550$ kg/m^3.

Ranked Samples	Vertical conductivity		Horizontal conductivity	
	K_v (cm/sec)	R^2	K_h (cm/sec)	R^2
1	0.00019	0.867	0.00021	0.901
2	0.00021	0.946	0.00033	0.946
3	0.00023	0.913	0.00041	0.976
4	0.00032	0.970	0.00044	0.979
5	0.00041	0.974	0.00052	0.984
6	0.00046	0.980	0.00059	0.985
7	0.00051	0.976	0.00064	0.980
8	0.00055	0.981	0.00074	0.981
9	0.00060	0.984	0.00077	0.986
10	0.00064	0.986	0.00081	0.984
11	0.00070	0.984	0.00084	0.987
12	0.00074	0.982	0.00089	0.983
13	0.00078	0.981	0.00091	0.978
14	0.00085	0.979	0.00097	0.977
15	0.00090	0.730	0.00112	0.970
16	0.00110	0.901	0.00131	0.918
17	0.00116	0.918	0.00135	0.965
18	0.00122	0.965	0.00147	0.879
19	0.00124	0.970	0.00157	0.912
20	0.00131	0.975	0.00177	0.743

6.5 Statistical Analysis

Different statistical parameters were calculated from the data as tabulated in the previous section. These include average ($\bar{x}$), standard deviation (σ) and coefficient of variation ($C_v = \sigma/\bar{x}$) of saturated hydraulic conductivity for each density and the corresponding Confidence Interval (C.I.) of mean at 95% confidence level, which was computed by the following expression:

$$C.I.\ of\ Mean \ = \ \bar{x} \pm \ 1.96 \left(\frac{\sigma}{\sqrt{n}} \right) \qquad (6.10)$$

Where n denotes the number of observations.

These statistical parameters of the experimental data are tabulated in Tables 6.8 and 6.9 for the vertical and horizontal saturated hydraulic conductivities respectively. The arithmetic mean values for the vertical saturated conductivity are 1.2×10^{-1}, 1.0×10^{-2}, 2.6×10^{-3} and 7.1×10^{-4} cm/sec for the dry densities of 400, 450, 500 and 550 kg/m^3 respectively. The arithmetic mean values for horizontal saturated conductivity are 2.7×10^{-1}, 2.0×10^{-2}, 3.9×10^{-3} and 8.8×10^{-4} cm/sec for the dry densities of 400, 450, 500 and 550 kg/m^3 respectively. The coefficient of variation varies from 51% to 63% for the vertical conductivity and 49% to 63 % in case of the horizontal conductivity. For each density, 20 samples cover to some extent variability from sample to sample. Moreover, C.I. for each density was calculated in order to cover the range of variation in hydraulic conductivity values from sample to sample.

Table 6.8. Statistical Analysis of Vertical Experimental Results.

Dry density (kg/m^3)	n	$\bar{x}$ (cm/sec)	95% C.I. of $\bar{x}$	σ (cm/sec)	C_v (%)
400	20	1.2×10^{-1}	$\bar{x} \pm 3.4 \times 10^{-2}$	7.8×10^{-2}	63
450	20	1.0×10^{-2}	$\bar{x} \pm 2.8 \times 10^{-3}$	6.4×10^{-3}	62
500	20	2.6×10^{-3}	$\bar{x} \pm 6.0 \times 10^{-4}$	1.4×10^{-3}	52
550	20	7.1×10^{-4}	$\bar{x} \pm 1.6 \times 10^{-4}$	3.6×10^{-4}	51

Table 6.9. Statistical Analysis of Horizontal Experimental Results.

Dry density (kg/m^3)	n	$\bar{x}$ (cm/sec)	95% C.I. of $\bar{x}$	σ (cm/sec)	C_v (%)
400	20	2.7×10^{-1}	$\bar{x} \pm 7.5 \times 10^{-2}$	1.7×10^{-1}	63
450	20	2.0×10^{-2}	$\bar{x} \pm 5.5 \times 10^{-3}$	1.2×10^{-2}	62
500	20	3.9×10^{-3}	$\bar{x} \pm 9.6 \times 10^{-4}$	2.2×10^{-3}	57
550	20	8.8×10^{-4}	$\bar{x} \pm 1.9 \times 10^{-4}$	4.3×10^{-4}	49

The values of vertical and horizontal hydraulic conductivities against dry density of pulverised waste are plotted on semi-log paper, as shown in Figure 6.12. The trend of the data shows an exponential decay in the values of permeability as the waste density increases.

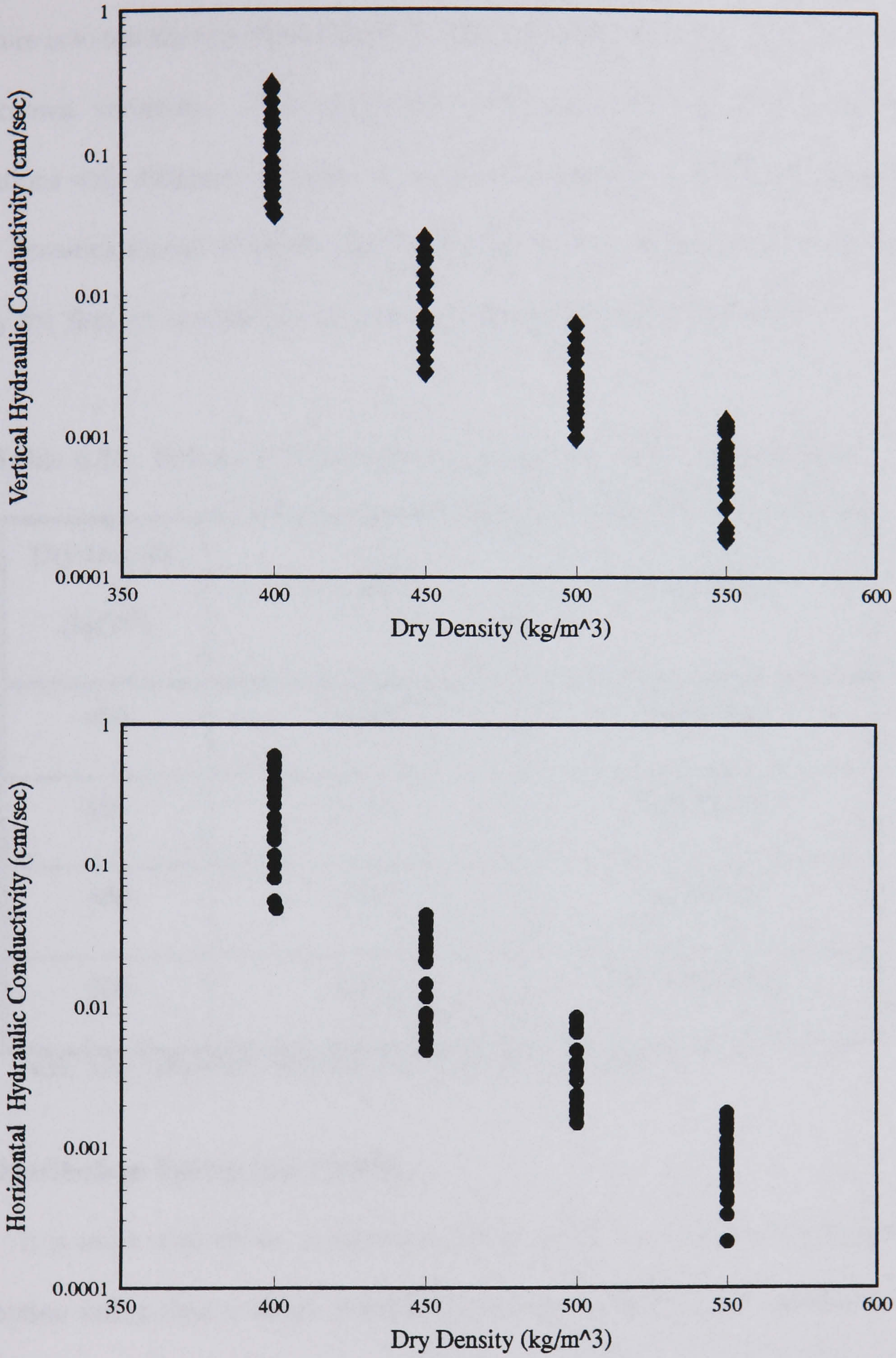


Figure 6.12. Hydraulic Conductivity versus Dry Density.

A *z-test* was used to determine the difference between means of vertical and horizontal conductivities values for a particular density (Chatfield, 1989). The procedure is to test the hypothesis about the difference between two population means with known variances. The comparison between means of two independent populations with different variances is shown in Table 6.10. The test is significant for all densities except at higher density of 550 kg/m^3. This is because at higher density the flow in vertical and horizontal directions is almost the same.

Table 6.10. Results of z-Test for the comparison of two sample means.

Dry Density (kg/m^3)	z statistic	Conclusions
400	3.547	Significant
450	3.143	Significant
500	2.165	Significant
550	1.409	Not significant

N.B. The tabulated value of z [α = 95 %] = 1.960.

6.6 Distribution Fitting and Plotting

It is more appropriate to represent the conductivity in terms of a probability distribution rather than a single deterministic value. The *Kolmogorov-Smirnov test* (Kolmogorov, 1933) was applied to fit the appropriate distribution. As is evident from the literature that for the soil systems, hydraulic conductivity is distributed log-normally (Oweis and Khera, 1990). First, a log-normal (two-parameters) distribution was tried to fit the experimental data. The results of the *Kolmogorov-Smirnov test* are summarized in Table 6.11. The critical value of statistics D for n=20 and α= 95 %, from Table A-1 (Appendix) is 0.294, which is greater than all the calculated values of D, means accepting the null hypothesis of log-normality.

Table 6.11. Results of Kolmogorov-Smirnov Test for K_s.

Dry Density (kg/m^3)	Kolmogorov-Smirnov statistic D_n	
	Vertical	*Horizontal*
400	0.080	0.136
450	0.114	0.197
500	0.075	0.110
550	0.096	0.120

N.B. The critical value of D [n=20, α= 95 %] = 0.294

The lognormal (two-parameter) probability density function in each case for the 20 values is calculated using the following equation:

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma_y} \exp\left[- \frac{(y - \mu_y)^2}{2\,\sigma_y^2} \right] \qquad \textbf{(6.11)}$$

where μ_y is a mean and σ_y is standard deviation of the y variate (=ln(x)).

The vertical and horizontal saturated hydraulic conductivities values with corresponding probabilities f(x) are plotted graphically in Figures 6.13 and 6.14, by transforming their values to standardized conductivity values range from 0 to 1.

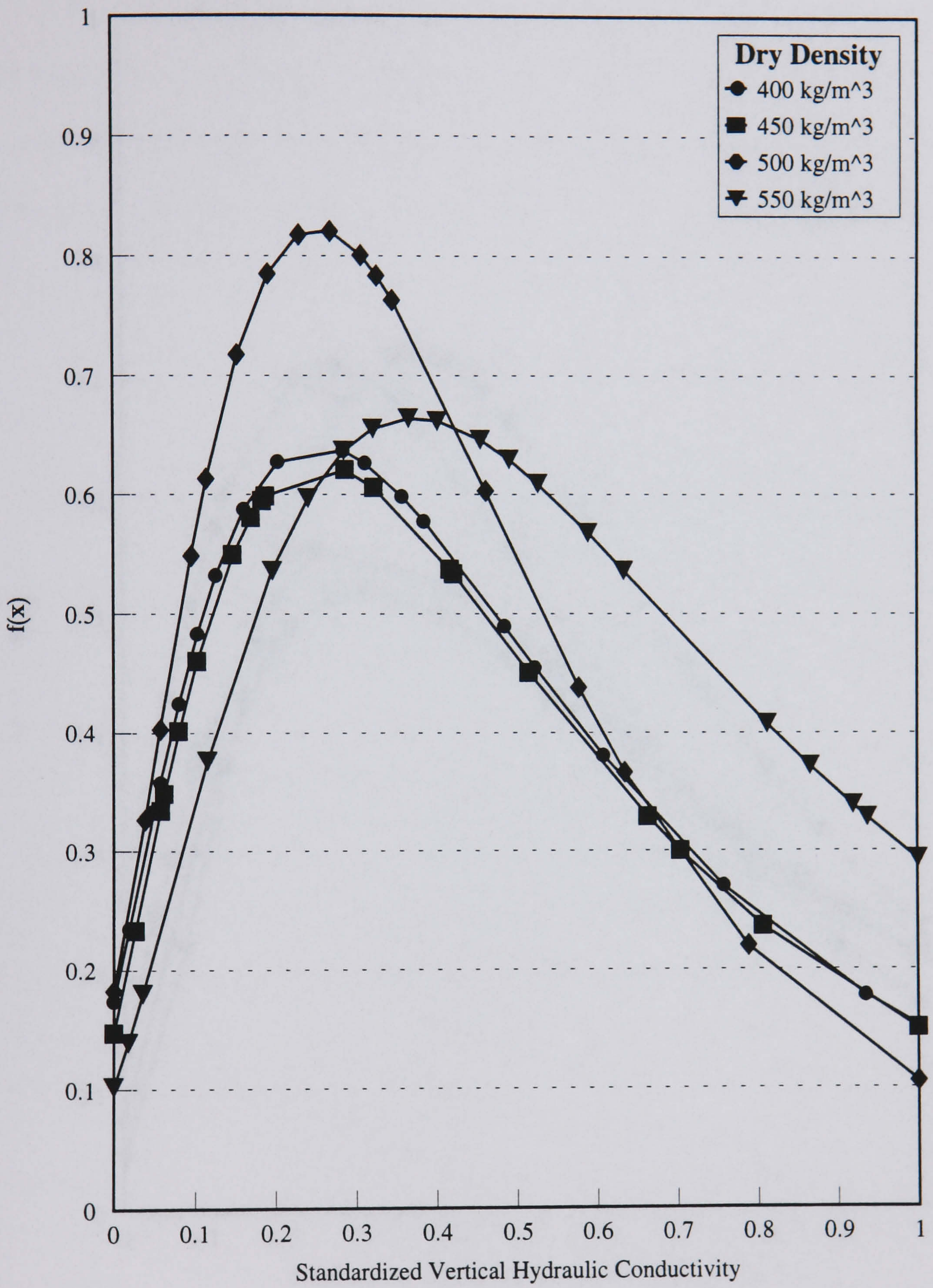


Figure 6.13. Lognormal Probability Density Function of Kv.

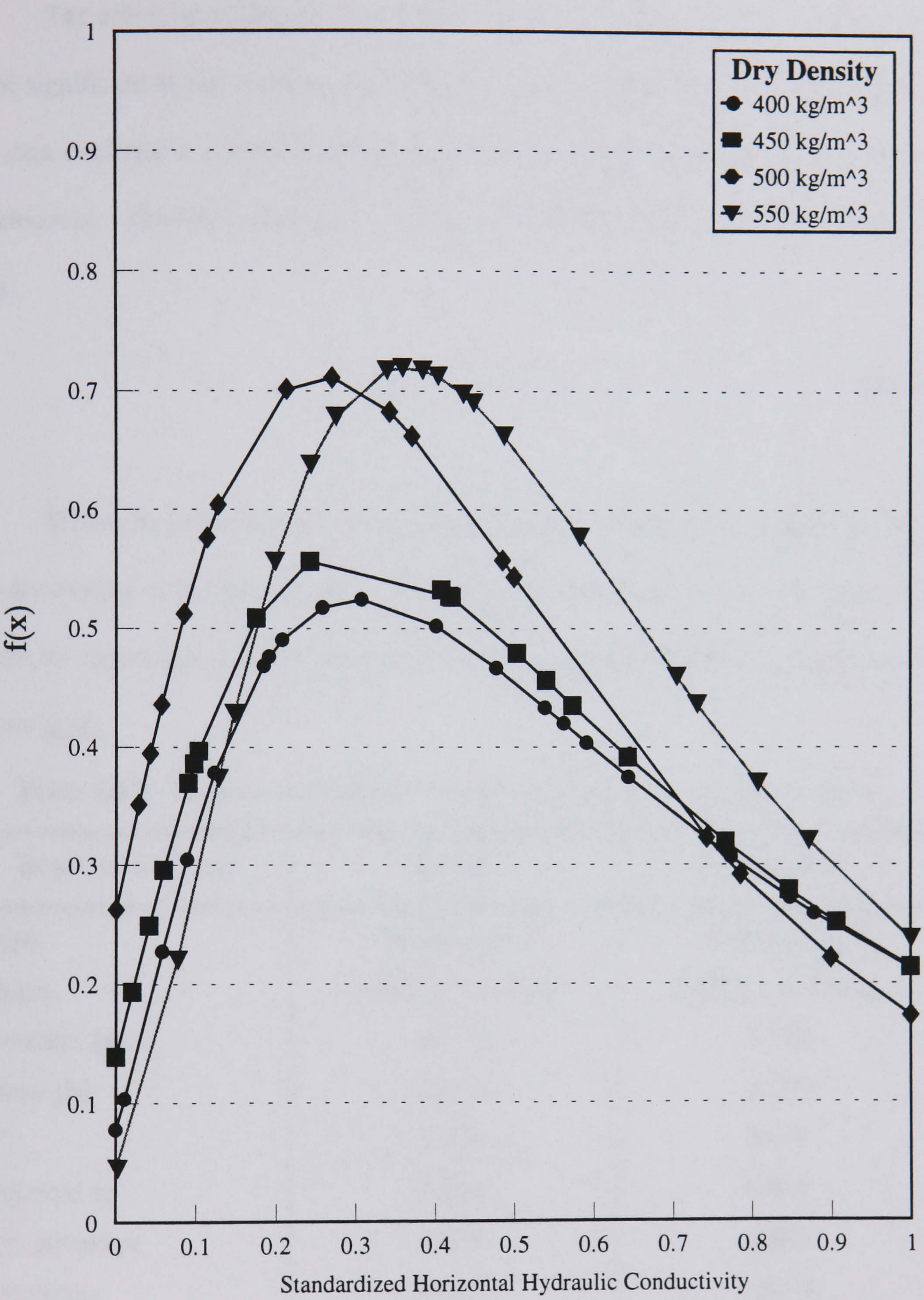


Figure 6.14. Lognormal Probability Density Function of Kh.

6.7 Model Fitting for Saturated Hydraulic Conductivity

The effect of density on the saturated hydraulic conductivity was determined to be significant in both vertical and horizontal cases (Figure 6.12). Visualization of the data confirms a nonlinear relationship between density and saturated hydraulic conductivity. The following exponential relationship was tried to fit the experimental data.

$$K_s = e^{a + b\rho_d} \tag{6.12}$$

Where K_s is the vertical or horizontal saturated hydraulic conductivity, ρ_d is the dry density of pulverized waste, 'a' is a coefficient and 'b' is an exponent. The results of regression analysis are given in Table 6.12 and graphically displayed in Figure 6.15.

Table 6.12. Regression Statistics between Conductivity and Dry Density.

Regression Output	Vertical	Horizontal
Type	Exponential	Exponential
Shape	$\ln[K_s] = a + b\,\rho_d$	$\ln[K_s] = a + b\,\rho_d$
Intercept [a]	10.773	12.938
Slope [b]	-0.033	-0.037
R^2	0.890	0.896
Adjusted R^2	0.889	0.895
S.E. Intercept	0.636	0.681
S.E. Slope	0.0013	0.0014
S.E. Regression	0.665	0.712
Observations	80	80

S.E. Standard Error

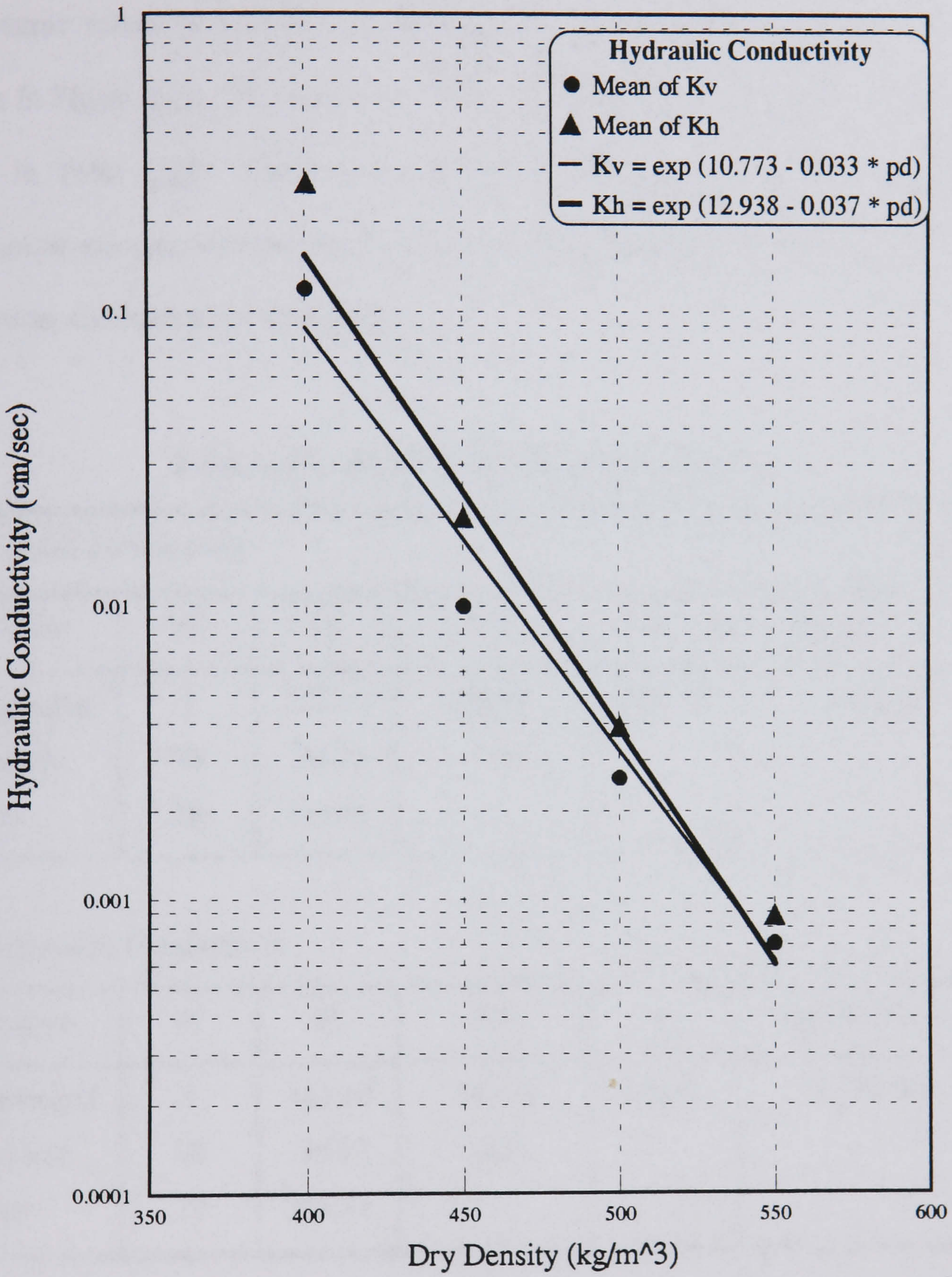


Figure 6.15. Regression Fit between Hydraulic Conductivity and Dry Density.

An ANOVA (Analysis of variance) was used as a mechanism for gaining information in favour of the hypothesis that there is a linear relationship between logarithmic values of hydraulic conductivity and density of the waste material, as shown in Figure 6.15. The results of ANOVA, applied to the regression models are given in Table 6.13. The test results are significant in favour of exponential relationship existing between waste density and saturated hydraulic conductivity, both in vertical and horizontal directions.

Table 6.13. ANOVA for Regression Models.

Vertical Conductivity					
Source	df	SS	MS	F	Significance F
Regression	1	280.00	280.00	633.75	3.39E-39
Residual	78	34.46	0.44		
Total	79	314.46			
Horizontal Conductivity					
Source	df	SS	MS	F	Significance F
Regression	1	341.98	341.98	674.92	3.77E-40
Residual	78	39.52	0.51		
Total	79	381.51			

6.8 Model Evaluation

The model developed in the previous section for vertical saturated hydraulic conductivity is further considered here. Its effect on unsaturated hydraulic conductivity was determined using the drainage model developed by Gilbert (1995). He compared six different types of drainage models and concluded that Irmay's model (1950) suits best to his experimental data using the same pulverized MSW as was used in this experimentation. The unsaturated hydraulic conductivity (K) function as developed by Irmay (1950) is given as,

$$K = K_s \left[\frac{\theta_i - \theta_f}{\theta_s - \theta_f} \right]^n \qquad \textbf{(6.13)}$$

where:

θ_i = initial moisture content (vol/vol)

θ_f = field capacity (vol/vol)

θ_s = saturated moisture content (vol/vol)

K_s = saturated hydraulic conductivity (L/T)

n = is an exponent depending on the type and density of waste material.

A relationship between an exponent 'n' and dry density of the pulverized MSW from the same source determined by Gilbert (1995) is shown graphically in Figure <u>6.16</u> and is expressed mathematically as:

$$n = -10.77 + 0.03\,\rho_d \qquad \textbf{(6.14)}$$

where ρ_d is the dry density of waste material in kg/m^3. The author performed experiments with three densities of 400, 450 and 500 kg/m^3.

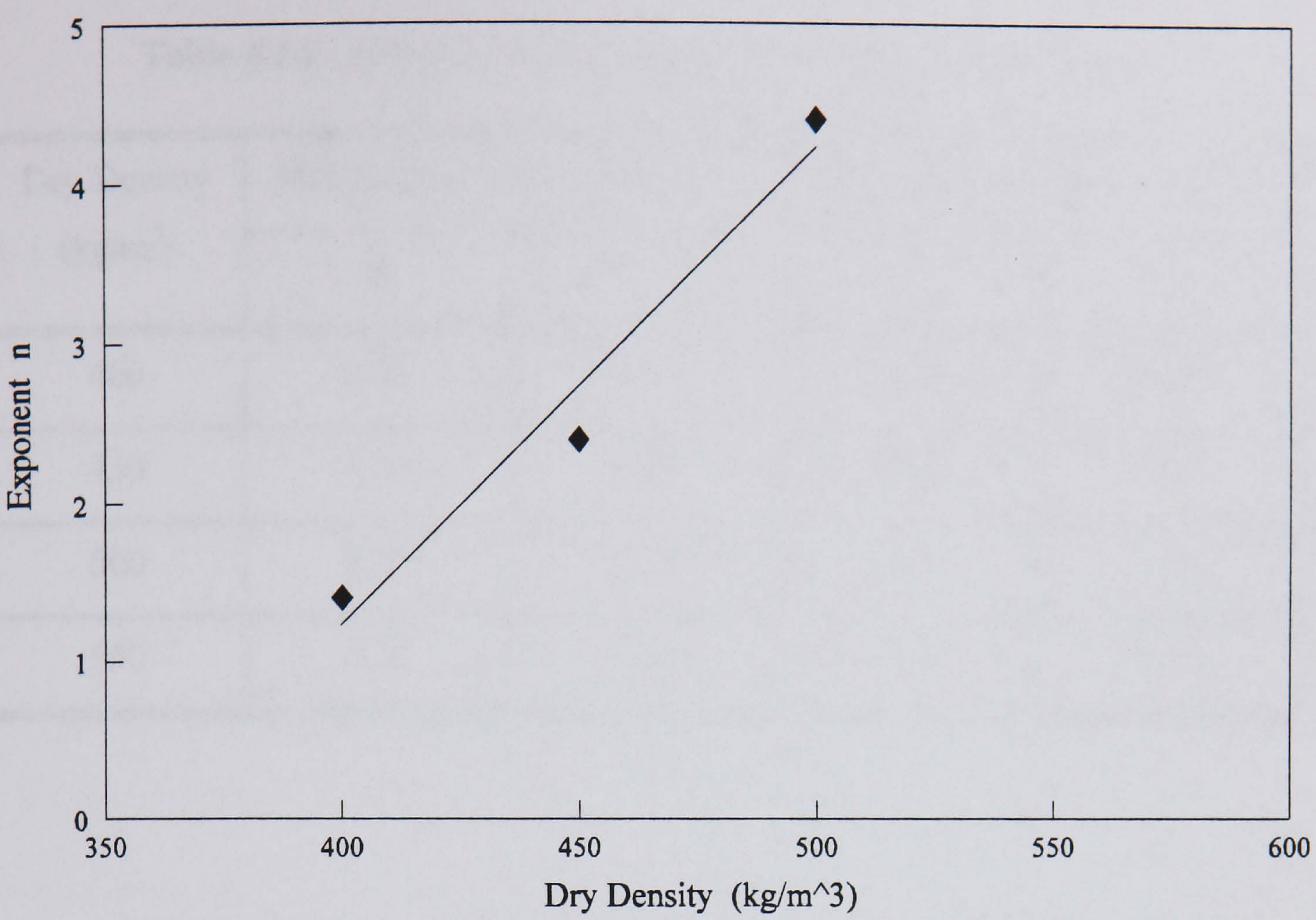


Figure 6.16. Regression fit between exponent 'n' of Irmay's model and dry density of pulverised waste (Gilbert, 1995).

A relative hydraulic conductivity K/K_s is plotted against normalised moisture content θ_i/θ_s, as shown in Figure 6.17. The moisture capacities used are given in Table 6.14, which are reported by Gilbert (1995) for the pulverised waste used in this study. The comparison is made of vertical hydraulic conductivity for the different dry densities of waste material. Three waste densities of 400, 450, and 500 kg/m^3 are included in the analysis. It is evident from this graph that as the waste density increases, the value of relative hydraulic conductivity approaches to unity. It is concluded that at higher density, waste has no further capacity to absorb moisture.

Table 6.14. Average moisture capacities for pulverized waste.

Dry Density (kg/m^3)	Moisture on wet weight basis		Moisture on volume basis	
	θ_f	θ_s	θ_f	θ_s
400	0.36	0.49	0.29	0.39
450	0.38	0.45	0.34	0.40
500	0.37	0.39	0.37	0.39
550	0.35	0.36	0.39	0.40

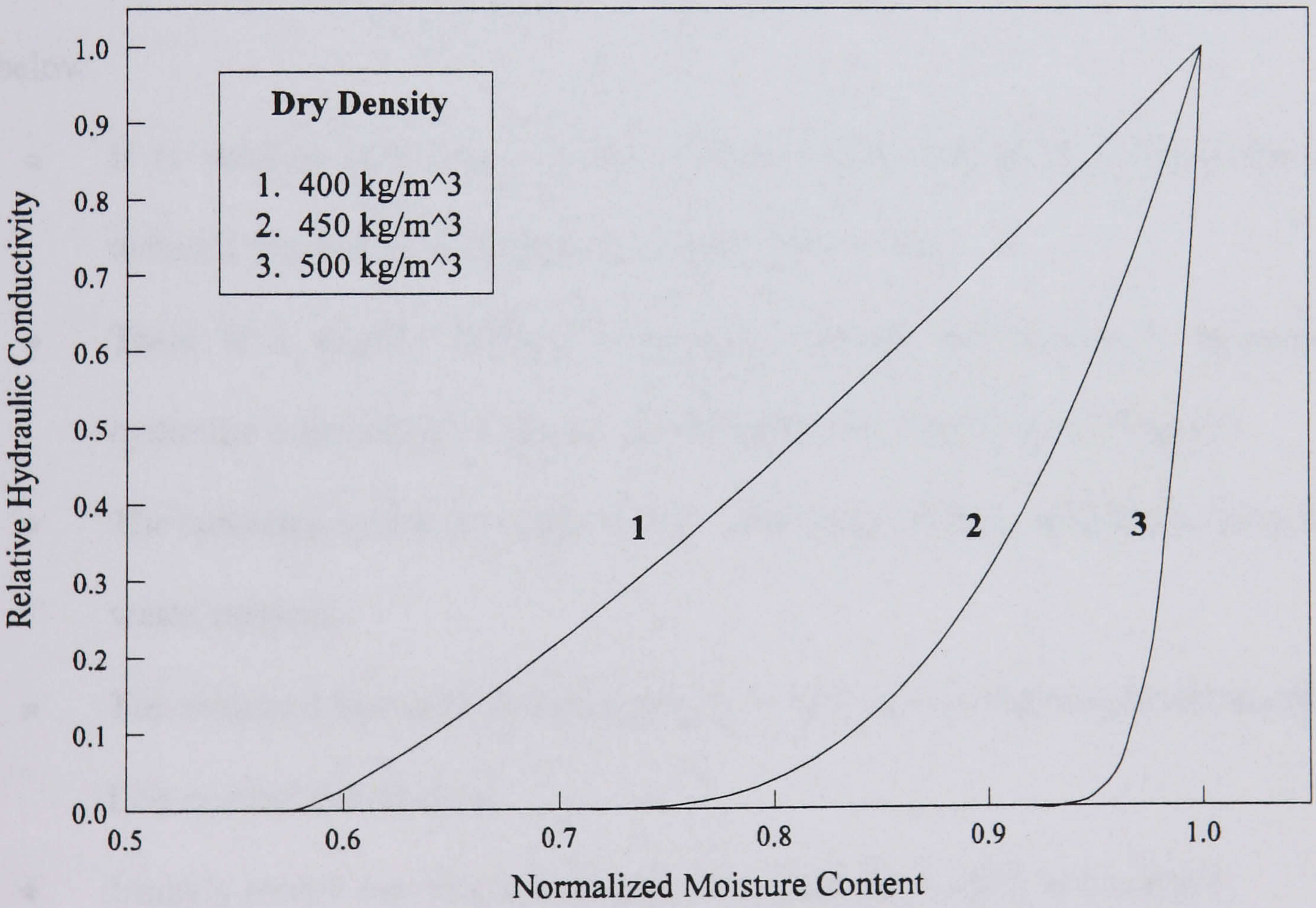


Figure 6.17. Effect of the normalized moisture content on relative hydraulic conductivity for different densities.

6.9 Conclusions

It is concluded from the laboratory investigation that the effect of compaction is significant on both vertical and horizontal hydraulic conductivities of waste material. Four compaction levels (i.e., 400, 450, 500, and 550 kg/m^3) were chosen ranging from minimum (i.e., in loose state) to maximum possible using laboratory compaction. For each density, twenty samples were tested which represent a wide range of material variability. Two design curves have been established from the results of 80 laboratory experiments and will be used in the development of the model that simulates the movement of the water in the waste material. The statistical properties of the hydraulic conductivity vary widely and confirm that log-normal distribution can be used to describe it. The findings of the research are summarized below:

- ★ It is verified that Darcy's law generally holds for the pulverised waste material for hydraulic gradients ranging from 0 to 4.
- ★ There is a marked difference between vertical and horizontal saturated hydraulic conductivities except at the higher dry density of 550 kg/m^3.
- ★ The saturated hydraulic conductivity varies exponentially with the density of waste material.
- ★ The saturated hydraulic conductivity (both vertical and horizontal) follows the Log-normal distribution.
- ★ Irmay's model can be used to calculate drainage out of a waste layer.

The findings of this experimentation will be incorporated in the development of the new model, which is discussed in the next chapter.

Chapter 7

MODEL THEORY AND DEVELOPMENT

An applied numerical model **NUMMOL** (*NUMerical Modelling of Leachate*) has been developed to simulate the water movement into, through and out of landfills. The model accepts precipitation, potential evapotranspiration and landfill design site data, as inputs from the user. It uses solution techniques that account for the runoff, infiltration, surface storage, percolation, lateral subsurface drainage, leachate recirculation, unsaturated flow, saturated flow, flow to drainage systems and seepage losses through a clay liner. These processes in a landfill are linked together in a sequential order starting at the surface, proceeding downwards through the landfill profile to the bottom. The solution procedure is applied repetitively for each day as it simulates the water routing throughout the simulation period. The primary purpose of the model is to estimate the leachate quantity and to assist in the comparison of landfill design alternatives as judged by their water balances.

7.1 Overview of the Model

This section provides an overview of the NUMMOL model, which simulates the movement and distribution of leachate within a landfill site. The program is written in FORTRAN 77 with options to allow easy access for future modifications and changes. The main module INTERFACE serves as a control centre to lead the user through the different options of the NUMMOL model. It initiates the major calls to the other main subroutines. The main subroutines have been grouped as control and simulation modules. The control module performs such functions as editing, saving, viewing and printing of files. The simulation module includes sub-programs; SURFACE, UNSATURATED, RESERVOIR, and COLLECTOR which are responsible for the evaluation of different simulation tasks. These main routines then call other subroutines as required.

During the development of this model, emphasis was given to a user-friendly interactive software interface, with the capability to improve the package by adding modules and/or modifying existing modules. The major functions currently performed by the INTERFACE module include:

- Pop-up menu system to control different tasks
- Data file selection
- Editing features including range checking
- Choice for allocation of default values for some input parameters
- Access to the data base system
- Input data and results can be directed to screen, file, and printer
- Graphic view is incorporated to view the plan and sections of landfill
- Time plots of the main input and output variables
- Context sensitive help with addition to the general help facilities
- Printing facility for printing data files and different graphs
- Graphic images can be exported in a PCX formatted files

7.2 Model Approach and Description

The NUMMOL model is developed to estimate daily water movement on the surface and through the landfill. Precipitation is partitioned into runoff, evapotranspiration and infiltration. Infiltration water stored in soil cover has either to percolate through the clay liner or flow laterally to drain. The NUMMOL model computes runoff by the Soil Conservation Service (SCS) runoff curve number method (USDA, SCS, 1972) and percolation by Darcy's law for saturated flow with modification for unsaturated conditions. The seepage between the cells is determined by Darcy's law with special consideration of layer effects and cell geometry. In the case of containment sites, lateral drainage from under drainage systems is computed analytically from a linearized Boussinesq's equation (McEnroe and Schroeder, 1988).

A practical completed landfill site may consist of different cells having proper geometry, layer sequencing and bunds. Figure 7.1 is a definition sketch for a typical closed landfill cell profile. There are three mainly distinct parts: landfill cover, waste and intermediate soil layers, and bottom drainage and liner systems. The top portion of the profile is the cap or cover. The bottom portion of the landfill is with or without a drainage system. The middle sub-profile contains the waste and intermediate soil layers.

The different processes contributing to the hydrology of a landfill cell are shown in Figure 7.1, and are grouped into four subgroups as surface, unsaturated, saturated and drainage systems. Four major modules (Figure 7.2) are developed for the simulation purposes and are described below in detail.

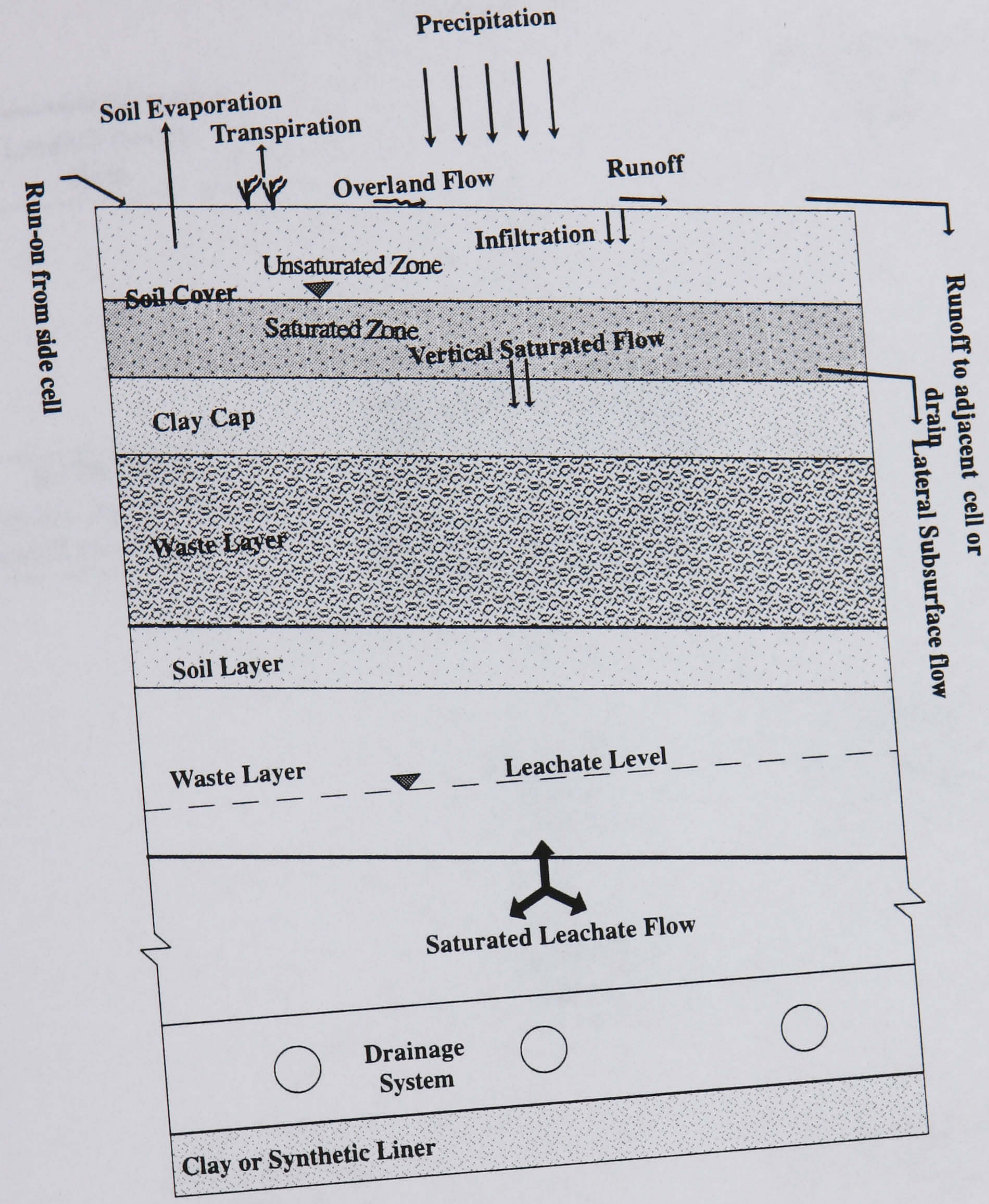


Figure 7.1. Simulation Processes in the NUMMOL Model.

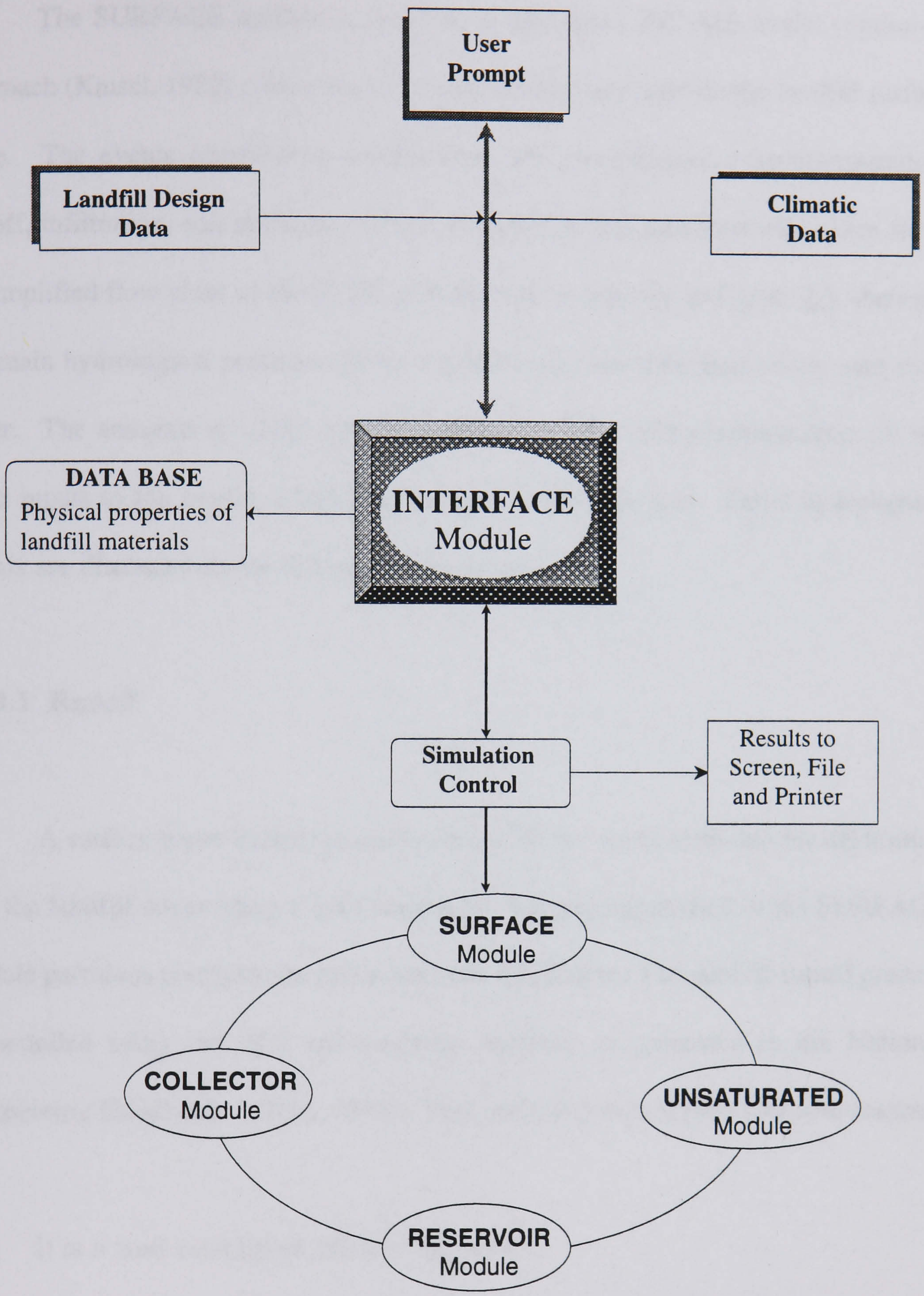


Figure 7.2. Generalized Flow Chart of NUMMOL Model.

7.2.1 SURFACE Module

The SURFACE module is based on a modified CREAMS model (option-1) approach (Knisel, 1980) which takes into account the processes on the landfill surface zone. The events contributing to this zone are precipitation, evapotranspiration, runoff, infiltration, soil moisture storage, percolation and saturated subsurface flow. A simplified flow chart of the SURFACE Module is depicted in Figure 7.3, showing the main hydrological processes of the landfill cover and their interaction with each other. The amounts of daily precipitation and potential evapotranspiration are the main inputs to the model, which will be specified by the user. Other hydrological events are discussed in the following sub-sections.

7.2.1.1 Runoff

A surface water balance is used to estimate the water available for infiltration into the landfill cover using a daily time step. The algorithm used in the SURFACE module partitions precipitation into runoff and infiltration. The rainfall-runoff process is modelled using the SCS curve-number method, as presented in the National Engineering Handbook (USDA, 1985). This procedure was selected for four reasons:

1. It is a well established reliable procedure.
2. It is computationally efficient.
3. The required input is generally available.
4. Various soil types, land use and management practices can be conveniently handled.

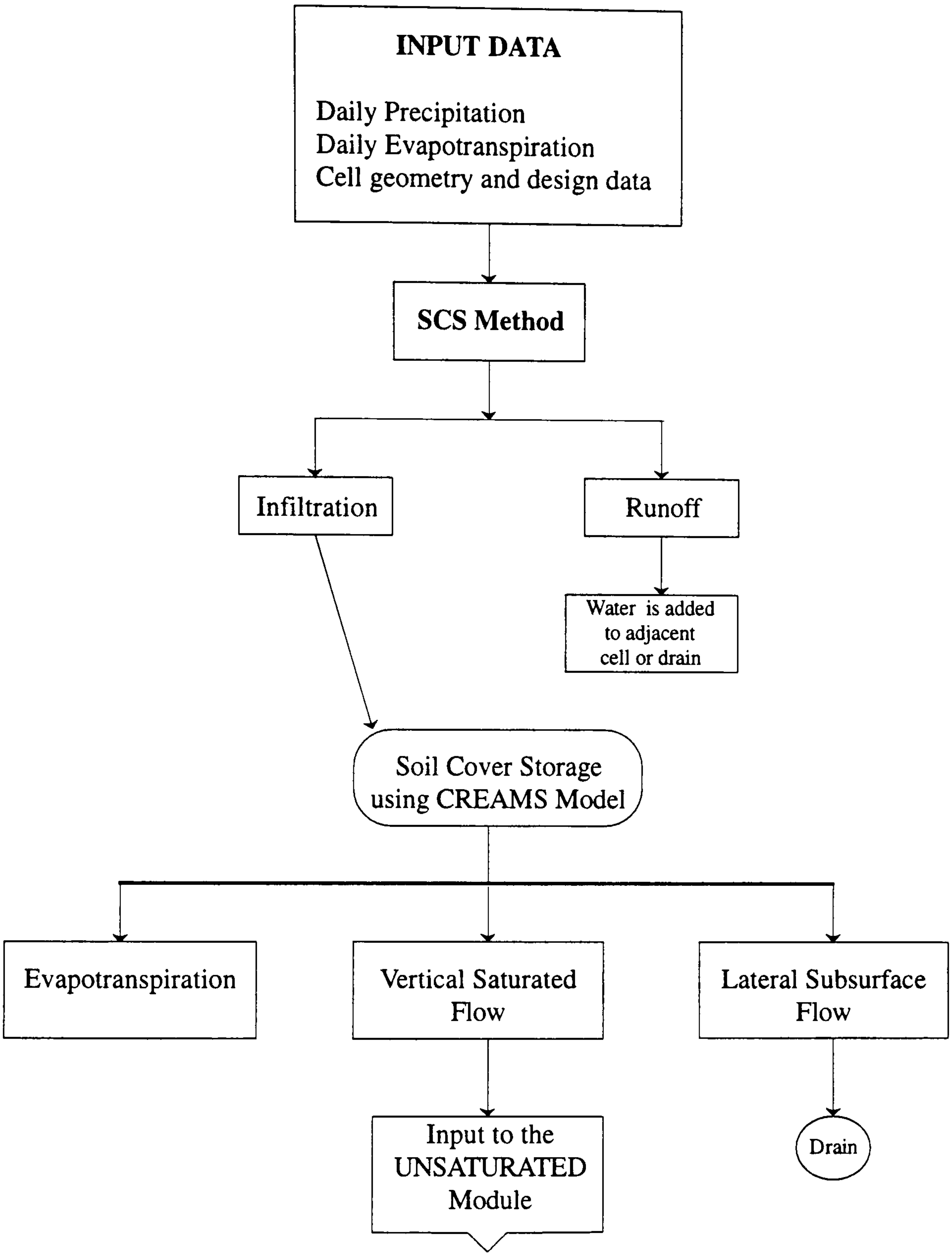


Figure 7.3. Flow Chart of SURFACE Module.

The relation between precipitation, runoff, and retention for a particular set of environmental conditions is:

$$R = \frac{(P - I_a)^2}{(P + S - I_a)} \tag{7.1}$$

where

R = daily runoff [cm]

P = daily precipitation [cm]

I_a = initial abstraction [cm]

S = retention parameter or catchment storage [cm]

In most cases, initial abstraction is estimated as a function of catchment storage, typically taken to be 10% of catchment storage.

The retention parameter, S, is transformed into a so-called runoff curve number, CN, to make interpolating and weighing operations more linear. The relationship between CN and S is

$$S = 2.54\left[\frac{1000}{CN} - 10\right] \tag{7.2}$$

The retention parameter, S, for a given soil varies as a function of the soil moisture in the underlying soil (Knisel, 1980)

$$S = S_{mx}\left[1 - \frac{\theta - \theta_w}{\theta_s - \theta_w}\right] \tag{7.3}$$

where

S_{mx} = maximum value of the retention parameter [cm]

θ = soil water content in the upper soil layer [vol/vol]

θ_s = upper limit moisture content in the upper soil layer [vol/vol]

θ_w = wilting point moisture content in the upper soil layer [vol/vol]

The upper limit of soil moisture content is the moisture content at saturation and is numerically equal to the effective porosity. The wilting point moisture content is the lowest naturally occurring soil water content.

Since soil water is not distributed uniformly throughout the soil profile and the soil moisture near the surface influences infiltration more strongly than that located elsewhere, the retention parameter is depth-weighted. The soil profile in the uppermost soil layer is divided into seven segments. The thickness of the top segment is set equal to one thirty-sixth of the total upper layer thickness and the thickness of the second segment is five thirty-sixths of the layer's thickness. The thickness of each of the bottom five segments in the uppermost soil layer is defined as one-sixth of the total layer thickness. The depth-weighted retention parameter is computed from the following equation (Knisel, 1980):

$$S = S_{mx}\left[1 - \sum_{j=1}^{7} W_j \left(\frac{\theta(j) - \theta_w(j)}{\theta_s(j) - \theta_w(j)}\right)\right] \qquad (7.4)$$

where

W_j = weighting factor for segment j

$\theta(j)$ = soil moisture content of segment j [vol/vol]

$\theta_s(j)$ = upper limit moisture content of segment j [vol/vol]

$\theta_w(j)$ = wilting point moisture content of segment j [vol/vol]

The weighting factors decrease with the depth of the segment in accordance with the following equation from the CREAMS model (Knisel, 1980):

$$W_j = 1.0159 \left[e^{-4.16 \frac{D_{j-1}}{D}} - e^{-4.16 \frac{D_j}{D}} \right] \tag{7.5}$$

where:

D_j = depth to bottom of segment j [L]

D = vegetative or evaporative zone depth [L]

For the assumed segment thicknesses, this equation gives weighting factors of 0.111, 0.397, 0.254, 0.127, 0.063, 0.032 and 0.016 for segments 1 through 7. The top segment is the highest weighted in a relative sense since its thickness is 1/36 of the evaporative zone depth while the thickness of the second segment is 5/36 and the others are 1/6.

The runoff curve number required as input to the program is that corresponding to antecedent moisture condition II (AMC-II) in the SCS method. AMC-II represents an average soil-moisture condition. The corresponding curve number is denoted by CN_{II}.

The value of the maximum moisture retention parameter, S_{mx}, is assumed to equal the value of S for a dry condition, antecedent moisture condition I (AMC-I) in the SCS method (USDA, SCS, 1985). S_{mx} is related to the curve number for AMC-I, as follows:

$$S_{mx} = 2.54\left[\frac{1000}{CN_I} - 10\right] \tag{7.6}$$

CN$_I$ is related to CN$_{II}$ by the following polynomial (Knisel, 1980):

$$\begin{aligned} CN_I = {} & 3.751\times10^{-1}\,CN_{II} + 2.757\times10^{-3}\,CN_{II}^2 \\ & - 1.639\times10^{-5}\,CN_{II}^3 + 5.143\times10^{-7}\,CN_{II}^4 \end{aligned} \tag{7.7}$$

Given CN$_{II}$ from input, CN$_I$ and S$_{mx}$ are computed once using Equations 7.7 and 7.6, respectively. S is computed daily using Equation 7.4. The daily runoff resulting from the daily rainfall is computed using Equation 7.1.

7.2.1.2 Infiltration

Daily infiltration into the landfill is determined from a surface-water balance. The depth of infiltration can be assessed by comparison of rainfall and runoff depths at a particular time (say daily) as,

$$IN_i = P_i - R_i - I_a \tag{7.8}$$

It is accepted practice to assume that initial abstraction losses do not contribute to infiltration; these generally represent interception by vegetation and hence water which is subsequently evaporated.

7.2.1.3 Evapotranspiration

Evapotranspiration from a landfill surface is a function of climatic conditions, vegetation, soil moisture and the ability of the soil to transmit water. A two-step approach is taken to calculate evapotranspiration. First, the potential evapotranspiration is an input to the model by the user and is denoted by EPT_i on day i. The second step involves estimating the availability of water, stored as soil moisture in the vegetative zone, to meet the evapotranspiration demand. The available soil moisture is estimated as a function of the moisture content above the wilting point in the upper soil layer (root zone). The user must take care in defining the thickness of this layer so that its depth accurately reflects the depth over which evapotranspiration takes place. If the top of the landfill is vegetated, it is suggested that the uppermost layer thickness corresponds to the root zone depth.

The soil moisture level above which soil moisture is available, is linearly interpolated over this depth as shown in Figure 7.4. That is, a triangular distribution is assumed from the surface to the bottom of the uppermost layer with the maximum soil moisture taken from near the surface. This approach is similar to that used in the PRZM model (Carsel et al., 1984). The available moisture for evapotranspiration can be expressed as:

$$AW_i = 100 \sum_{j=1}^{7} (\theta(j) - [\theta_w + \frac{z_j}{D} (\theta - \theta_w)]) \Delta z_j \qquad (7.9)$$

where

AW_i = water available for evapotranspiration on day i [cm]

D = the thickness of the uppermost layer [m]

θ_w = wilting point moisture content in the upper soil layer [vol/vol]

θ = soil water content in the upper soil layer [vol/vol]

Δz_j = thickness of segment j [m]

$\theta(j)$ = soil water content in segment j

z_j = depth to the centre of segment j [m]

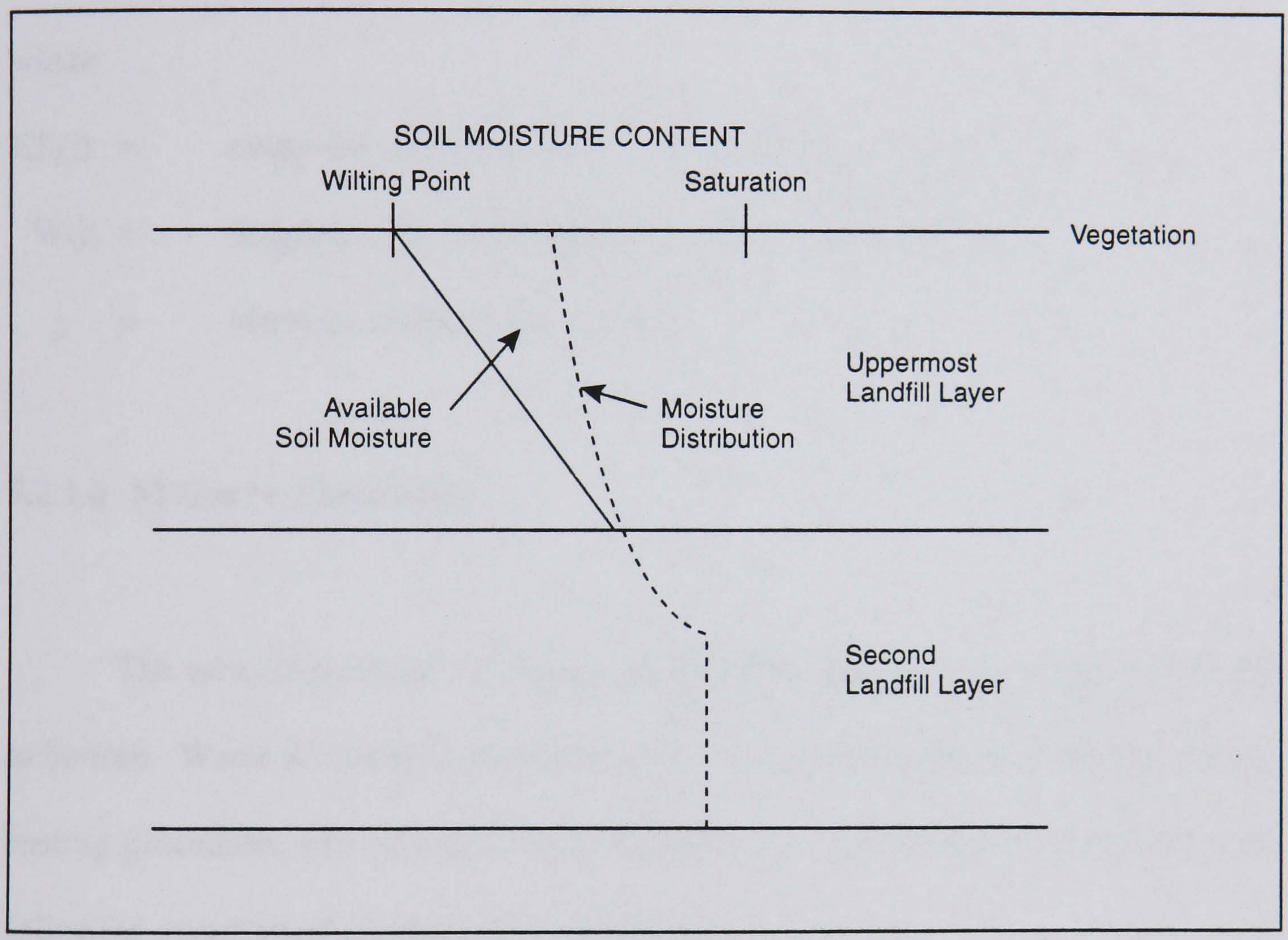


Figure 7.4. Soil moisture available for evapotranspiration.

The potential evapotranspiration and the available soil moisture are compared and the lesser of the two amounts is assigned as the actual evapotranspiration. Thus, the actual evapotranspiration of any day is:

$$ET_i = \min(EPT_i, AW_i) \tag{7.10}$$

where ET_i is the actual evapotranspiration demand on day i. This demand is distributed throughout the seven segments in the evaporative zone, by the following equation:

$$ET_i(j) = ET_i \cdot W(j) \tag{7.11}$$

where

$ET_i(j)$ = evapotranspiration demand on segment j on day i [cm]

$W(j)$ = weighting factor for segment j, from Equation 7.6.

j = segment numbers from 1 to 7.

7.2.1.4 Moisture Distribution

The subsurface water routing proceeds first in the soil cover system, from top to bottom. Water is routed downwards from one segment to the next using a storage routing procedure, with storage evaluated at the end of each day. It is based on the following equation of continuity for any segment:

$$\theta_i = \theta_{i-1} + \frac{IN_i - DR_i - ET_i}{D} \tag{7.12}$$

where

θ_i = soil moisture storage at the end of day i [vol/vol]

θ_{i-1} = soil moisture storage at the day i-1 [vol/vol]

IN_i = input to segment during day i [cm]

ET_i = evapotranspiration from segment on day i [cm]

DR_i = drainage out of segment on day i [cm]

D = depth of segment [cm]

The daily vertical drainage (DR_i) out of a segment in the above equation is calculated using Darcy's law ($q = K(\theta)\cdot i$), assuming a unit hydraulic gradient (i). The unsaturated hydraulic conductivity ($K(\theta)$) is a function of soil moisture and varies from zero to the saturated hydraulic conductivity value, K_s. The unsaturated hydraulic conductivity is estimated by Campbell's equation (Campbell, 1974).

$$DR_i = K_s \left(\frac{\theta - \theta_f}{\theta_s - \theta_f} \right)^{3 + \frac{2}{\lambda}} \tag{7.13}$$

where

DR_i = drainage out of segment on day i [cm/day]

K_s = saturated hydraulic conductivity [cm/day]

θ = actual volumetric water content [vol/vol]

θ_f = field capacity [vol/vol]

θ_s = total porosity [vol/vol]

λ = pore-size distribution index [dimensionless]

The value of λ is estimated from Brooks and Corey (1964) relationship as:

$$\lambda = 0.263 \cdot \ln \left(\frac{\theta_f - \theta_r}{\theta_w - \theta_r} \right) \tag{7.14}$$

where θ_r is residual volumetric water content and is equal to the amount of water remaining in a layer under infinite capillary suction. A regression equation (θ_r =

0.014 + 0.253 * θ_w) developed by Rawls et al. (1982) is used to calculate the residual volumetric water content.

Soil water is distributed among seven segments in the evaporative zone and one extra zone if the depth of soil cover is greater than the evaporative zone. The depth of the extra segment (8th segment) is equal to the difference between depth of soil cover and evaporative zone. The module initially distributes the infiltration water in a landfill soil cover composed of n segments as follows.

For segment 1

$$\theta_i(1) = \theta_{i-1}(1) + \frac{IN_i(1) - DR_i(1) - ET_i(1)}{D(1)} \tag{7.15}$$

where:

$\theta_i(1)$ = soil moisture storage at the end of day i

$\theta_{i-1}(1)$ = soil moisture storage at the day i-1

IN_i = infiltration during day i [cm]

$ET_i(1)$ = evapotranspiration from segment 1 on day i [cm]

$DR_i(1)$ = drainage out of segment 1 on day i [cm]

$D(1)$ = depth of segment 1 [cm]

For segment j; j = 2 to n-1

$$\theta_i(j) = \theta_{i-1}(j) + \frac{DR_{i-1}(j-1) - DR_i(j) - ET_i(j)}{D(j)} \tag{7.16}$$

where:

$DR_{i-1}(j-1)$ = drainage out of segment (j-1) during day i-1 [cm]

$ET_i(j)$ = evapotranspiration from segment j on day i [cm]

$DR_i(j)$ = drainage out of segment j on day i [cm]

For segment n

$$\theta_i(n) = \theta_{i-1}(n) + \frac{DR_{i-1}(n-1) - ET_i(n)}{D(n)} \qquad ET_i(8) = 0 \tag{7.17}$$

where:

$DR_{i-1}(n-1)$ = drainage out of segment (n-1) during day i-1 [cm]

Moisture routing in the soil cover proceeds sequentially from the top segment to the bottom segment, assuming free drainage at the bottom of each segment except the last segment. An estimate of infiltration from Equation 7.8 provides the inflow to the top segment and a priori estimate of drainage from Equation 7.13 provides the outflow from top segment. A new moisture level for the segment is established daily. The outflow from first segment is available as inflow to the second segment, and the same process of updating the moisture levels are continued for the remaining segments. Because drainage into a segment is dependent only on the segment above, a segment may receive more moisture than it can hold. If the moisture content of a segment is greater than its total porosity, the excess moisture is added to the segment above it. In this way, the moisture contents of segments are corrected by backing up water from bottom to top. If the entire profile becomes saturated, any excess moisture at the surface is added to the runoff for the day.

7.2.1.5 Soil Capping Layer Percolation and Lateral Drainage

After the moisture content of each segment is calculated, the total head of water column or depth of saturation in the soil cover is computed by comparing segment moisture contents with their corresponding total porosities. The head computation begins at the bottom of soil cover, consisting of 'n' segments. The heads computed within consecutive segments are accumulated from the lowest segment of soil cover above the clay cap. When a segment, m, that is not saturated is encountered while moving up the profile, depth of saturation is set equal to the accumulated head. The average head on the entire surface of clay liner is computed using the following equation:

$$(h_w)_i = \begin{cases} \sum\limits_{j=m+1}^{n} D(j) + D(m)\left[\dfrac{\theta(m)_i - \theta_f}{\theta_s - \theta_f}\right] & for\ \theta(m)_i > \theta_f \\ \sum\limits_{j=m+1}^{n} D(j) & for\ \theta(m)_i < \theta_f \end{cases} \qquad (7.18)$$

where:

$(h_w)_i$ = average hydraulic head on clay liner during day i [cm]

D(j) = thickness of the segment j [cm]

$\theta(m)_i$ = soil moisture storage of segment m at the end of day i [vol/vol]

θ_f = field capacity of soil cover [vol/vol]

θ_s = saturation capacity of soil cover [vol/vol]

m = number of the lowest unsaturated segment in soil cover

n = number of the segment directly above the clay liner

The vertical percolation through the clay cap and lateral drainage over the clay cap are assumed to be at steady-state, i.e., saturation head is constant during a day under consideration. The module assumes that clay liner remains saturated at all times. Percolation and lateral drainage is only allowed to take place when there is a positive saturation head (greater than 0).

Percolation :

The rate of percolation through the clay cap depends on the thickness of the saturated material directly above it, as computed from Equation 7.18. The depth of this saturated zone is termed the hydraulic (pressure) head on the clay liner. The model assumes that clay cap remains saturated at all times. Percolation is predicted to occur only when there is a positive hydraulic head on top of the liner. The daily percolation through a clay liner is computed using Darcy's law, assuming free drainage from the bottom of the liner as:

$$q_P = K_{clay} \left[\frac{(h_w)_i + D_{clay}}{D_{clay}} \right] \tag{7.19}$$

where

q_P = percolation rate through clay liner [cm/day]

K_{clay} = saturated hydraulic conductivity of clay liner [cm/day]

D_{clay} = thickness of the clay liner [cm]

Clay liners are installed to minimize the percolation of water from soil cover and have no flaws at the time of construction. But it is evident from experience that cracks occur due to settlement and overburden pressure and allow water through (Peyton and Schroeder, 1990). A certain degree of failure (C_L) will be assigned by the user to compensate for clay leakage. A zero value indicates no leakage at all.

Lateral Drainage :

Lateral drains are commonly utilized in landfill design to remove excess water which may accumulate above the clay cap. Therefore, they serve to reduce percolation through the landfill. The lateral drainage from the surface cover is modelled by the Boussinesq equation, as described in Chapter 2. An analytical solution as developed by McEnroe and Schroeder (1988) is used here and is given by the following equation:

$$\bar{y}^* = \left[\frac{\pi \sqrt{q_D^*}}{4 \cos\alpha}\right] \cdot (0.403)^{\left(\frac{q_D^*}{0.4 \sin^2\alpha}\right)^{-0.55}} \qquad for \quad q_D^* \geq 0.4 \sin^2\alpha \tag{7.20}$$

where

y^* = y / L , nondimensional depth of saturation above liner

q_D^* = q_D / K_D , nondimensional lateral drainage rate

y = depth of saturated lateral drainage ($h - x \tan \alpha$) [cm]

K_D = saturated hydraulic conductivity of drain layer [cm/day]

L = total horizontal length [cm]

α = inclination angle of liner surface

q_D = lateral drainage rate [cm/day]

The above equation is solved by the Regula Falsi Method as described in the Appendix.

7.2.2 UNSATURATED Module

The SURFACE module simulates different processes in the landfill cover, one of which is daily percolation water. This water is available as input to the UNSATURATED module, which is the main contribution towards the leachate. As mentioned earlier a landfill cell consists of many waste layers with intermediate soil layers between them. The UNSATURATED module distributes the percolation water and leachate recirculation into the top waste layer of a cell. The approach employed here is based on a lumped parameter model (LPM) as described in Chapter 2 for the soil system. The original LPM is modified by including waste moisture capacities, drainage models and hydraulic conductivity functions, which have been developed as a result of laboratory experimentation and are reported in Chapter 6.

The unsaturated zone of a landfill cell consisting of waste and intermediate soil layers is shown in Figure 7.5. The model partitions each of the waste layers into a number of segments referred here as 'modelling layers' depending on the depth chosen. The water content of each modelling layer is updated by the following simplified equation,

$$\theta_i = \theta_{i-1} + \frac{A_m}{V_m}\left[q_{in} - q_{out}\right] \tag{7.21}$$

where

θ_i = the average volumetric water content on day i [vol/vol]

θ_{i-1} = the average volumetric water content on day i-1 [vol/vol]

A_m = the cross-sectional area of the modelling layer [cm^2]

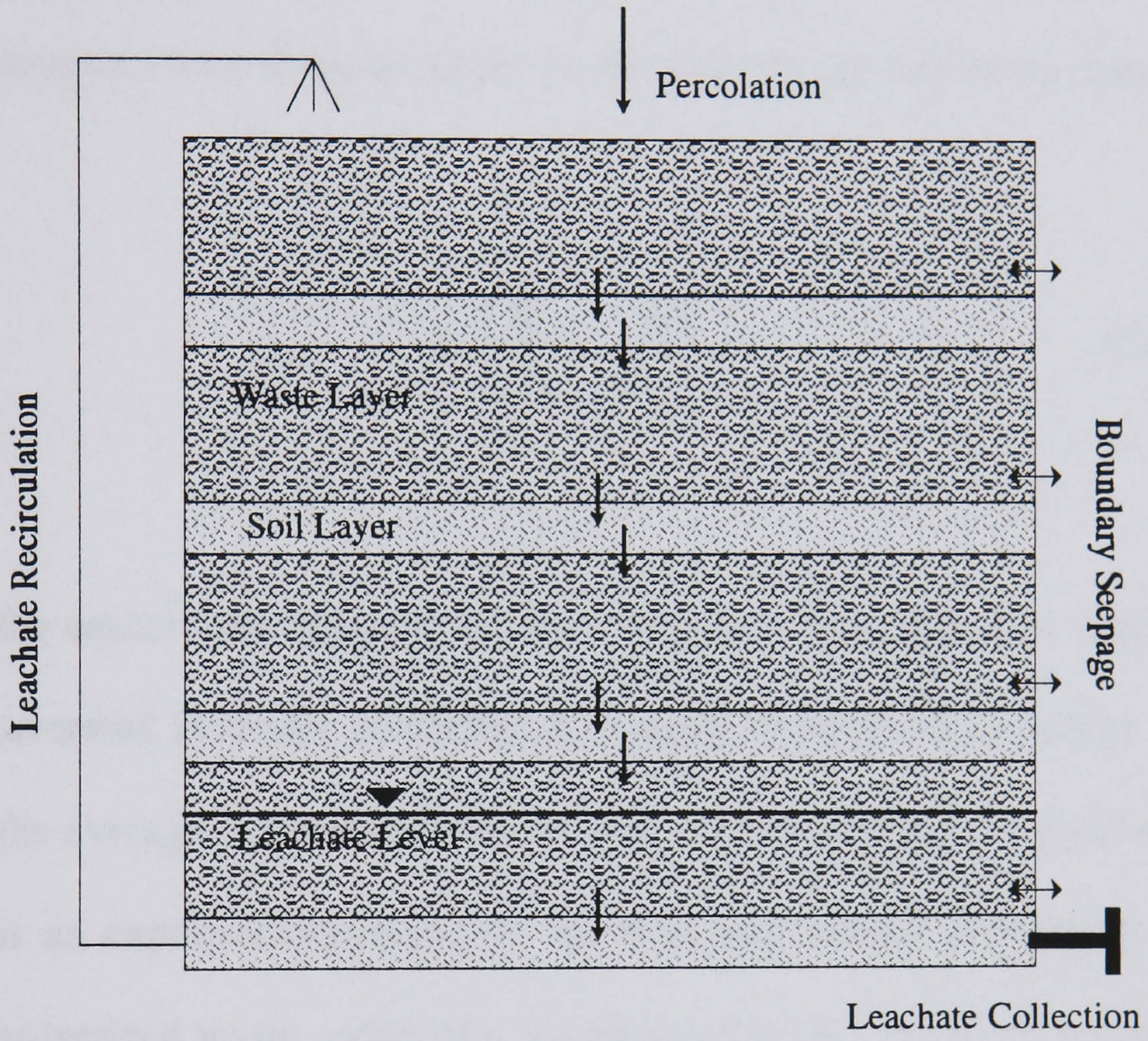


Figure 7.5. Simulation Processes in the Unsaturated Zone.

V_m = the volume of modelling layer [cm^3]

q_{in} = total input depth into modelling layer [cm/day]

q_{out} = total output depth from modelling layer [cm/day]

The inputs into the top modelling layer are; daily percolation depth from surface cover calculated by the SURFACE Module and daily leachate recirculation depth specified by the user. The output from each modelling layer except the bottom layer (which is assumed zero at the moment) is calculated by the following equation,

$$q_{out} = K_s \left(\frac{\theta_{i-1} - \theta_f}{\theta_s - \theta_f} \right)^n \qquad (7.22)$$

where:

q_{out} = the unsaturated hydraulic conductivity of waste or soil layer [cm/day]

K_s = saturated hydraulic conductivity of waste or soil layer [cm/day]

θ_{i-1} = the average volumetric water content on previous day i-1 [vol/vol]

n = is an exponent depending on the type and density of material. For pulverized waste, value of n is calculated from $n = -10.77 + 0.03\ \rho_d$, where ρ_d is dry density of waste material in kg/m^3.

The daily drainage depth from the top modelling layer as calculated from the above equation, is made available as input to the second modelling layer. The daily drainage depth of leachate is computed from the 2nd layer using above equation, by substituting the previous moisture capacity. A moisture level is updated depending on the capacity of 2nd layer, assuming that it will store leachate upto saturation.

After the moisture content of each layer is calculated and corrected for excess water content, the total leachate head in a cell is computed using Equation 7.18. For each waste layer, its moisture content is compared with saturation capacity and perched leachate levels are established. This leachate is allowed to drain both in vertical and lateral directions. In the case of horizontal flow from the side of a cell, the flow rate is calculated using Equation 7.22 by employing horizontal saturated hydraulic conductivity function. The flow chart of UNSATURATED module is shown in Figure 7.6.

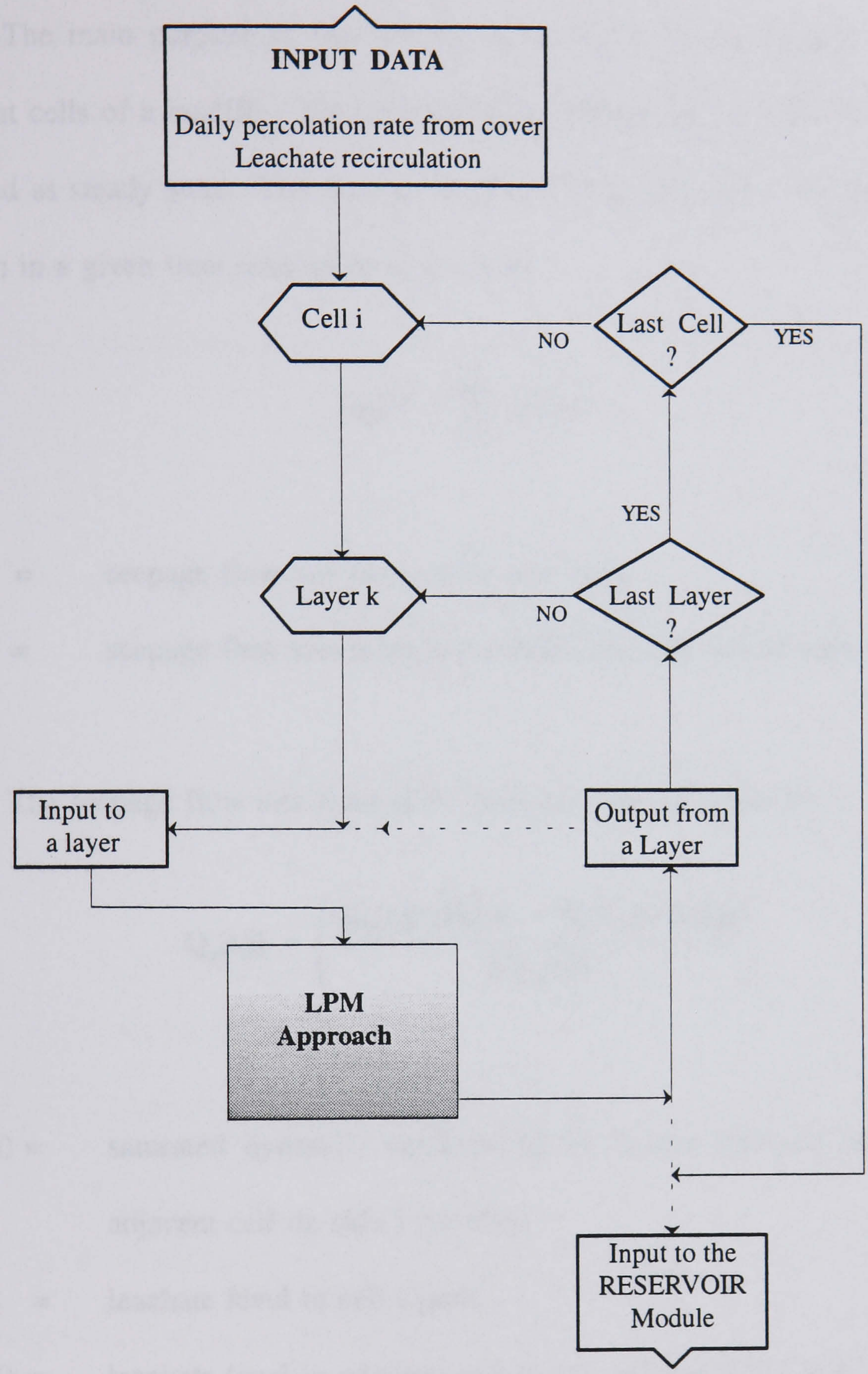


Figure 7.6. Flow Chart of UNSATURATED Module.

7.2.3 RESERVOIR Module

The main purpose of this module is to distribute the leachate among the different cells of a landfill. The saturated flow among the 'n' cells of a landfill is assumed as steady state. The seepage flow rate from any cell i having number of sides m in a given time interval Δt is given by

$$Q_s(i) = \sum_{j=1}^{m} Q_s(i,j) \tag{7.23}$$

where

$Q_s(i)$ = seepage flow rate from cell i [cm^3/day]

$Q_s(i,j)$ = seepage flow rate from cell i to its adjacent cell on side j [cm^3/day]

The seepage flow rate from cell i from its side j is given by

$$Q_s(i,j) = \left(\frac{K_b(i,j) \left[H_L^2(i) - H_L^2(i,j) \right] L(i,j)}{2\, T_b(i,j)} \right) \tag{7.24}$$

where

$K_b(i,j)$ = saturated hydraulic conductivity of barrier between cell i and its adjacent cell on side j [cm/day]

$H_L(i)$ = leachate level in cell i [cm]

$H_L(i,j)$ = leachate level in adjacent cell to the side j of cell i [cm]

$L(i,j)$ = length of side j of cell i [cm]

$T_b(i,j)$ = thickness of barrier between cell i and its adjacent cell on side j [cm]

The inequality bracket function < > used in the above equation is only effective for positive values which means that leachate is flowing from cell i to its adjacent cell on side j. On the other hand if the value is negative than it becomes a zero. It is also assumed that there will be no flow from surrounding ground into the landfill site.

The updated leachate levels in cell i and its adjacent cells after time interval Δt are

$$H_L(i) = H_L(i) - \frac{\Delta t}{A(i)} Q_s(i) \tag{7.25}$$

$$H_L(i,j) = H_L(i,j) + \frac{\Delta t}{A(i,j)} Q_s(i,j) \tag{7.26}$$

where

$A(i)$ = plan area of cell i [cm^2]

$A(i,j)$ = plan area of adjacent cell to the side j of cell i [cm]

The same procedure is repeated for other cells of a landfill. Care should be taken while considering a cell with side attached to the ground. The complete flow chart of the module is shown in Figure 7.7.

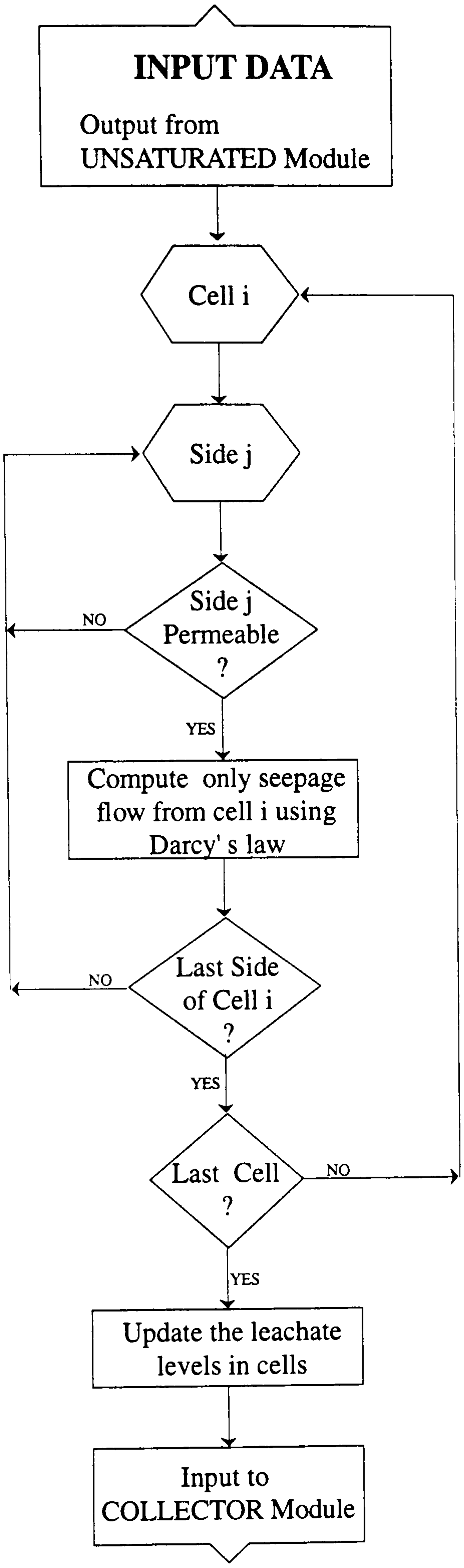


Figure 7.7. Flow Chart of RESERVOIR Module.

7.2.4 COLLECTOR Module

This module is based on two different approaches depending on landfill design practices. The two common landfill design practices are "attenuate and disperse sites" and "containment sites". Dilute and disperse has been the principal method of leachate management in the UK (North-West WDO, 1991). This method rarely, if ever, requires the construction and maintenance of leachate drainage and collection systems. The recent development of engineered and lined landfill sites with leachate containment means that drainage and collection systems have now become a vital element in landfill design and operation.

This module accepts leachate levels as input from RESERVOIR module and calculates the amount of leachate discharged to the collection system or surrounding ground. Depending on the landfill practice being applied, various outputs from the bottom of a cell are to be expected:

- In the case when a drainage layer is provided at the bottom of landfill, then the amount of leachate discharged is calculated by Darcy's law (Equation 7.19). The flow rate will depend on the hydraulic conductivity of layer and the leachate head present on the top of that layer.

- In the case of dilute and disperse sites, the flow through a landfill liner can be obtained using the analogy of two interconnected reservoirs. The detailed description of the approach is mentioned in the Hydrological and Hydraulic

Models for Landfill (Buchanan, 1993). The flow rate Q (L^3/T) is given as,

$$Q = -K\left(A_c + \frac{P\,(h_g + h_l)}{2}\right)\frac{h_g - h_l}{dL} \qquad (7.27)$$

where:

K = the hydraulic conductivity of the barrier material [L/T]

A_c = the plan area of a cell [L^2]

P = the perimeter of a cell [L]

h_g = the ground water level measured relative to the base [L]

h_l = the cell leachate level measured relative to the base [L]

dL = the length of the flow path (thickness of barrier) [L]

- In case of leachate recirculation, the amount of leachate will be deducted from the leachate mound and will be added to the top waste layer for the next simulation day.

The flow chart of the module is given in Figure 7.8.

Landfill Settlement:

The annual landfill settlement rate function is derived from the data mentioned in Chapter 3 Section 3.7.1. At the end of each year, the model calculates the settlement rate (S) in percentage by the following relation

$$S = S_o - 1.9 * Year \qquad (7.28)$$

where S_0 is the initial or first year settlement rate normally equal to 10% and 'Year' is the number of year.

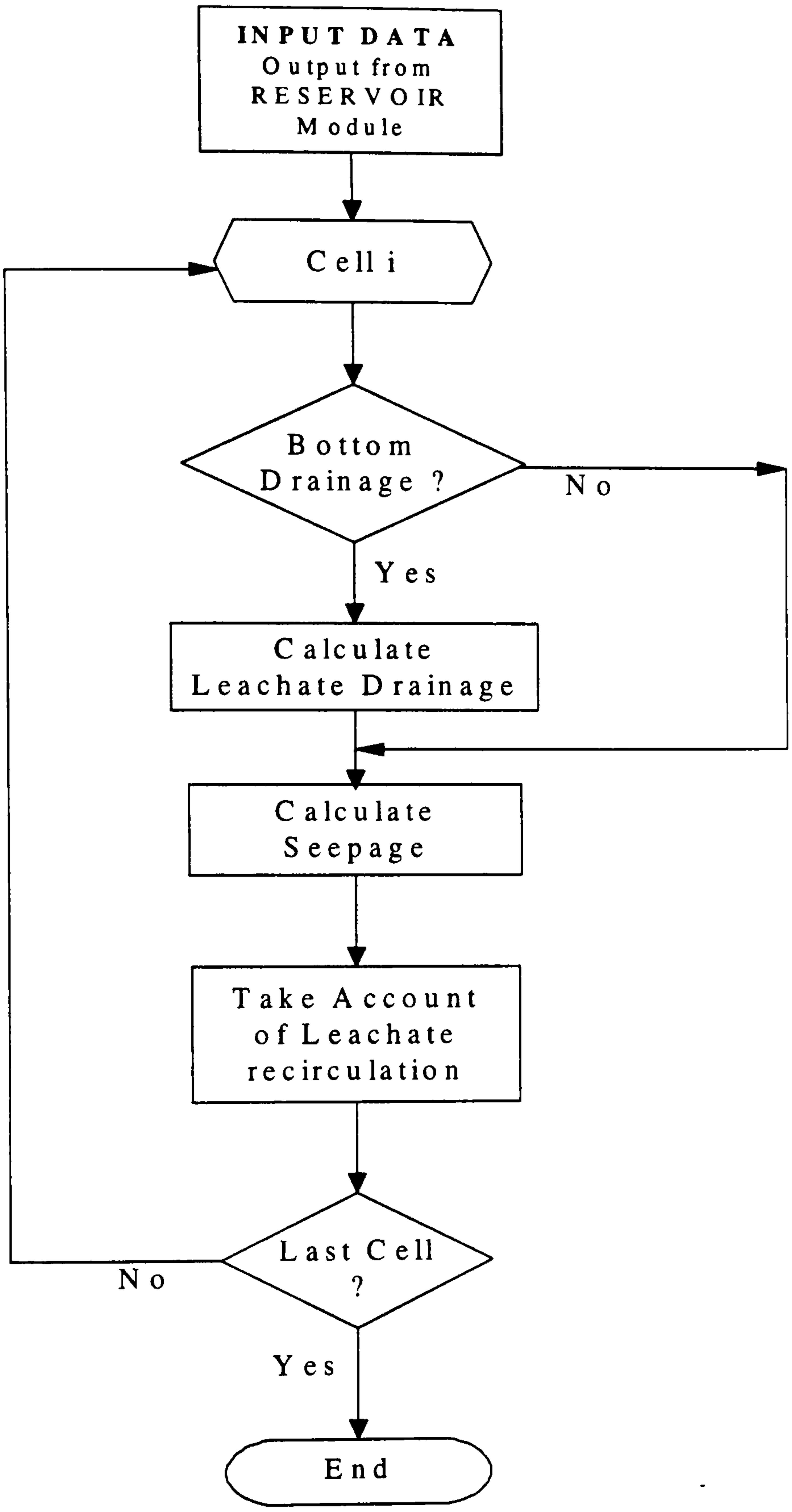


Figure 7.8. Flow Chart of COLLECTOR Module.

7.3 Data Requirements

The NUMMOL model is based on the minimum data requirements from the user. The data needed for simulation is divided into five groups which are shown in Table 7.1 and are explained in detail later.

Table 7.1. Parameters required for NUMMOL Model.

Parameters	Units	State
Climatic data		
Daily Precipitation	[mm/day]	User
Daily Potential Evapotranspiration	[mm/day]	User
Landfill Data		
Number of cells	[dimensionless]	User
Height of each cell	[m]	User
Distance of each cell from datum	[m]	User
Leachate level in each cell	[m]	User
Leachate recirculation to each cell	[mm/day]	User
Topographic data		
Number of sides of each cell	[dimensionless]	User
Coordinates of cell nodes	[m]	User
Boundary conditions for each cell	[dimensionless]	User
Thickness of barrier between cells	[m]	User
Hydraulic conductivity of barrier	[cm/sec]	Default or user
Section data		
Number of layers in each cell	[dimensionless]	User
Type of filling material	[waste or soil]	User
Depth of each layer	[m]	User
Density of each layer	[kg/m^3]	User
Hydraulic conductivity of each layer	[cm/sec]	Default or user
Initial moisture content of each layer	[vol/vol]	User
Moisture contents of materials		
Θ_w wilting point of soil	[vol/vol]	Default or user
Θ_f field capacity of soil and waste	[vol/vol]	Default or user
Θ_s saturation capacity of soil, waste and clay	[vol/vol]	Default or user

A data base system is incorporated as a source for different modelling parameters. The system includes different physical properties of soil taken from standard tables and for waste materials, which are selected from laboratory experiments with addition to various waste management papers.

7.4 Conceptual Landfill Site

A conceptual top view of a completed landfill site is depicted in Figure 7.9 and section view through the landfill is shown in Figure 7.10. Figure 7.9 is to be scaled by plotting it on x-y plane (as shown in Figure 7.11). The landfill plan is converted to polygons of more than two sides.

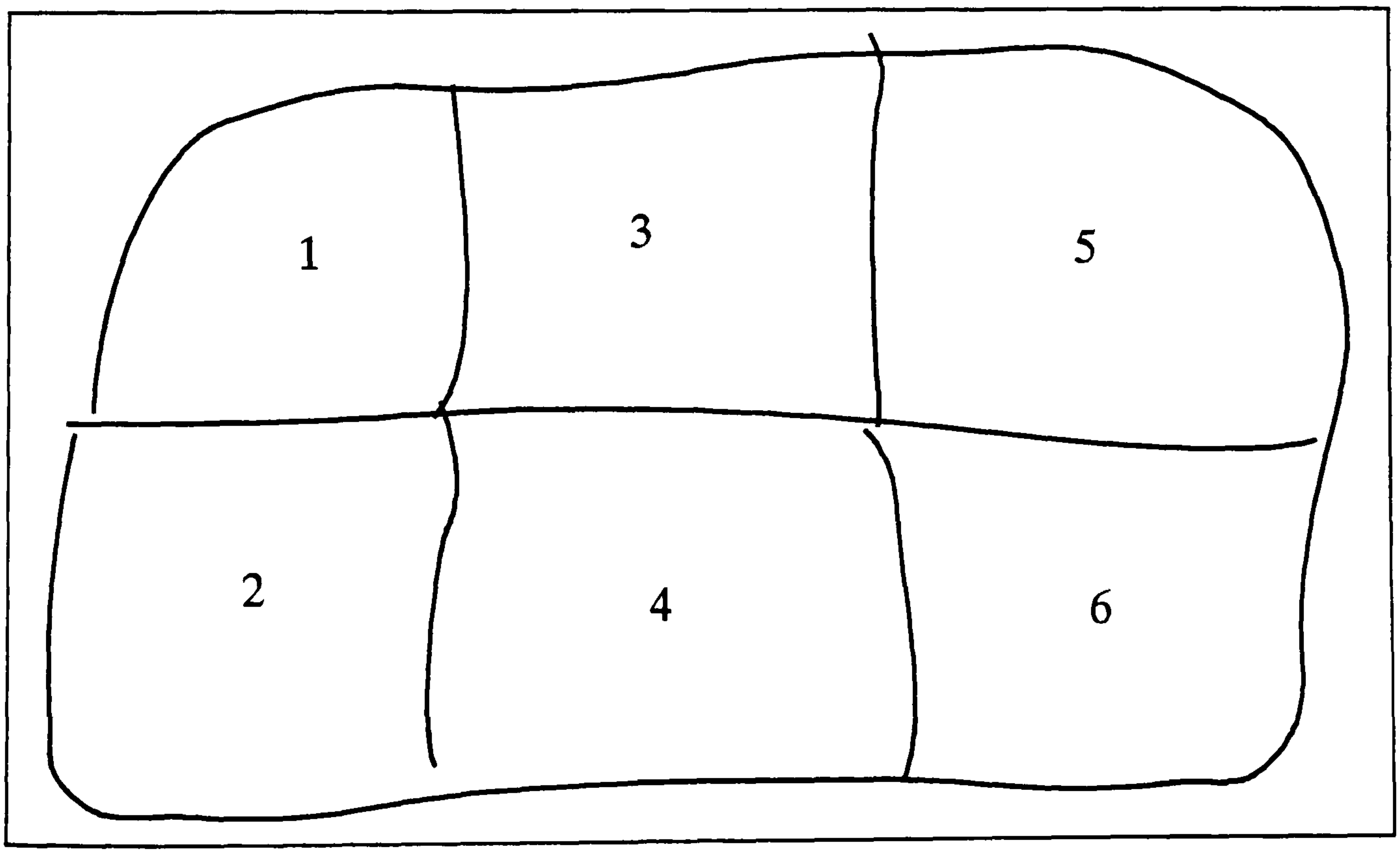


Figure 7.9. Conceptual top view of landfill.

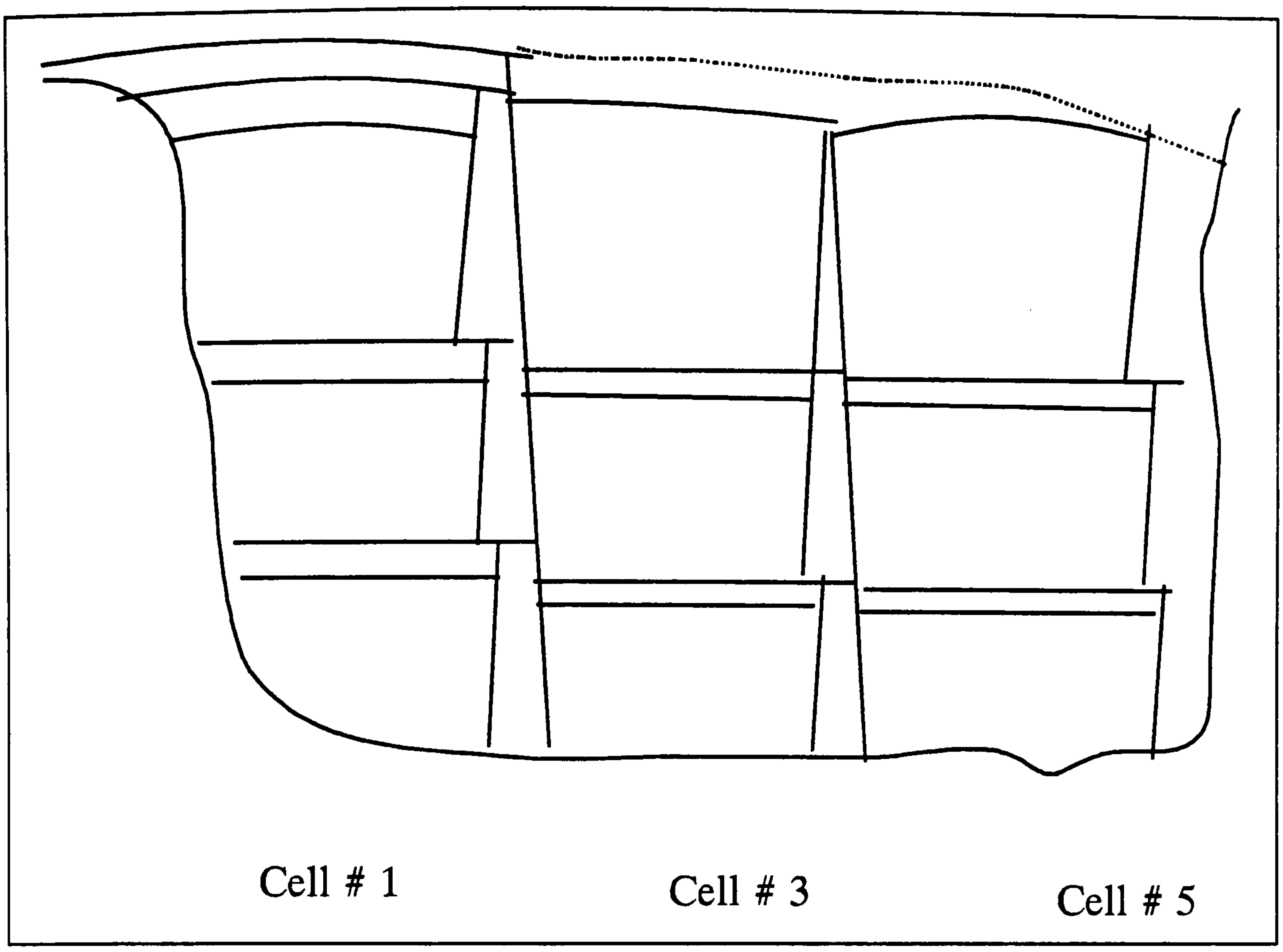


Figure 7.10. Section view through conceptual landfill.

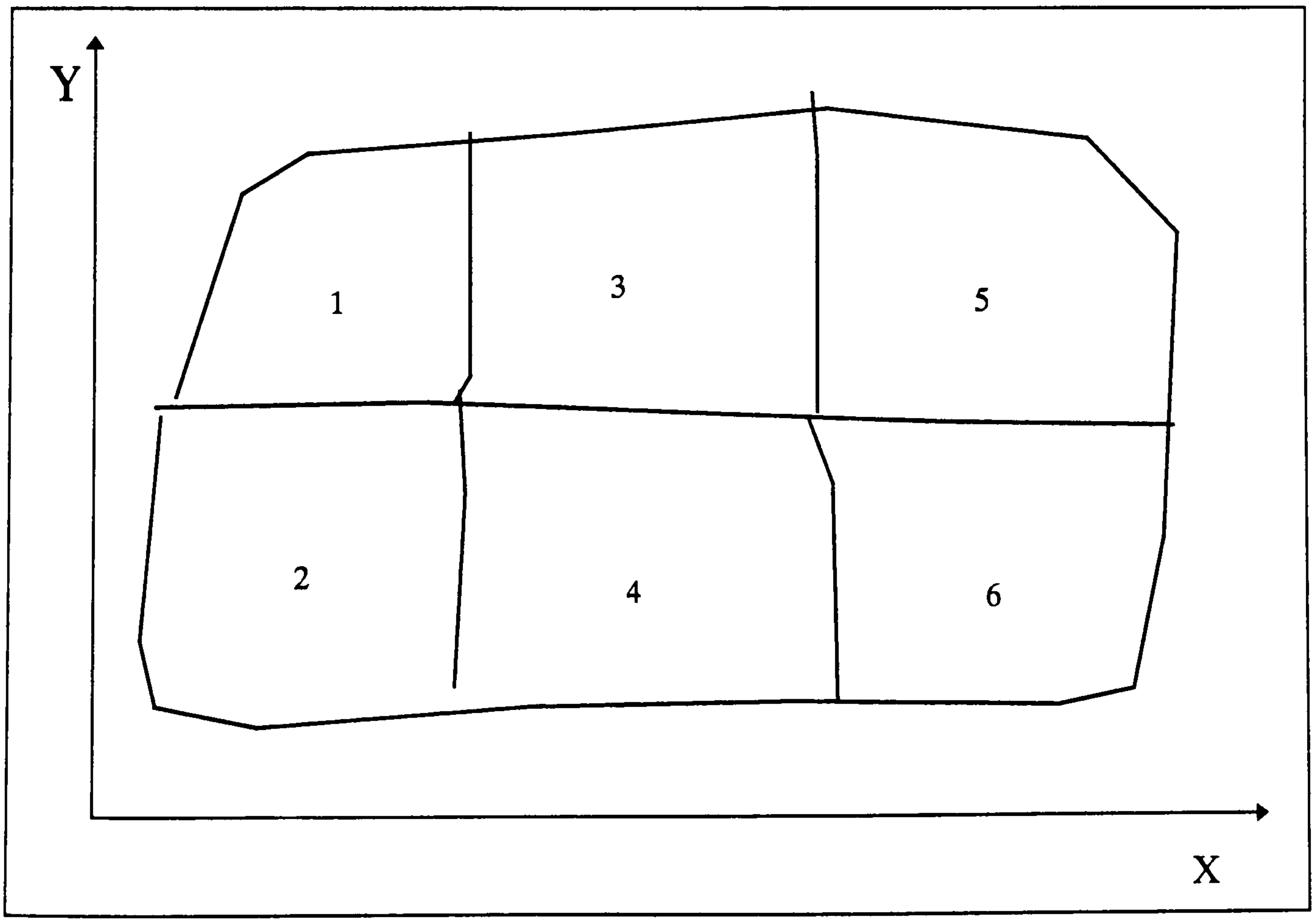


Figure 7.11. Scaled view of conceptual landfill.

Each cell forms a type of polygon as shown in Figure 7.12. The different sides of the cell are numbered in an anti clockwise direction. The coordinates XY of each side are the coordinates of the starting point of that side. From this information the model calculates the surface area using the following equation,

$$A = \left| \sum_{i=2}^{n} (X_1 - X_i)\,(Y_{i+1} - Y_{i-1}) \right| \div 2 \qquad (7.29)$$

$$\textit{where} \qquad Y_{n+1} = Y_1$$

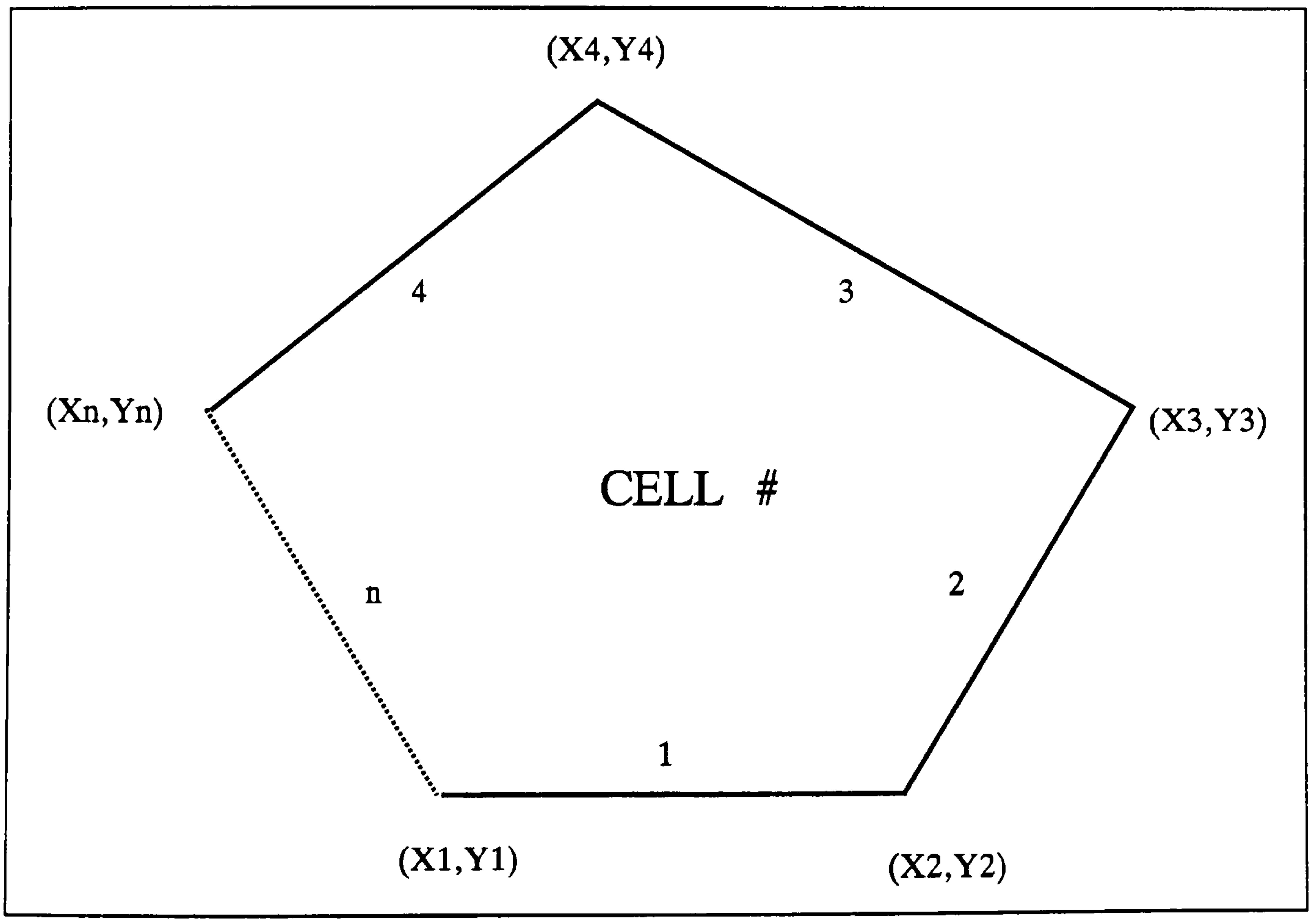


Figure 7.12. A representative cell polygon.

7.5 User Interactive Interface Module

A user interactive interface module has been developed for easy control of the model, which selects the different options provided in the model. A user-friendly approach is designed to provide the user with as much assistance as possible in preparing data to run the model. The user has top priority to keep easy control of the model. After providing landfill design data and climatic data, the module uses a in-built data base system for assigning physical properties to the landfill materials. In case of pulverized waste, the results from experimental models are also being incorporated. The interface module then transfers control to the simulation modules.

The four simulation modules operate in a sequential order on a daily basis. Starting from the landfill surface, SURFACE module partitions the precipitation into runoff and infiltration, updates the soil moisture storage, marks the saturated and unsaturated zones, computes percolation through soil liner and lateral flow over the cap. Taking percolation and leachate recirculation as input, the UNSATURATED module distributes it in the waste layers and determines the leachate mound established at the bottom of the landfill cell. The RESERVOIR module distributes the leachate within landfill cells. Finally, COLLECTOR module calculates leachate discharged to the drainage system (if available) and deduces the amount of leachate recirculation (if allowed). The simulation process ends when all the time steps are completed. The simulation results are directed to screen, files, printer etc., whichever option is mentioned. Landfill geometry and graphs of different parameters can also be seen.

The main starting window of the INTERFACE module is shown in Figure 7.13 and has the following main components: 1. Define Problem, 2. Simulation, 3. Results, 4. Exit.

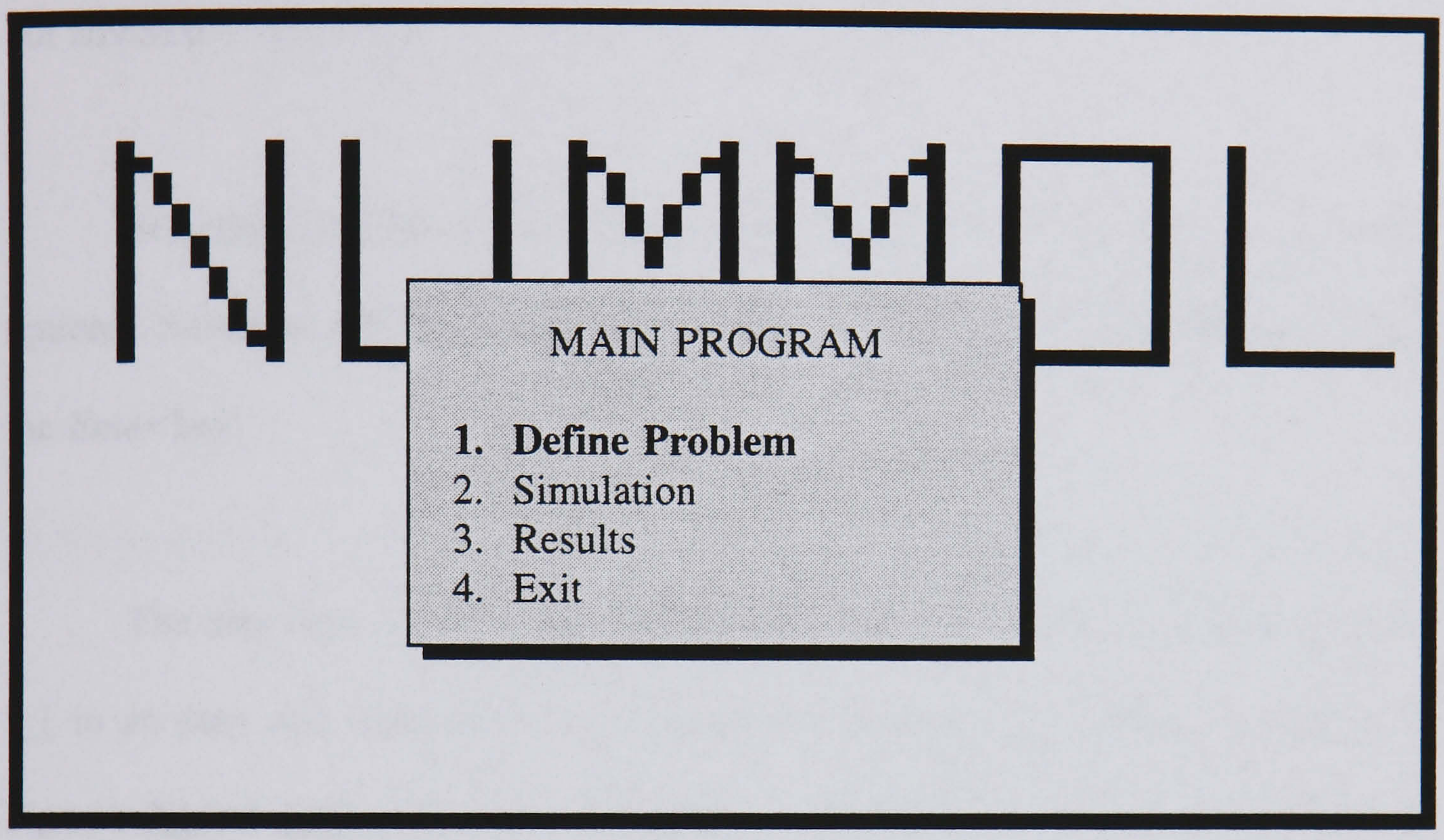


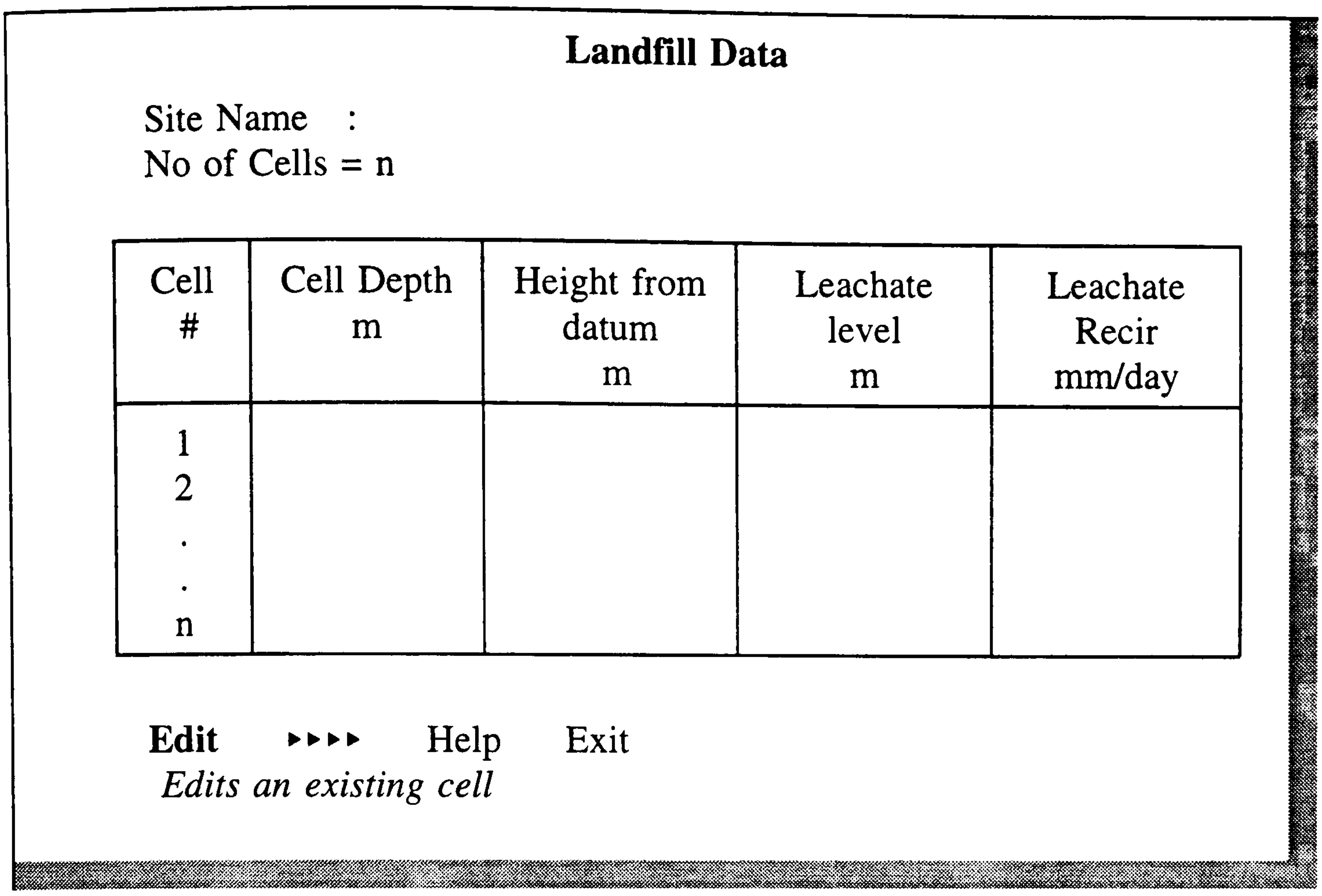
Figure 7.13. Main window of INTERFACE Module.

The program automatically solicits input from the user based on the option selected. There are a few fundamental rules regarding the input facility that a user must keep in mind when using the model. These rules should be followed to move around the screens and to move within the same screen. These screens are divided into three categories: input screen, selection screen and on-line help screen. General help is available to the user from any window on the screen.

When the program highlights a number of spaces (called an "input cell"), an input from the user is expected. At any input cell, the user has one of several options: enter the data requested, accept existing values, seek on-line help, or escape. Each cell is associated with a variable that is used directly or indirectly in the NUMMOL model. Therefore, every effort must be made to assign a value to each cell when applicable. If the user value is not an appropriate value, the program will not advance.

Selection cells are displayed in a window that is used to select from a list of options. Selection cells highlight one item at a time. Selection is made by pressing the *Enter* key.

The data input interface prompts the user to enter the data mentioned in Table 7.1 in an easy and controlled way via a series of different windows as shown in Figures 7.14 to 7.17. Once the data editing is completed, the program stores it in different specified files. In addition to this, climatic data can be specified by entering the file name in ASCII format having two columns representing daily precipitation and potential evapotranspiration. This type of file can be prepared using any spreadsheet software.



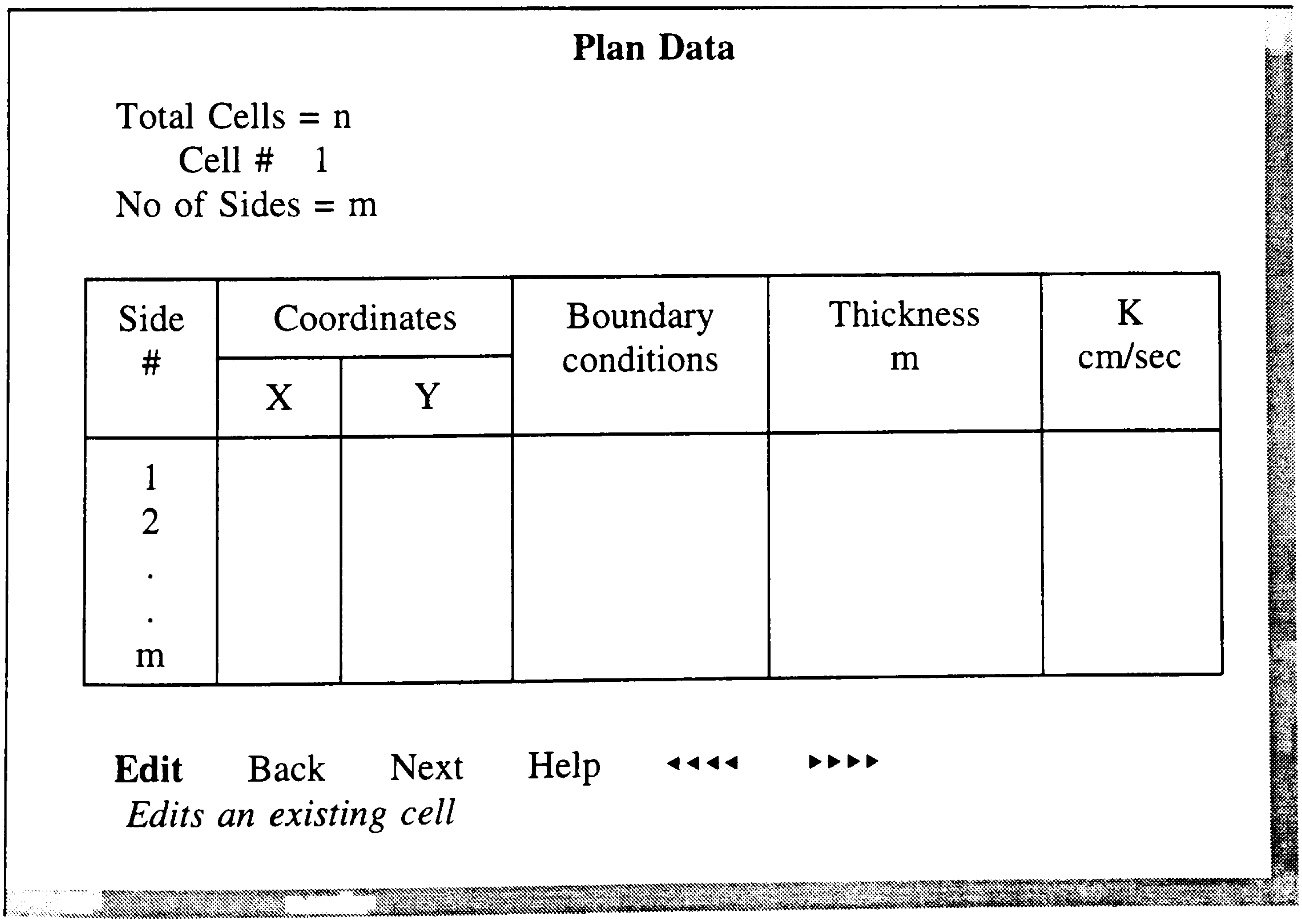
Landfill Data

Site Name :
No of Cells = n

Cell #	Cell Depth m	Height from datum m	Leachate level m	Leachate Recir mm/day
1 2 . . n				

Edits an existing cell

Figure 7.14. Editing window for landfill data.



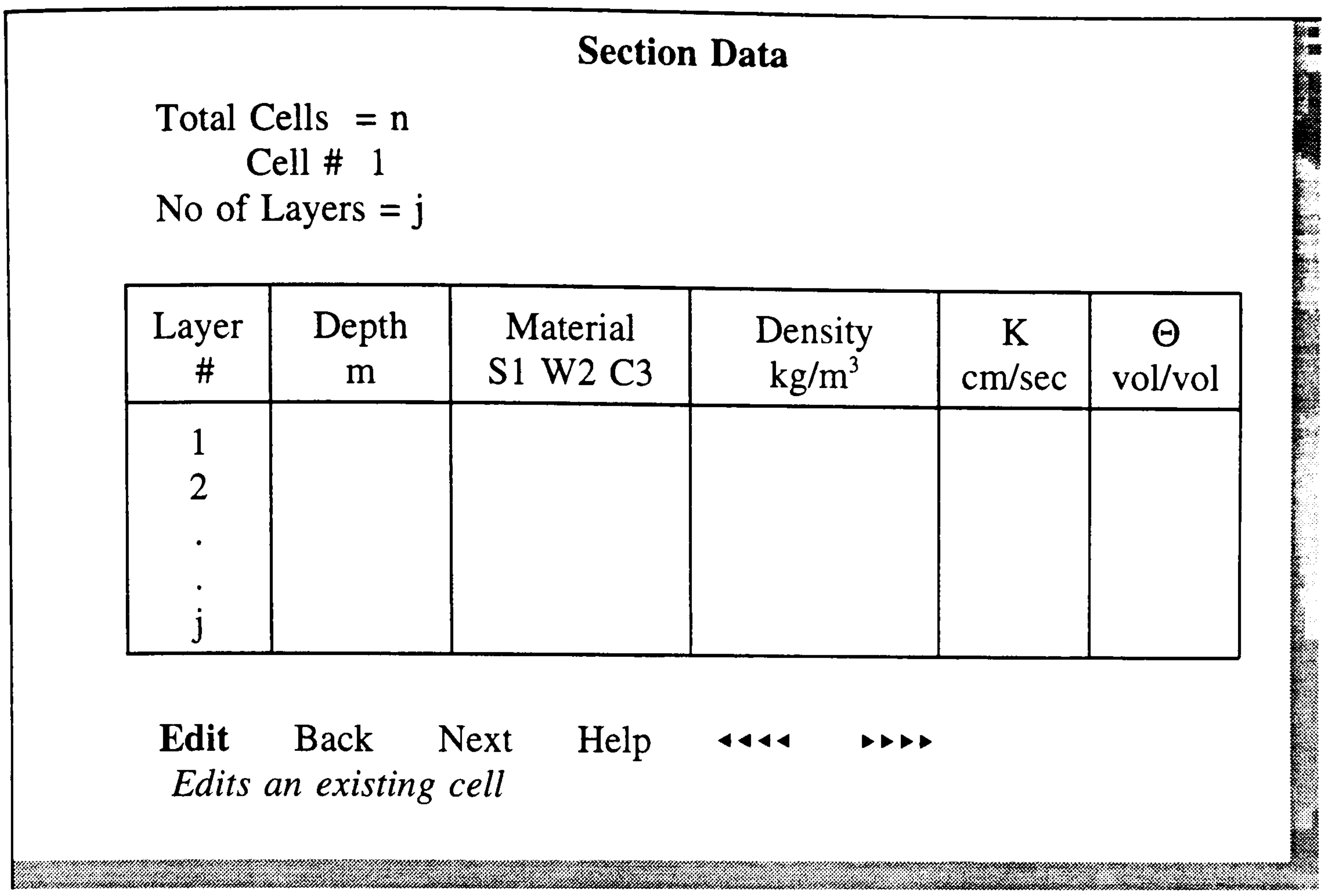
Plan Data

Total Cells = n
Cell # 1
No of Sides = m

Side #	Coordinates		Boundary conditions	Thickness m	K cm/sec
	X	Y			
1 2 . . m					

Edits an existing cell

Figure 7.15. Editing window for topographic data.



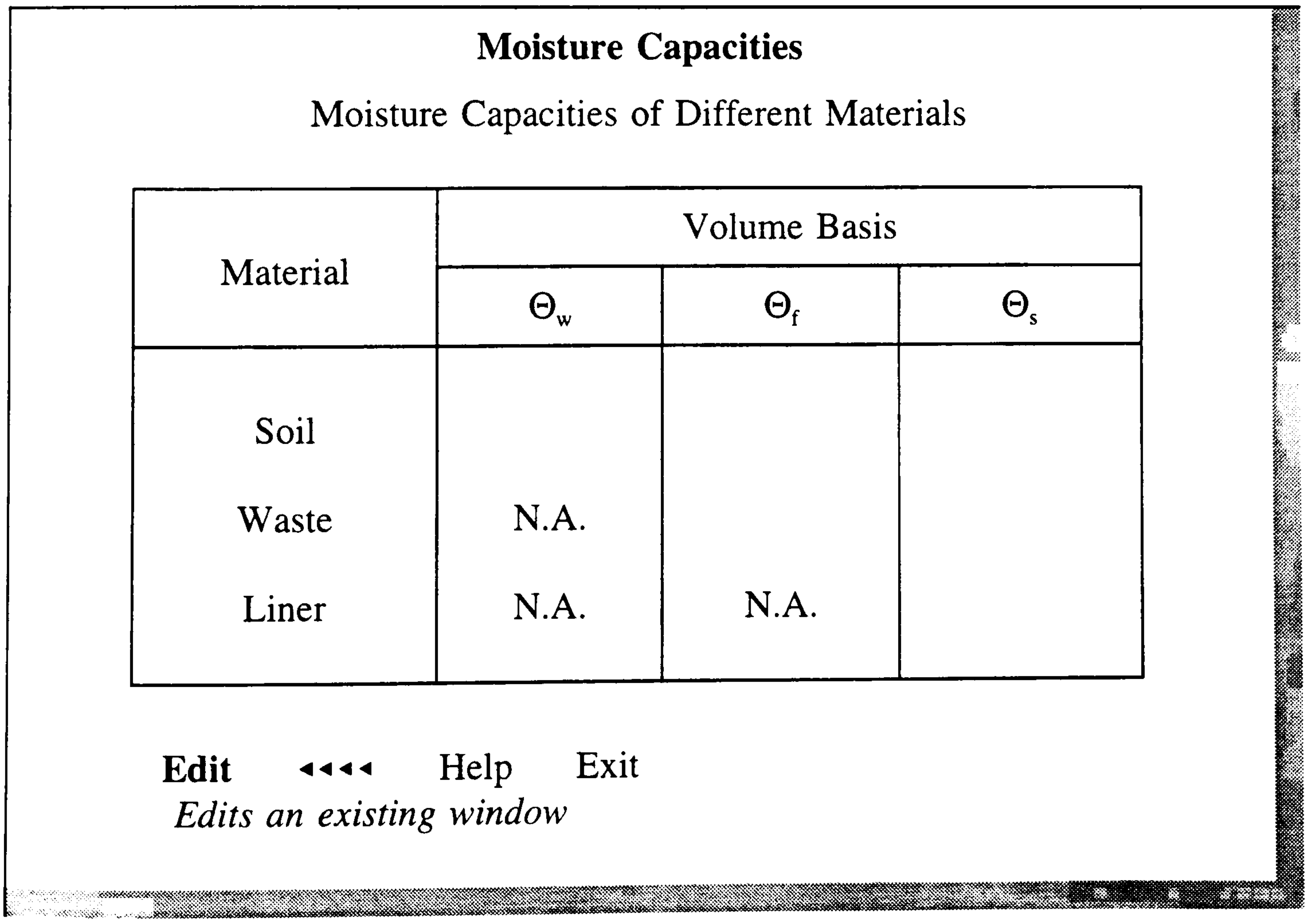
Section Data

Total Cells = n
Cell # 1
No of Layers = j

Layer #	Depth m	Material S1 W2 C3	Density kg/m^3	K cm/sec	Θ vol/vol
1					
2					
.					
.					
j					

Edits an existing cell

Figure 7.16. Editing window for section data.



Moisture Capacities

Moisture Capacities of Different Materials

Material	Volume Basis		
	Θ_w	Θ_f	Θ_s
Soil			
Waste	N.A.		
Liner	N.A.	N.A.	

Edits an existing window

Figure 7.17. Editing window moisture contents of waste.

7.6 Model Assumptions and Limitations

The modelling procedures documented in the previous sections are based on many simplifying assumptions. Most of these are stated in the sections documenting the individual procedures. Generally, these assumptions are reasonable and consistent with the objectives of the program when applied to standard landfill designs. However, some of these assumptions may not be reasonable for unusual designs. The major assumptions and limitations of the program are summarized below.

Runoff is computed using the SCS method based on daily amounts of rainfall and effective moisture content of soil cover. The program assumes that areas adjacent to the landfill do not drain onto the landfill. The time distribution of rainfall intensity is not considered. The program cannot be expected to give accurate estimates of runoff volumes for individual storm events on the basis of daily rainfall data. However, because the SCS rainfall-runoff relationship is based on considerable daily field data, long-term estimates of runoff should be reasonable. One would expect the SCS method to underestimate runoff from short duration, high intensity storms; larger curve numbers could be used to compensate if most of the precipitation is from short duration, high intensity storms. The SCS method does not explicitly consider the length and slope of the surface over which overland flow occurs.

The overland flow function is not included in the model because it has no effect on small catchment areas such as landfill cells. A similar conclusion was drawn by Dickson (1987) that with smaller land areas the overland flow function calculates an excess level of flow (actual flow is restricted by water availability), and the function would perform more adequately on catchments with larger areas or slope lengths.

The daily potential evapotranspiration is input to the model from the user, and is available from the Metrological Office. The program itself does not calculate evapotranspiration rate, but it calculates the moisture of soil cover available for evapotranspiration. Then by comparing the two values, the minimum is accepted and considered as effective evapotranspiration on that day.

The moisture content in the soil cover is updated daily based on the storage routing technique as used in the CREAMS Model (Knisel, 1980). Vertical drainage in soil cover is assumed to be driven by gravity alone and is limited only by the saturated hydraulic conductivity and available storage of lower segments. If unrestricted, the vertical drainage rate out of a segment is assumed to equal the unsaturated hydraulic conductivity of the segment corresponding to its moisture content, provided that moisture content is greater than the field capacity. The unsaturated hydraulic conductivity is computed by Campbell hydraulic equation using Brooks-Corey parameters.

Percolation through clay liners is modelled by Darcy's law, assuming free drainage from the bottom of the liner. The liners are assumed to be saturated at all times, but leakage occurs only when the soil moisture of the layer above the liner is greater than the field capacity. The program assumes that an average hydraulic head can be computed from the soil moisture and that this head is applied over the entire surface of the liner. As such, when the liner is leaking, the entire liner is leaking at the same rate. The liners are assumed to be homogeneous and temporally uniform.

The lateral drainage model is based on the assumption that the lateral drainage rate and average saturated depth relationship that exists for steady-state drainage also holds for unsteady drainage. This assumption is reasonable for leachate collection, particularly for closed landfills where drainage conditions should be fairly steady. Where drainage conditions are more variable, such as in the cover drainage system, the lateral drainage rate is underestimated when the saturated depth is building and overestimated when the depth is falling. Overall, this assumption causes the maximum depth to be slightly overestimated and the maximum drainage rate to be slightly underestimated. The long-term effect on the magnitude of the water balance components should be small.

Leachate recirculation is assumed to be uniformly distributed throughout the top waste layer by a manifold or distribution system. Leachate collected on one day for recirculation is distributed steadily throughout the following day. The amount of leachate recirculation is input from the user to be checked out by the model.

The percolation water from the clay cap and leachate recirculation depth are the main contribution towards the leachate. The model partitions each of waste layer in a cell into discrete modelling layers depending on depth chosen. The water content of each modelling layer is updated by Lumped Parameter Model (LPM) approach. The drainage from a layer is modelled using Irmay's model (1950), which is only restricted by the intake capacity of lower layer .

The model has limits on the order that layers can be arranged in the landfill cell profile. Each layer must be described as soil cover, waste layer, intermediate soil layer, drainage layer or clay liner. The top layer must always be a soil cover layer. Several relations must exist between the moisture retention properties of a material. The porosity, field capacity and wilting point can theoretically range from 0 to 1 in units of volume per volume, but the porosity must be greater than the field capacity, and the field capacity must be greater than the wilting point.

The following limitations and assumptions are made in the model:

- The process of waste decomposition is not considered.
- The amount of water released as a result of waste decomposition is not taken into account.
- The program cannot simulate the actual filling operation of an active landfill.

Chapter 8

MODEL SENSITIVITY ANALYSIS AND APPLICATION

Sensitivity analysis is a technique for assessing the relative change in a model's response or output resulting from a change in inputs or in model parameters. Based on derived parameter values and representative values of the input variables, base values are selected. For a given set of base parameter values, computations are performed, and then the input variables are varied over a range of values and the computations repeated. The resulting computations show how the model outputs vary with changes in the input parameters. This shows how the model functions and how important each parameter is in determining the output. Such analysis also aids in parameter estimation. A detailed sensitivity analysis, performed to investigate the effect of various parameters on the model output is presented in this chapter. Model simulation was performed by first considering a single cell and then applying the model to an actual landfill site as a case study. The analysis includes examination of the cover system, waste lifts and lateral drainage system.

8.1 Single Cell Configuration

The behaviour of the NUMMOL model for all the input parameters has been investigated by considering a single landfill cell, allowing a closer examination of the model operation. The single landfill cell consists of a soil cover, clay cap, waste material and drainage system to collect leachate produced inside the cell. The cover or cap comprises of soil cover placed at a certain slope to encourage runoff. Below the soil cover is placed a clay barrier to further minimize the percolation of water through it by allowing water to drain laterally. The waste is placed in lifts separated by soil layers. The drainage system consists of a drain layer to facilitate the disposal of leachate and a bottom clay liner to control any leachate that seeps through the boundaries of a landfill cell. Such a representative cell is shown in Figure 8.1, which was used for the sensitivity analysis.

8.1.1 Base Model Run

The precipitation and evapotranspiration data for Glasgow required by the model are taken from Buchanan (1993) and have been used throughout this sensitivity analysis. The annual precipitation was 1348.7 mm which compares very closely with the long term average annual precipitation throughout Glasgow. However, there is a marked difference in distribution during the year from month to month. The daily cumulative meteorological data is plotted in Figure 8.2, while their monthly totals are shown in Figure 8.3. The annual potential evapotranspiration demand was 465 mm.

Other parameters required by the model for simulation are mainly grouped under: landfill design data, soil cover data and cover lateral drainage, barrier soil data, waste material data and bottom lateral drainage data. Each group has a number of parameters which define either cell geometry or the physical properties of the cell material. The physical properties for the cover soil include wilting point, field capacity, saturation capacity, initial moisture capacity and the saturated hydraulic conductivity. The same types of physical properties are also required for the waste

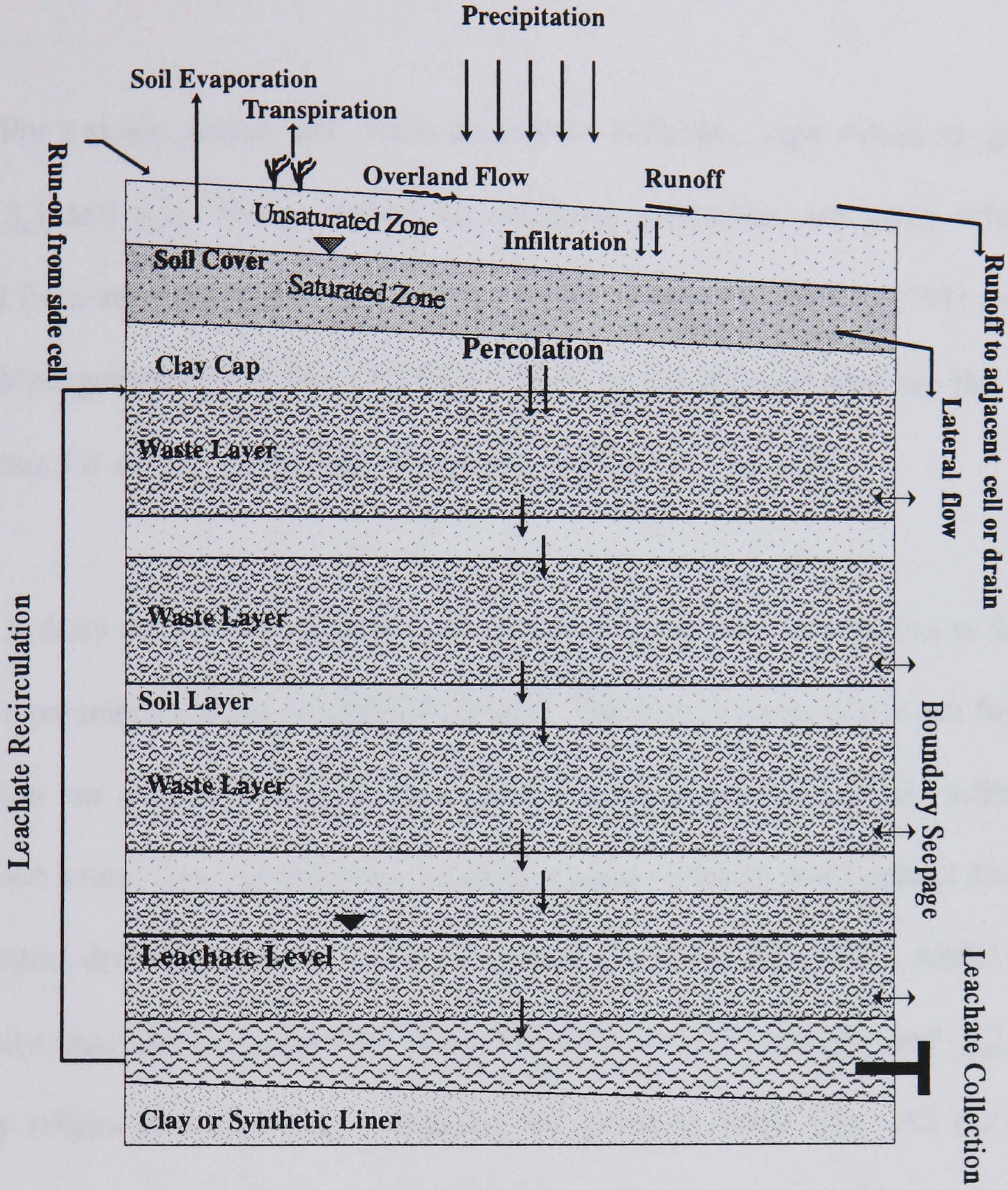


Figure 8.1. Geometry of a Single Landfill Cell.

material in addition to waste density and number of lifts. For the clay barrier and lateral drainage layer only saturated hydraulic conductivity is required, because it is assumed that those layers are at saturation capacity and allow free gravity drainage.

For a single landfill cell, these parameters with their base values are given in Tables 8.1 and 8.2. Range values for different parameters are given which are selected from various landfill management reports such as NWWDO(1991) and DoE Waste Management Paper No. 6 (1986). Most of the required data are the design parameters for an individual cell, which are supplied by the user.

A daily sensitivity analysis for a one year period was undertaken to find the sensitive parameters of the NUMMOL model. The main outputs of interest from this simulation on a daily, monthly and yearly basis were the runoff, infiltration, subsurface lateral flow, percolation, leachate mound variation and leachate discharge from bottom drainage system. The basic control run of the NUMMOL model for the sensitivity analysis was executed using the data from Tables 8.1 and 8.2. The monthly results of a one year simulation are given in Table 8.3. All the output parameters are in depth (mm) of water/leachate. The maximum precipitation of 218 mm was observed in the month of February and a minimum of 49 mm was observed in May and July. The peak evapotranspiration demand of 90 mm was observed in the month of June. The total annual evapotranspiration demand was 34% of annual rainfall. The precipitation was initially partitioned into 54% runoff and 46% infiltration. The evapotranspiration demand was satisfied from moisture available in the root zone.

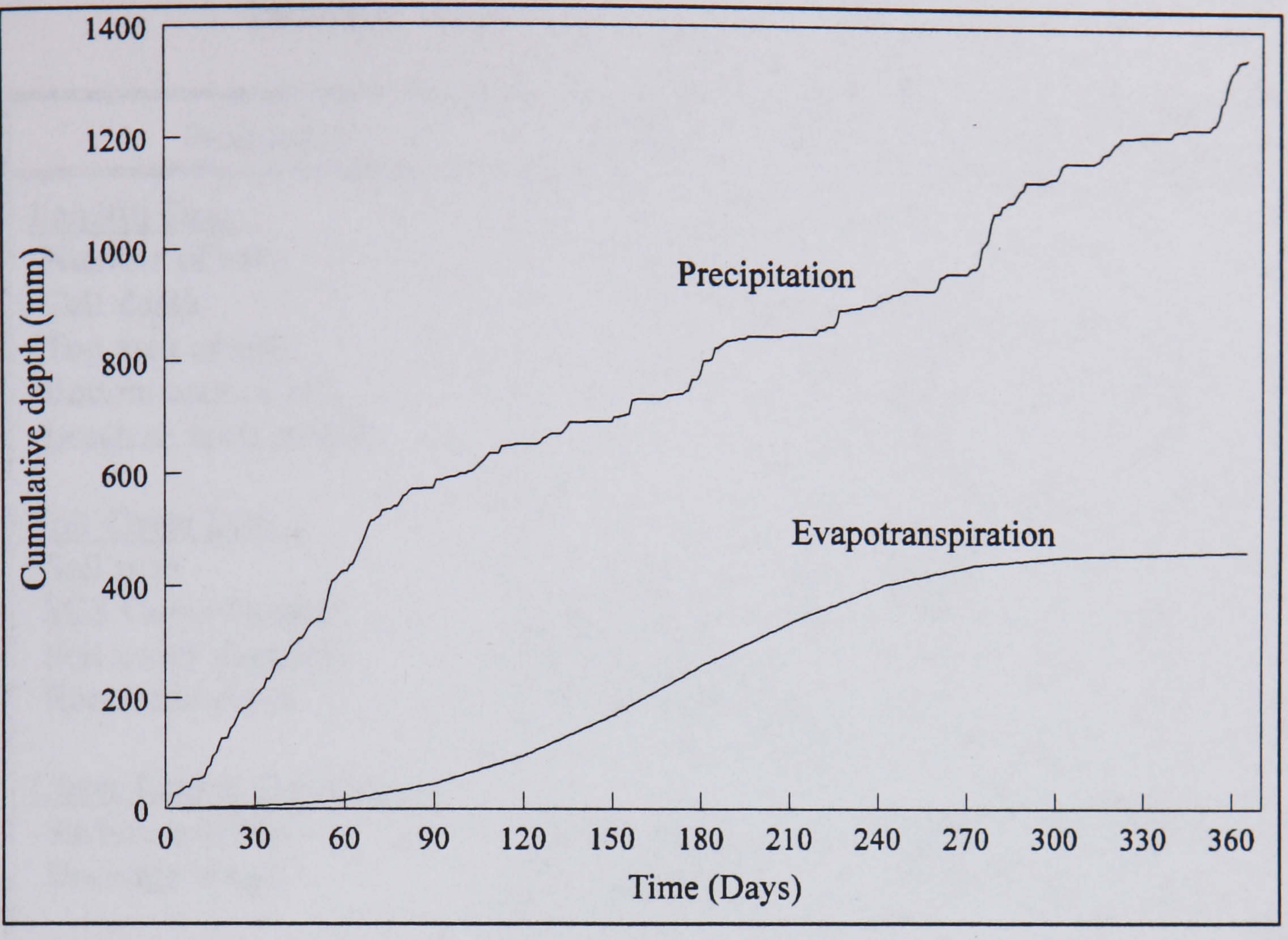


Figure 8.2. Daily Precipitation and Evapotranspiration Data.

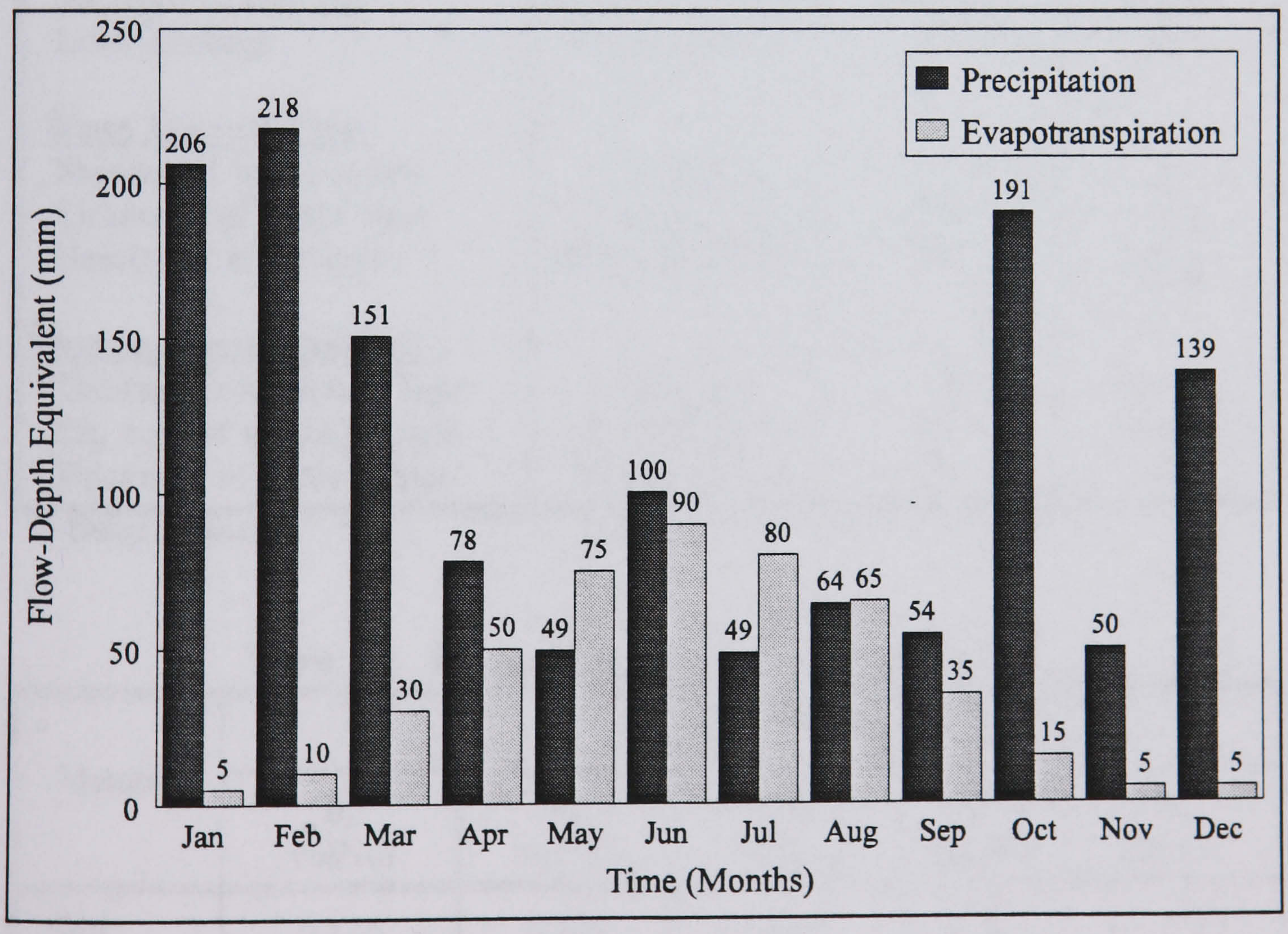


Figure 8.3. Monthly Precipitation and Evapotranspiration Data.

Table 8.1. Base Model Parameters for Single Cell.

Parameters	Range	Base Value	Units
Landfill Data :			
Number of cells	$0 \leq N_c < 11$	1	#
Cell depth	*	5.0	m
Top area of cell	*	900.0	m^2
Bottom area of cell	*	900.0	m^2
Leachate level in cell	-	0.0	m
Soil Cover Data :			
Soil type	*	Loam	-
SCS Curve Number	$0 < CN < 100$	74	#
Soil cover thickness	$0.75 < S_D < 1.5$	1.0	m
Root zone depth	$0.1 < R_D < 1.0$	0.6	m
Cover Lateral Drainage :			
Surface gradient	$1/30 < S_G < 1/6$	1/10	Ratio
Drainage length	one side	30.0	m
Barrier soil :			
Clay cap thickness	$1.0 < C_D < 2.0$	1.2	m
Sat. con. of clay cap	$10^{-6} < K_c < 10^{-8}$	2.3×10^{-7}	cm/sec
Liner Leakage	$0 < C_L < 20$	0	%
Waste Material Data:			
Number of waste layers	$1 \leq W_L$	1	#
Thickness of waste layer	$2 < W_d < 6$	3.0	m
Density of waste layer	$400 \leq \rho_d \leq 550$	450	kg/m^3
Bottom Lateral Drainage :			
Thickness of drainage layer	$1 < D_D < 2$	1.5	m
Sat. con. of drainage layer	$10^{-3} < K_D < 1$	0.01	cm/sec
Thickness of bottom liner	$1.0 < B_L < 2.0$	1	m

* Design parameter

Table 8.2. Physical Properties of Landfill Materials.

Material	Physical Property				
	θ_w vol/vol	θ_f vol/vol	θ_s vol/vol	θ_i vol/vol	K_s cm/sec
Soil	0.116	0.232	0.464	0.2	3.7×10^{-4}
Waste	-	0.340	0.400	0.24	1.1×10^{-2}
Liner	-	-	0.480	-	2.3×10^{-7}

Table 8.3. Results of Monthly Total of Base Model Run.

Landfill Hydrological Processes	**Months**												**Total**
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Precipitation (mm)	206.1	217.6	150.7	78.1	49.4	100.4	48.6	64.2	54.3	190.6	49.8	138.9	1348.7
Evapotranspiration (mm)	5	10	30	50	75	90	80	65	35	15	5	5	465.0
Runoff (mm)	115.30	129.38	80.02	27.70	13.42	64.85	17.18	28.64	21.99	124.29	17.72	91.19	732.4
Infiltration (mm)	90.80	88.22	70.68	50.40	35.98	35.55	31.42	35.56	32.31	66.31	32.08	46.99	616.32
Lateral Flow (mm)	0.05	5.0	11.05	10.93	9.72	9.02	9.32	9.32	9.02	9.32	9.22	10.53	102.52
Percolation (mm)	0.26	2.79	3.74	3.64	3.61	3.46	3.57	3.57	3.46	3.57	3.48	3.69	38.84
Leachate mound (mm)	0	0	0	0	0	0	0	0	0	0	0	0	0
Leakage (cm^3)	0	0	0	0	0	0	0	0	0	0	0	0	0

8.1.2 Sensitivity Trial Runs

The behaviour of the NUMMOL model for all the modelling parameters has been investigated to examine the response of the model to changes in the values of various simulation parameters. Individual trials were carried out for each individual parameter by keeping all other parameters to their base values. The parameter under consideration is altered to ± 50% of its base value, except the hydraulic conductivity which is altered by a factor of ±10. In some cases, a ± 50 % change in a parameter exceeds the limits of that parameter, so a low value was used. A ± 50 % change in a parameter value is a valid range for most parameters (Knisel, 1980). The simulation results of the model using altered parameters were then analysed and compared with the results from model control run. The effects of variables are graphically displayed and their monthly totals are also reported.

The input parameters used in the sensitivity trials include the landfill design parameters such as soil type and thickness, liner thickness, number of waste lifts and bottom drainage system. The physical properties of the landfill materials such as water capacities and hydraulic conductivity are also inspected. Sensitivity trials were run for a cell in a sequential order of different variables. The landfill cover system including soil and clay (barrier) layers are investigated first. Different designs of capping and its material physical properties were considered. The simulation results are presented in the form of comparisons between cumulative control run and corresponding altered parameters. The summary of the simulation results is given in Table 8.4.

Table 8.4. Effect of Landfill Cover Parameter Changes on Yearly Output.

Parameter		*Landfill Hydrological Processes*			
Description	Variation	Runoff mm	Infiltration mm	Percolation mm	Lateral Flow mm
Base	0	732.40	616.32	38.84	102.52
Saturated Hydraulic Conductivity K_s	10 times 0.1 times	723.02 751.20	625.68 597.50	16.10 37.79	181.31 9.95
Porosity θ_s	+ 10% - 25%	660.72 966.59	688.47 382.11	39.37 19.88	105.11 30.22
Initial capacity θ_i	+ 50% - 50%	734.11 731.50	614.54 617.20	45.02 29.68	143.93 45.47
Wilting capacity θ_w	+ 50% - 50%	759.85 717.94	588.85 630.76	38.19 39.15	101.48 106.33
Field capacity θ_f	+ 50% - 25%	960.01 667.68	388.69 681.02	0 42.81	0 118.81
Soil cover depth S_D	+ 50% - 25%	732.38 732.38	616.32 616.32	35.80 35.92	79.15 84.96
Root zone depth R_D	+ 50% - 50%	572.55 968.65	776.15 380.05	38.72 26.49	107.62 29.51
Surface gradient S_G	+ 50% - 50%	732.38 732.38	616.32 616.32	38.56 39.12	158.81 55.22
Curve number CN	+ 15% - 15%	770.48 710.88	578.22 637.82	38.45 39.69	101.67 107.66
Clay depth C_D	+ 50% - 15%	732.38 732.38	616.32 616.32	35.61 40.55	102.68 102.46
Clay saturated conductivity C_K	10 times 0.1 times	732.38 732.38	616.32 616.32	145.78 3.90	24.60 104.22
Clay liner leakage C_L	+ 5%	732.38	616.32	40.77	102.45

8.1.3 Effects of Soil Cover Parameters

The effects of soil cover parameters on model output are investigated first because soil cover is the first barrier to minimize the infiltration water. The capping system includes different parameters such as: soil cover depth, root zone depth, clay depth and the physical properties relate to the moisture retention parameters. The permeability is also included which is one of the key parameters in controlling the movement of water in soil cover.

8.1.3.1 Saturated Hydraulic Conductivity K_s

The saturated hydraulic conductivity controls the speed of saturated flow through the soil and has a significant effect on infiltration, runoff and lateral flow. The value of K_s of the soil cover is specified in the input, depending on soil type being used for surface cover. A 10 times increase in K_s value led to an increase of 1.5% in infiltration volume yearly, as shown in Figure 8.5. The effect of K_s on runoff is the opposite where a decrease takes place, although it is not as significant (Figure 8.4). It has significant effect on lateral flow as shown in Figure 8.6. A 10 times increase in value of K_s leads to a 76% increase in lateral flow yearly and, a 10 times decrease in its value leads to a 90% decrease in volumetric lateral flow yearly. It has very little effect on percolation through clay liner when the value of K_s is increased by 10 times as is evident from Figure 8.7.

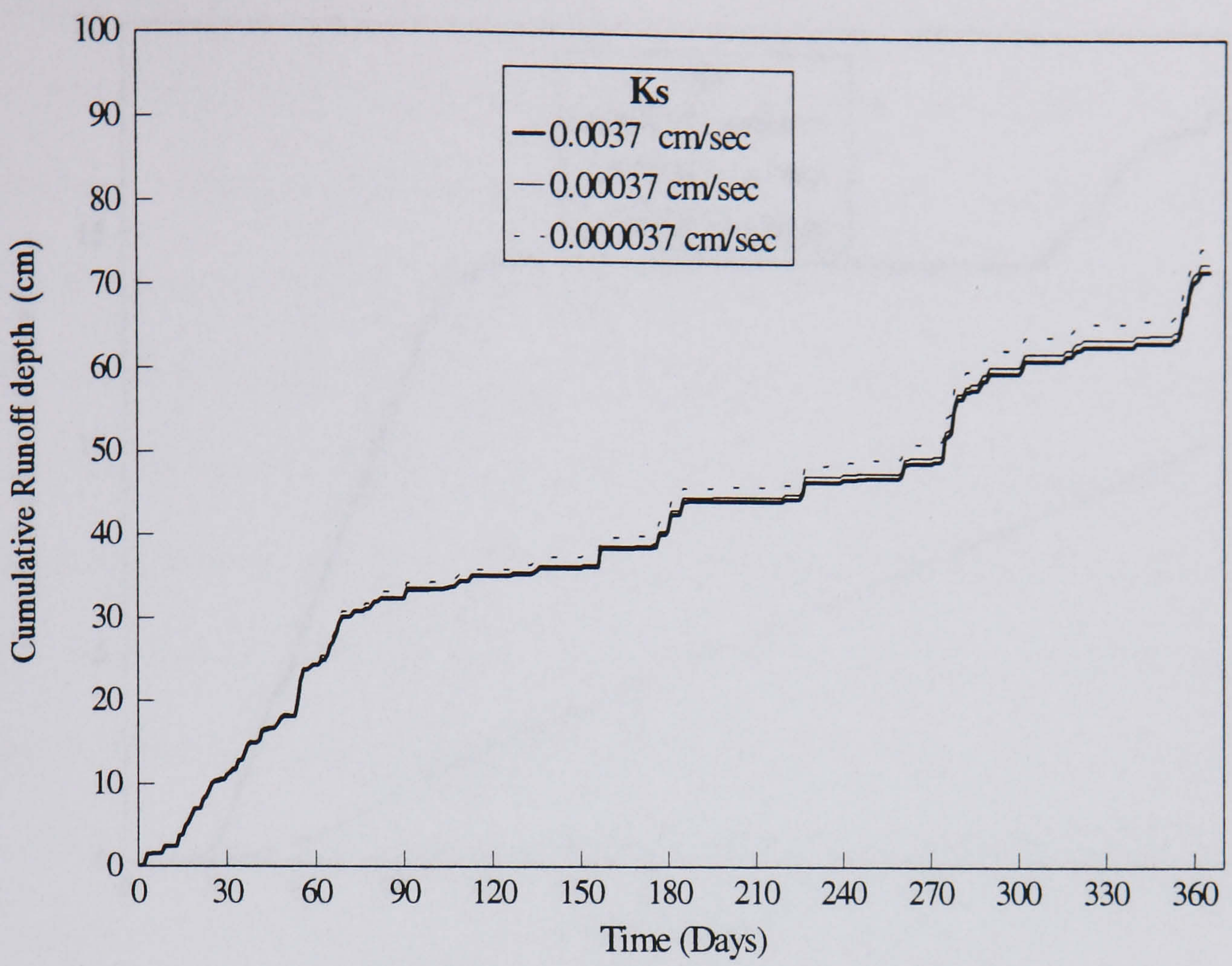


Figure 8.4. Effect of Ks on cumulative runoff depth.

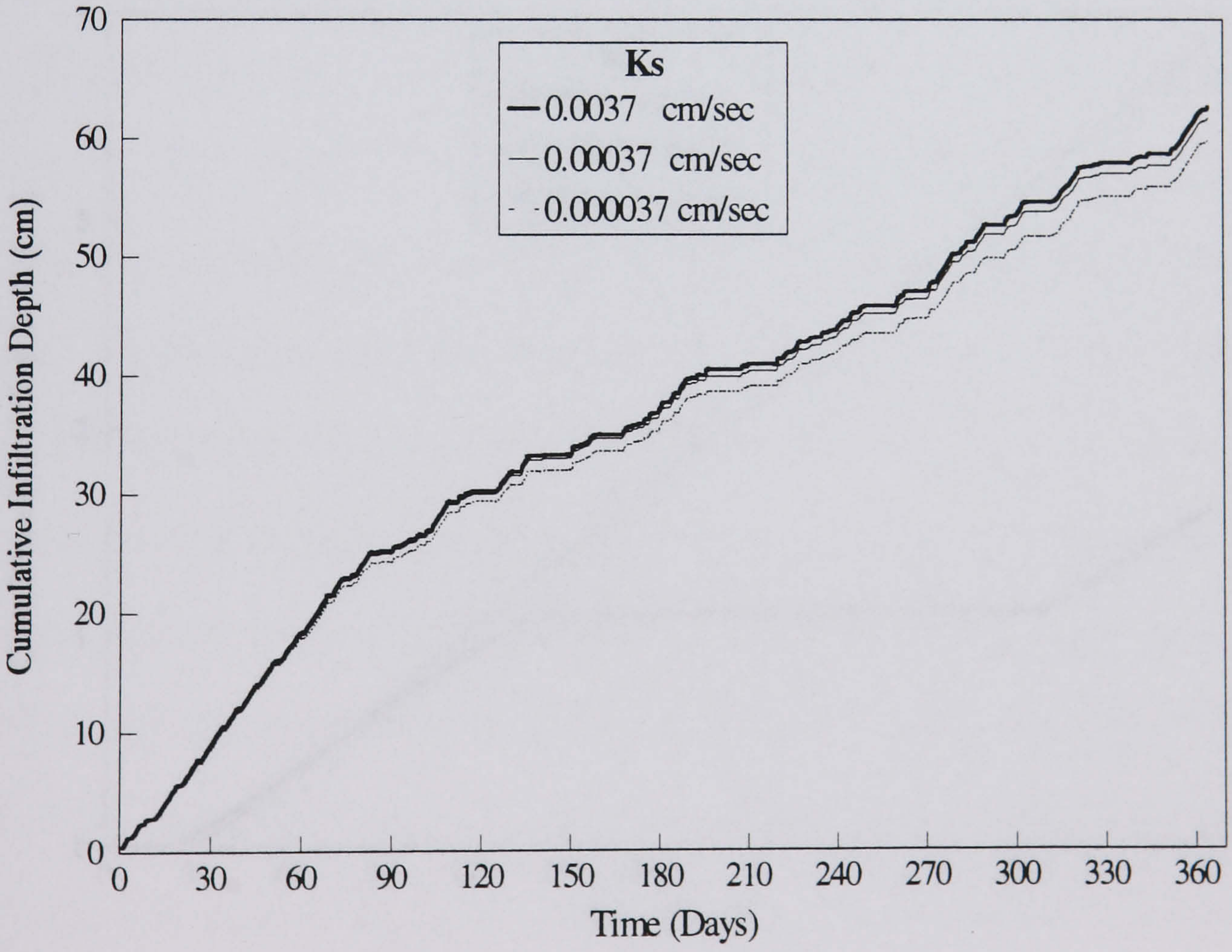


Figure 8.5. Effect of Ks on cumulative infiltration depth.

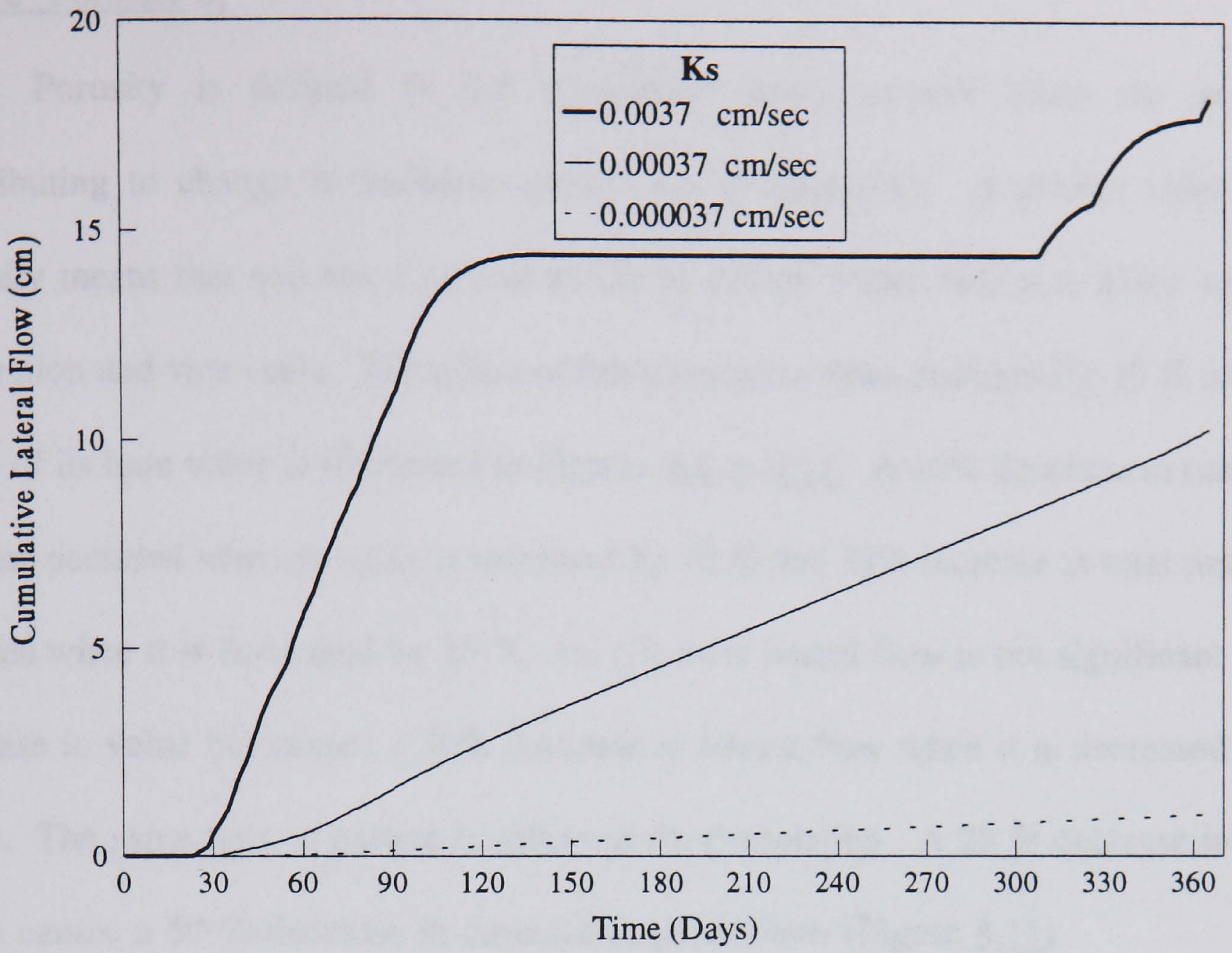


Figure 8.6. Effect of Ks on cumulative Lateral Flow depth.

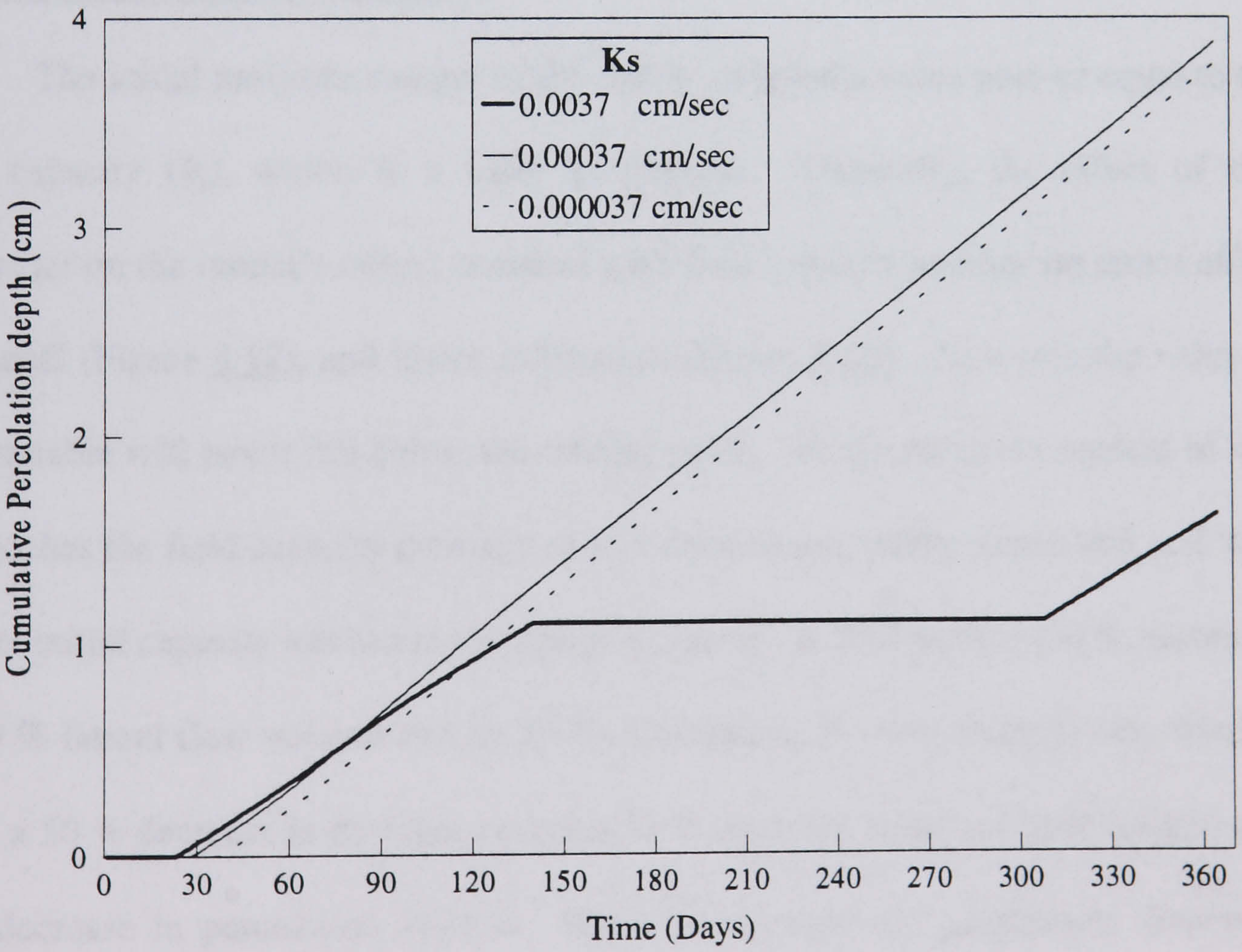


Figure 8.7. Effect of Ks on cumulative Percolation depth.

8.1.3.2 Porosity θ_s

Porosity is defined as the volumetric water content when the pores contributing to change in moisture storage are at saturation. A greater value of porosity means that soil has a greater ability to absorb water; that is to allow more infiltration and vice versa. The effect of this parameter when changed by 10 % and -25 % of its base value is illustrated in Figures 8.8 to 8.11. A 10% decrease in runoff volume occurred when porosity is increased by 10 % and 32% increase in total runoff volume when it is decreased by 25 %. Its effect on lateral flow is not significant for increase in value but causes a 70% decrease in lateral flow when it is decreased by 25 %. The same type of pattern is observed for percolation. A 25 % decrease in its value causes a 50 % decrease in cumulative percolation (Figure 8.11).

8.1.3.3 Initial Moisture Content θ_i

The initial moisture content of the soil is assigned a value near or equal to the field capacity (θ_f), which is a valid assumption. Generally, the effect of this parameter on the model's output is linked with field capacity and has no direct effect on runoff (Figure 8.12), and hence infiltration (Figure 8.13). As a rule the value of this variable will never fall below the wilting point. As the moisture content of soil approaches the field capacity drainage of soil commences which means that soil with greater initial capacity has lower absorption capacity. A 50% increase in θ_i, increases by 40 % lateral flow volume and by 16 % percolation of water through clay barrier, while a 50 % decrease in its value causes a 56 % decrease in lateral flow volume and 4 % decrease in percolation volume. These phenomena are graphically shown in Figures 8.14 and 8.15.

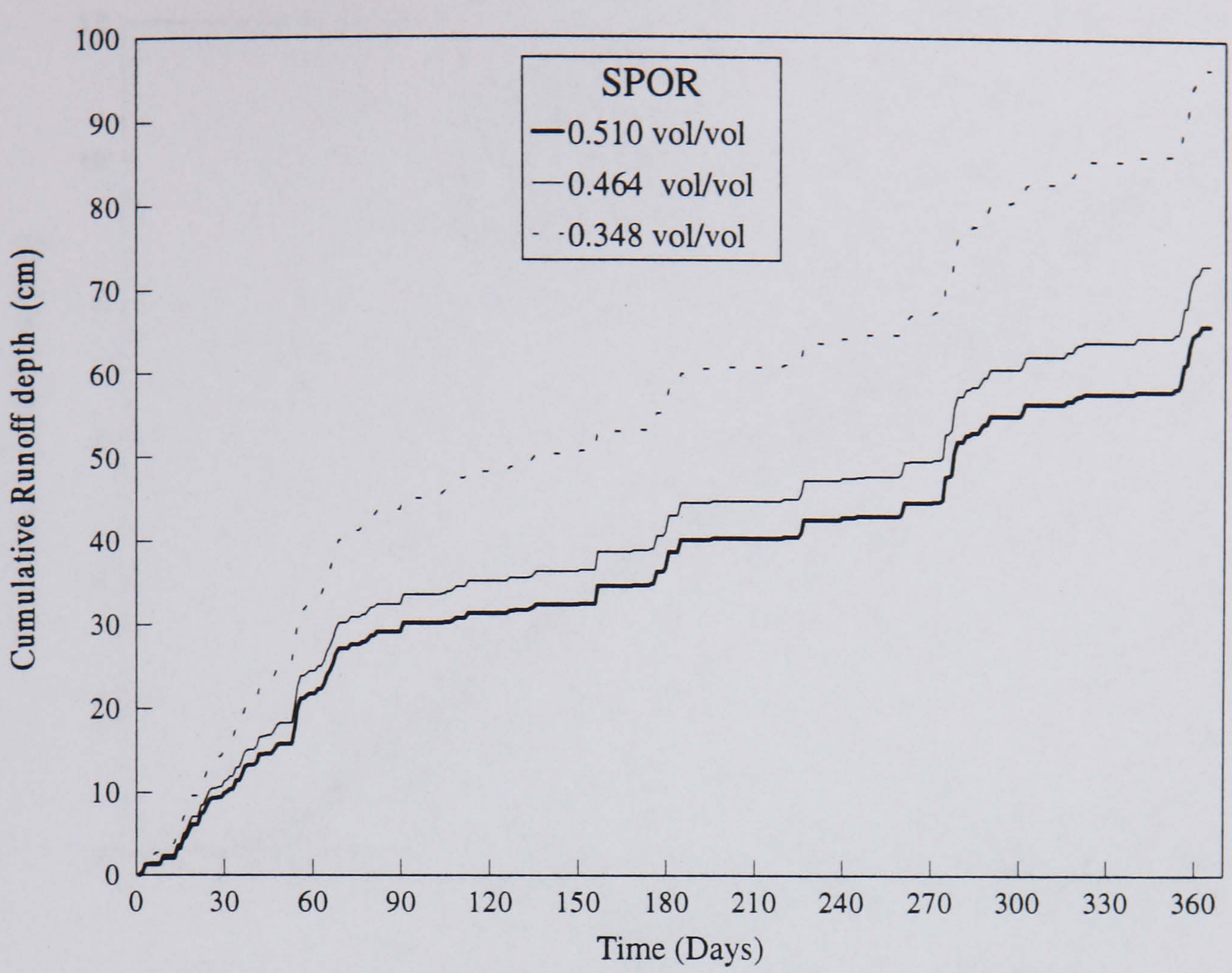


Figure 8.8. Effect of Porosity on cumulative Runoff depth.

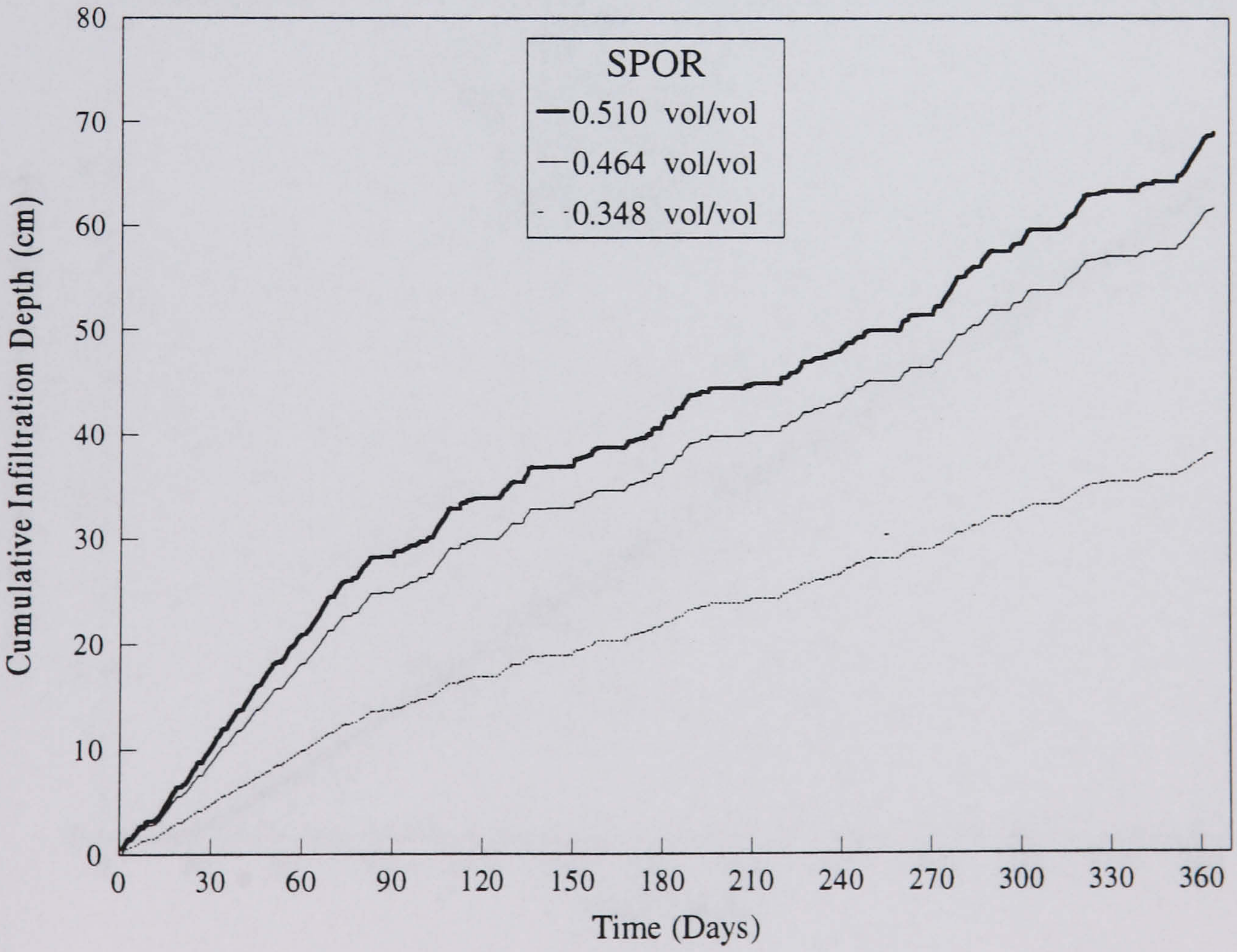


Figure 8.9. Effect of Porosity on cumulative infiltration depth.

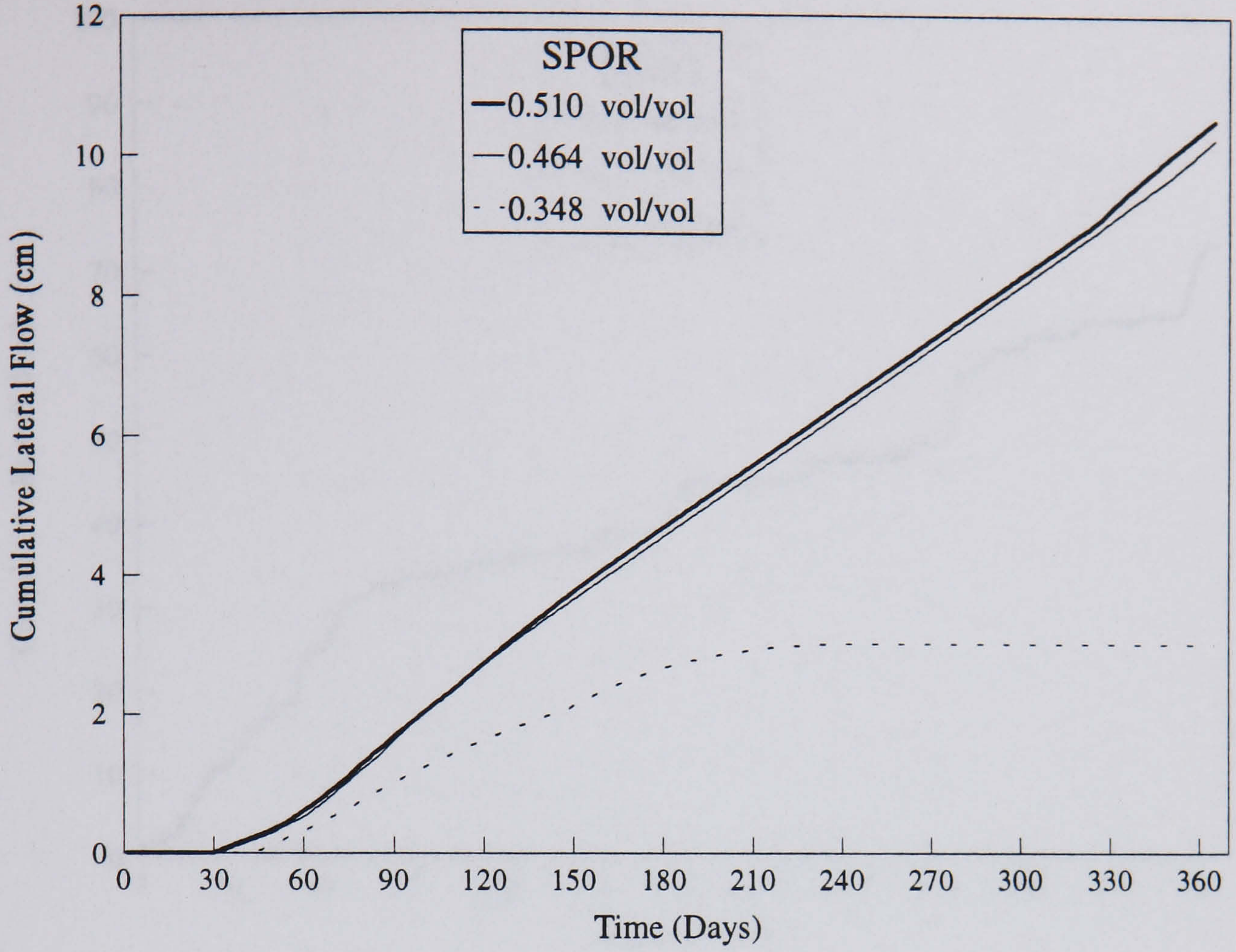


Figure 8.10. Effect of Porosity on cumulative Lateral Flow depth.

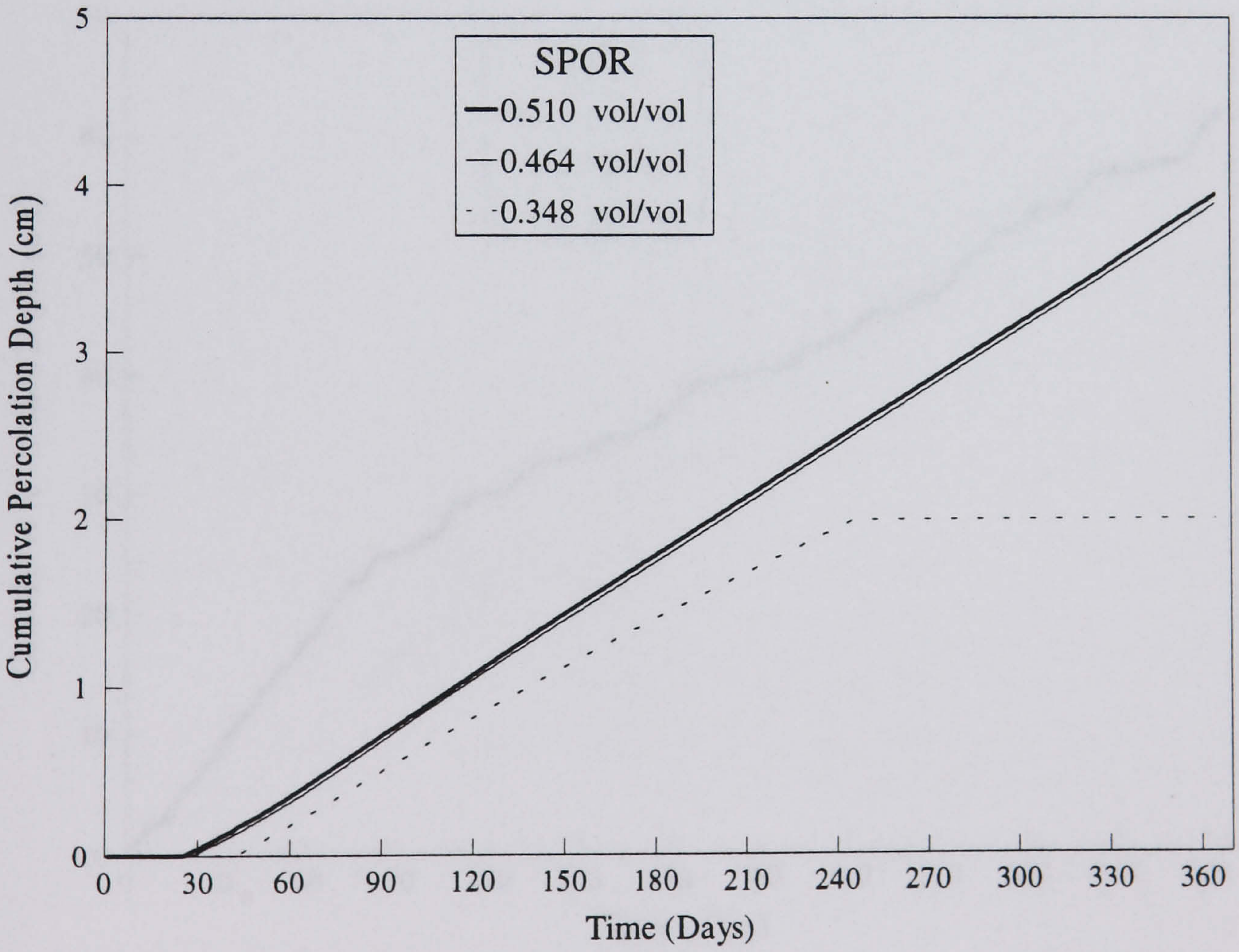


Figure 8.11. Effect of Porosity on cumulative Percolation depth.

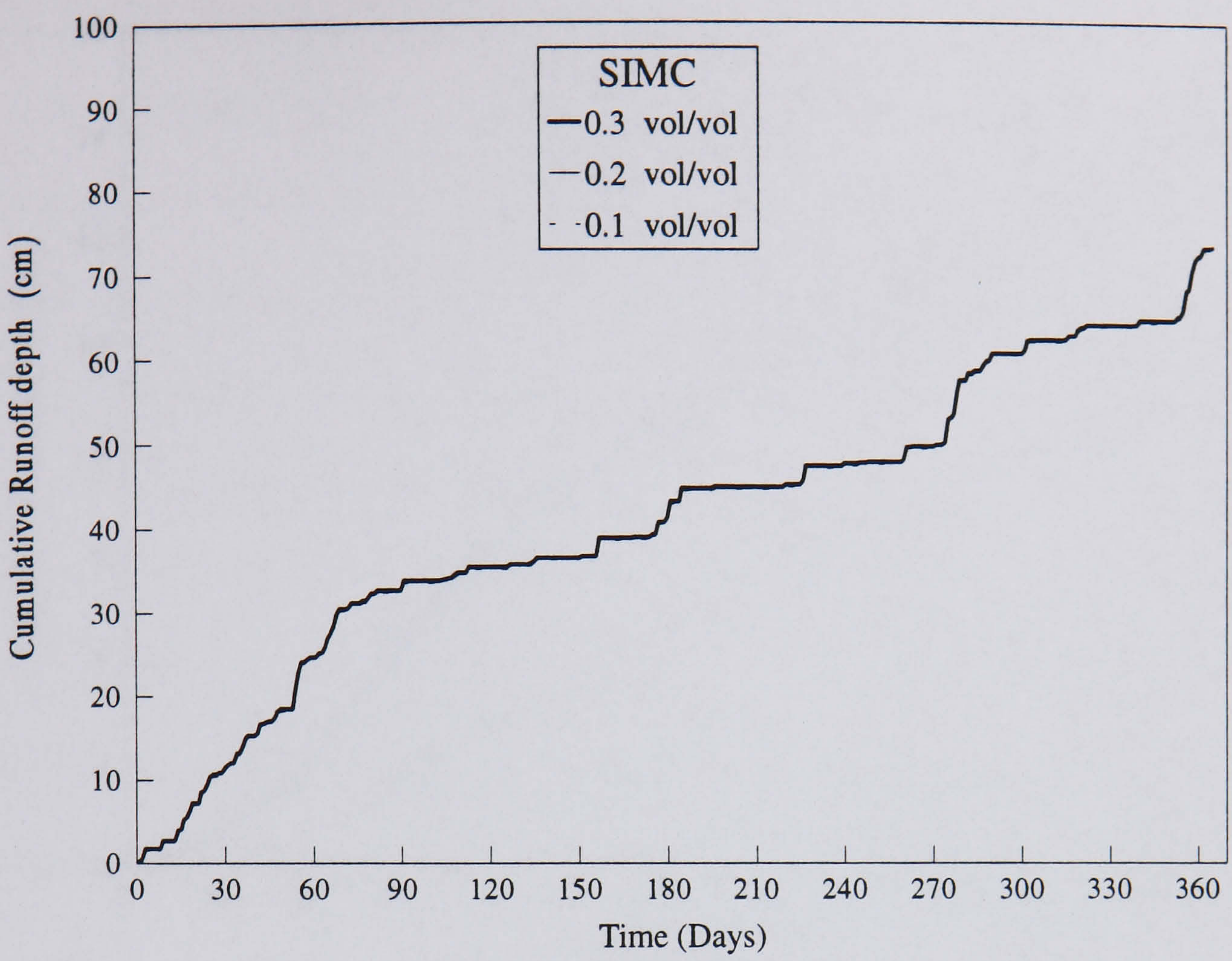


Figure 8.12. Effect of initial capacity on cumulative runoff depth.

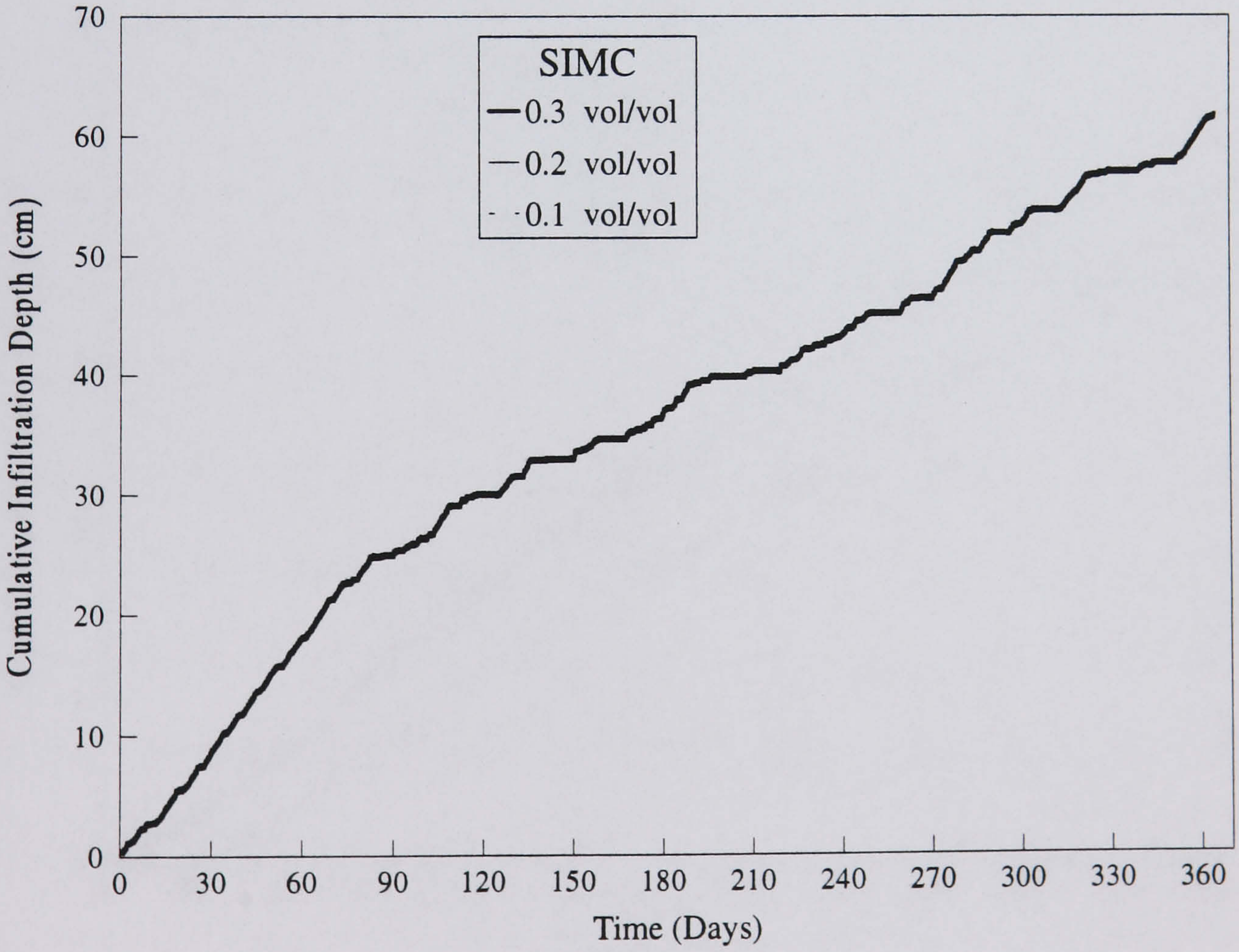


Figure 8.13. Effect of initial capacity on cumulative infiltration depth.

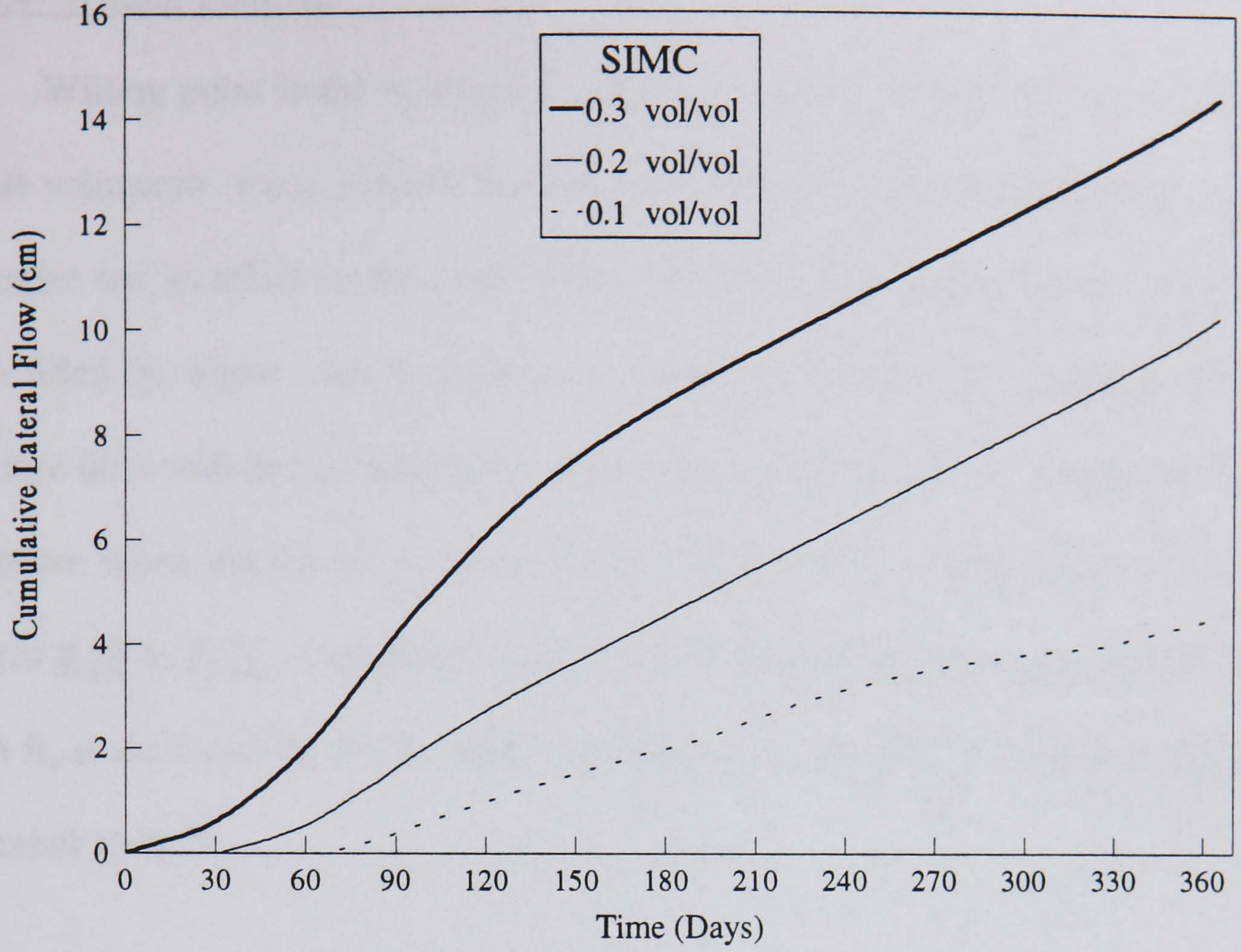


Figure 8.14. Effect of initial capacity on cumulative Lateral Flow depth.

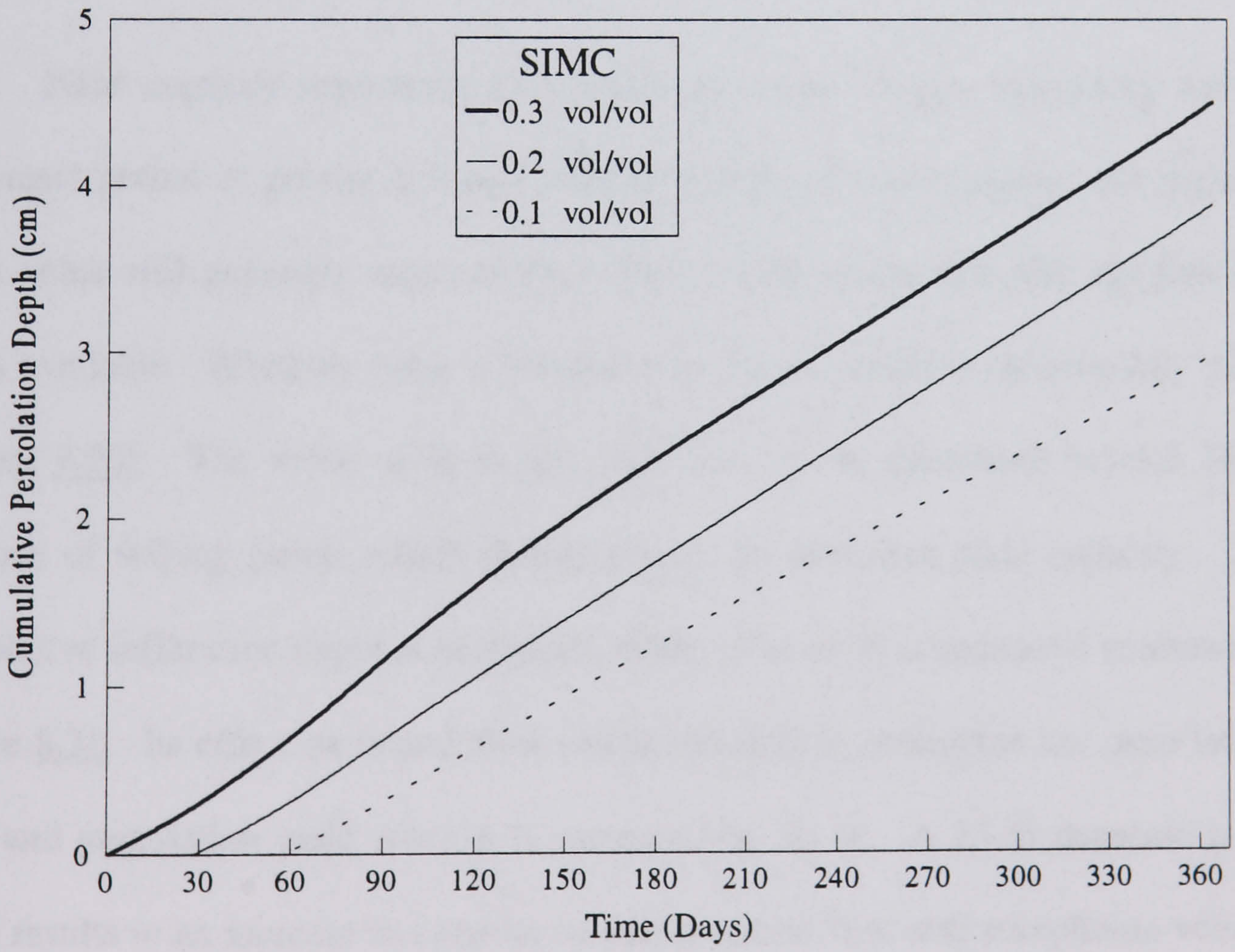


Figure 8.15. Effect of initial capacity on cumulative Percolation depth.

8.1.3.4 Wilting Point θ_w

Wilting point is the volumetric water content at a suction of 15 bars or the lowest volumetric water content that can be achieved by plant transpiration. This parameter has an effect on the total volume of voids which are available in the soil to be filled by water. An increase in its value will reduce the fillable voids and therefore there will be less infiltration opportunity, and vice versa. The effect of this parameter when altered by ± 50 % of its control value is graphically shown in Figures 8.16 to 8.19. Cumulative yearly runoff (Figure 8.16) is increased by 4 % when θ_w is increased by 50 %, while cumulative yearly infiltration (Figure 8.17) is decreased by 8 %.

8.1.3.5 Field Capacity θ_f

Field capacity represents the volumetric water content remaining after a prolonged period of gravity drainage without additional water supply. An increase in its value will generally increase the runoff, which means that soil has less free voids available. When its value is increased by 50 %, runoff is increased by 31 % (Figure 8.20). The value of θ_f in this case can not be decreased beyond 25 % because of wilting point, which should always be less than field capacity. The cumulative infiltration depth is decreased, when value of θ_f is increased as shown in Figure 8.21. Its effect on lateral flow and percolation is noticeable i.e., zero lateral flow and percolation yield when it is increased by 50 %. A 25 % decrease in its value results in an increase in cumulative yearly lateral flow and percolation volume (Figures 8.22 and 8.23).

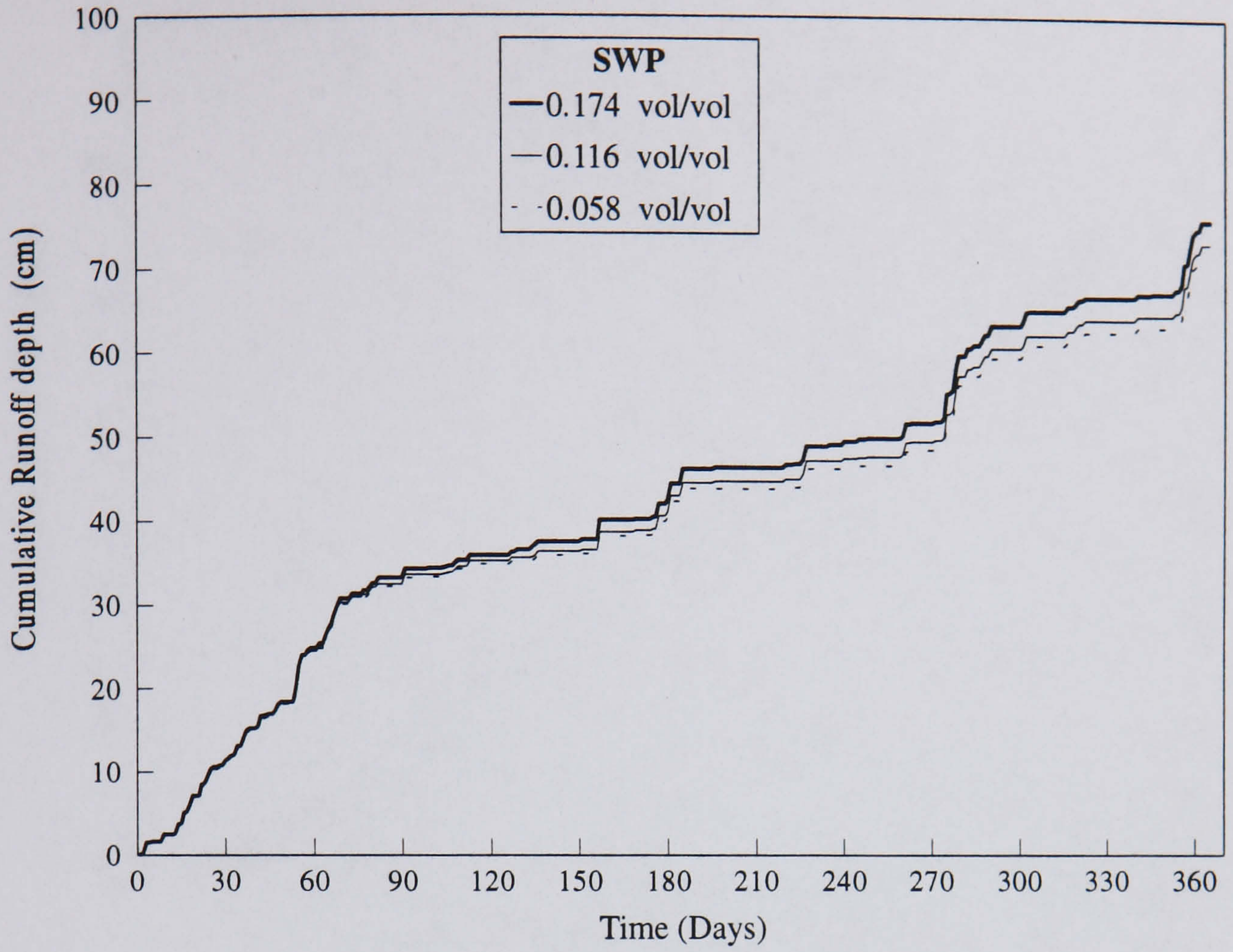


Figure 8.16. Effect of wilting capacity on cumulative runoff depth.

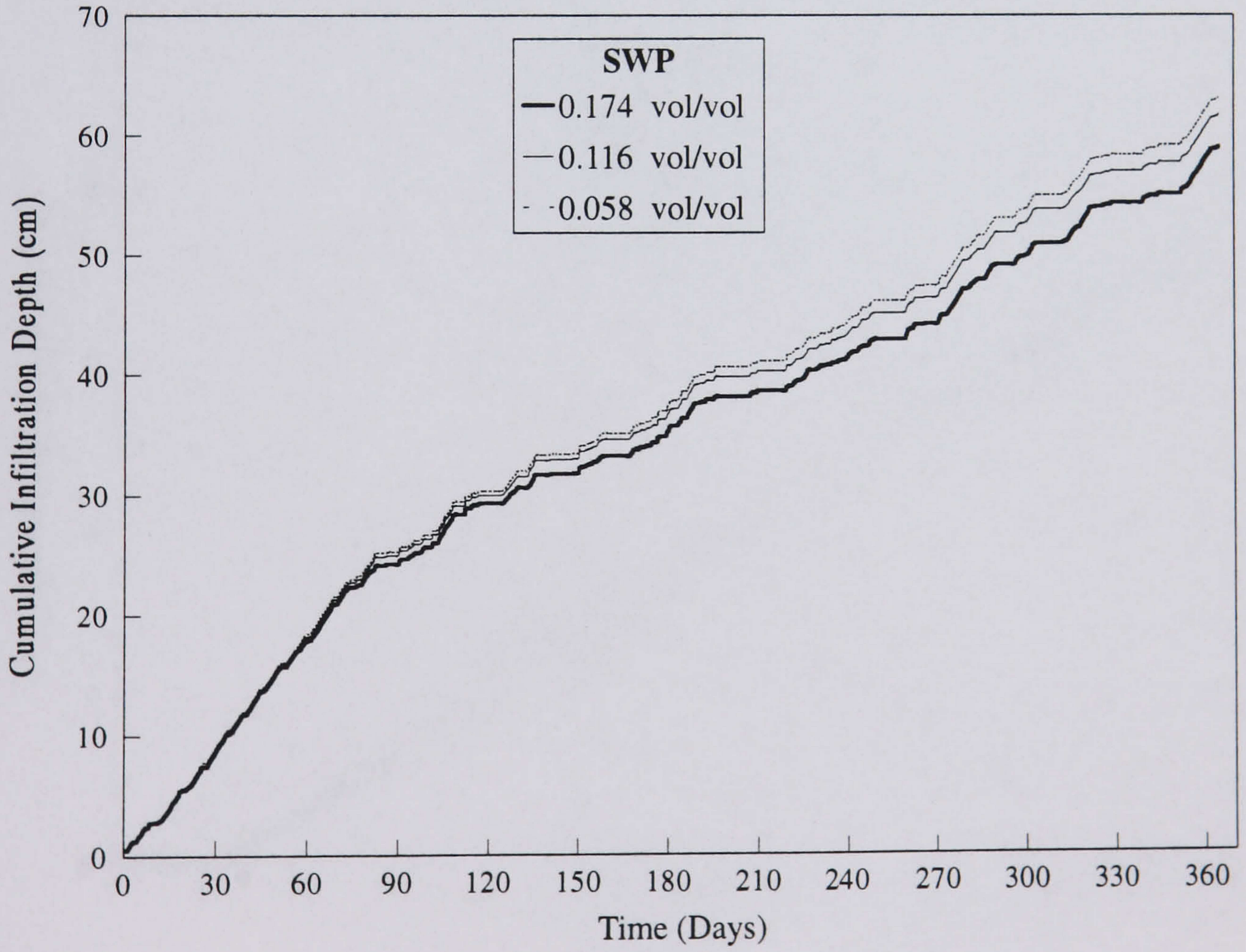


Figure 8.17. Effect of wilting capacity on cumulative infiltration depth.

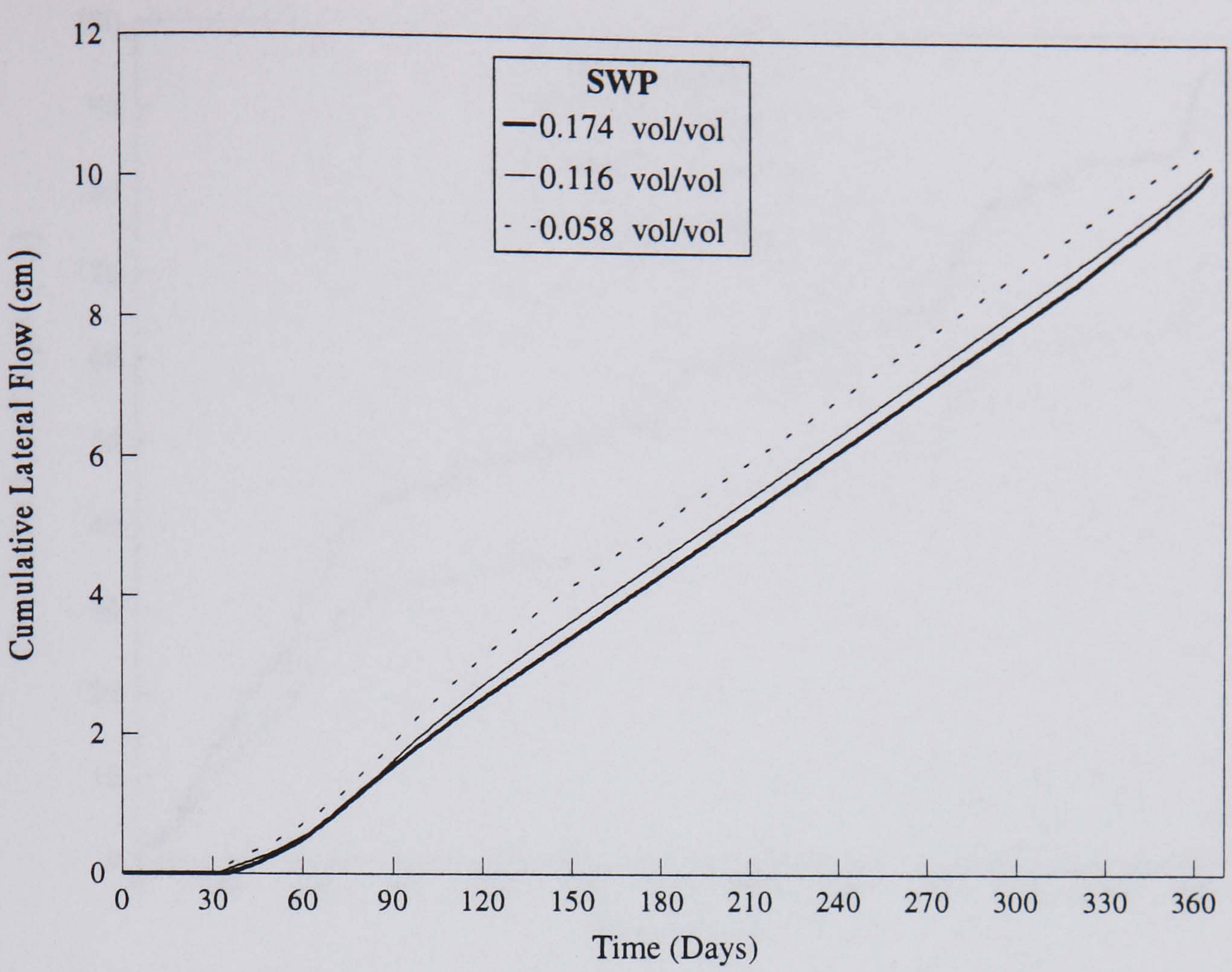


Figure 8.18. Effect of wilting capacity on cumulative Lateral Flow depth.

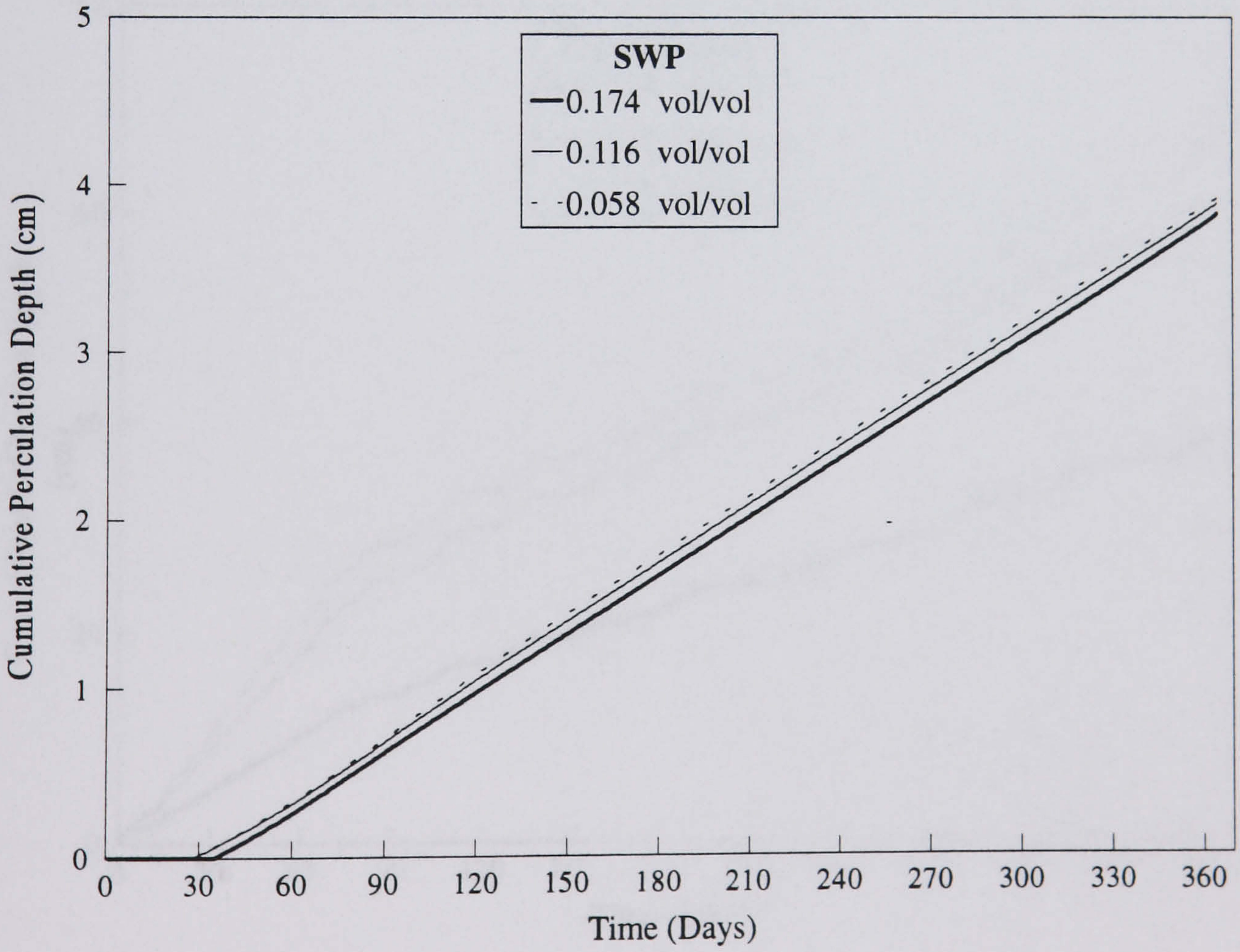


Figure 8.19. Effect of wilting capacity on cumulative Percolation depth.

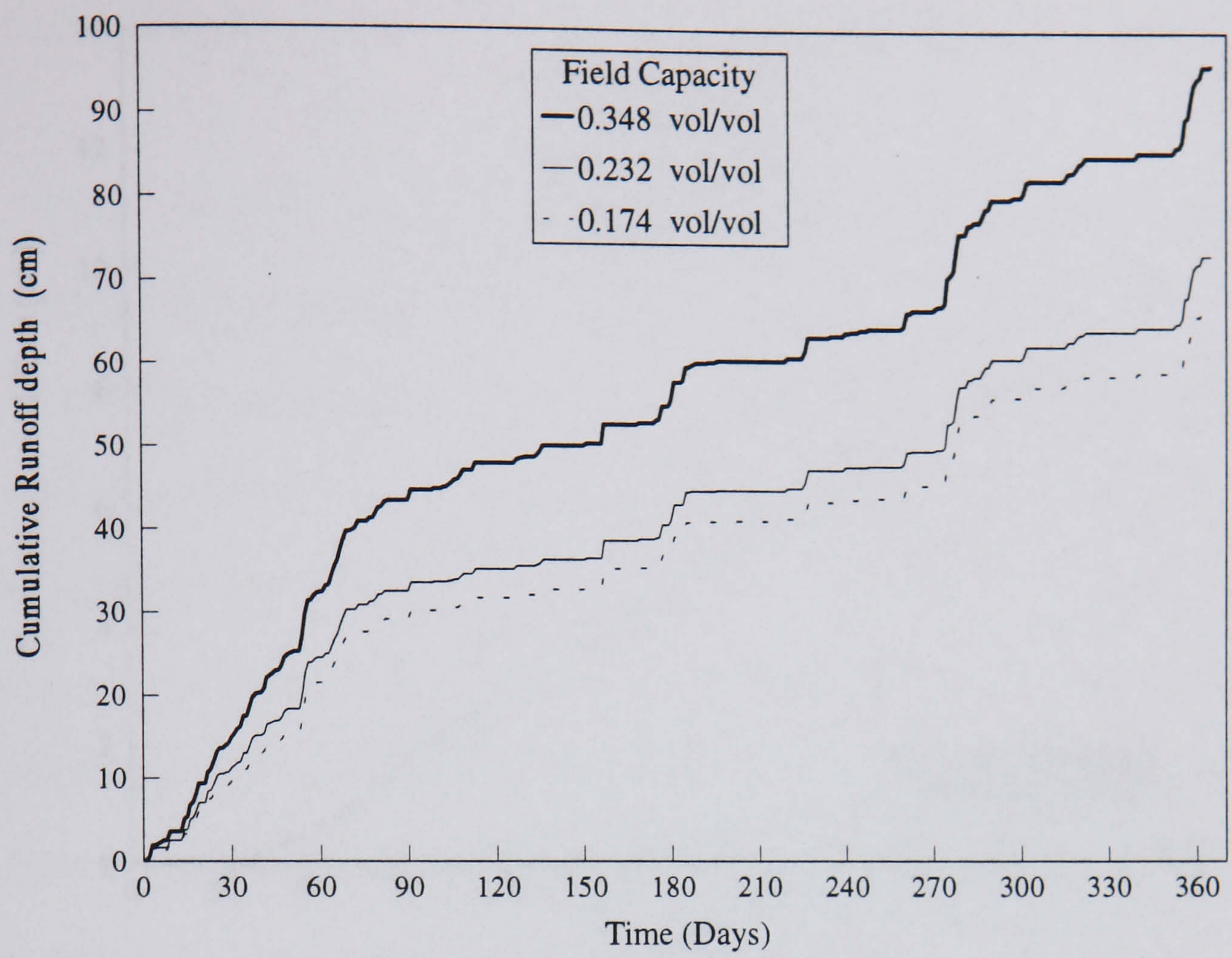


Figure 8.20. Effect of field capacity on cumulative runoff depth.

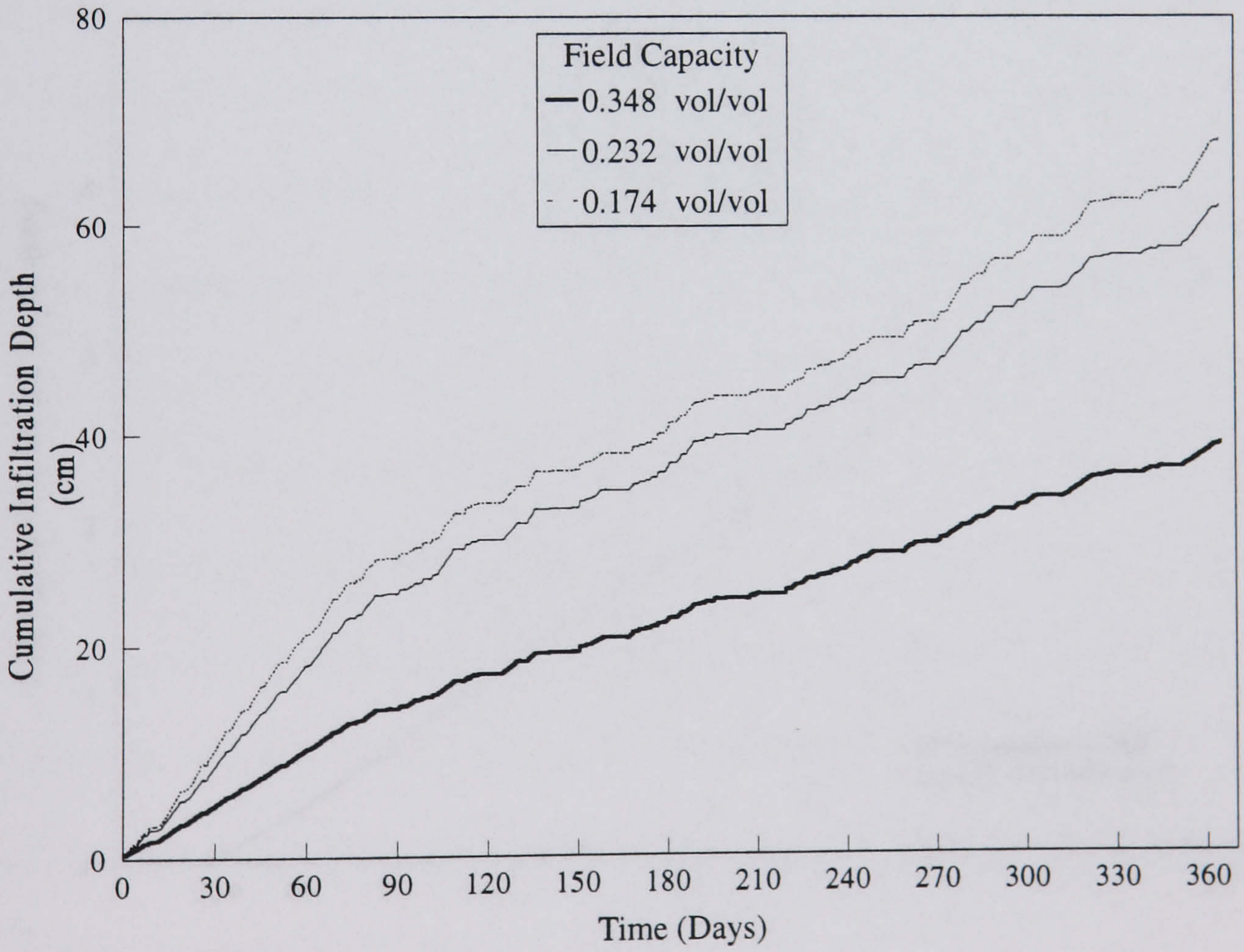


Figure 8.21. Effect of field capacity on cumulative infiltration depth.

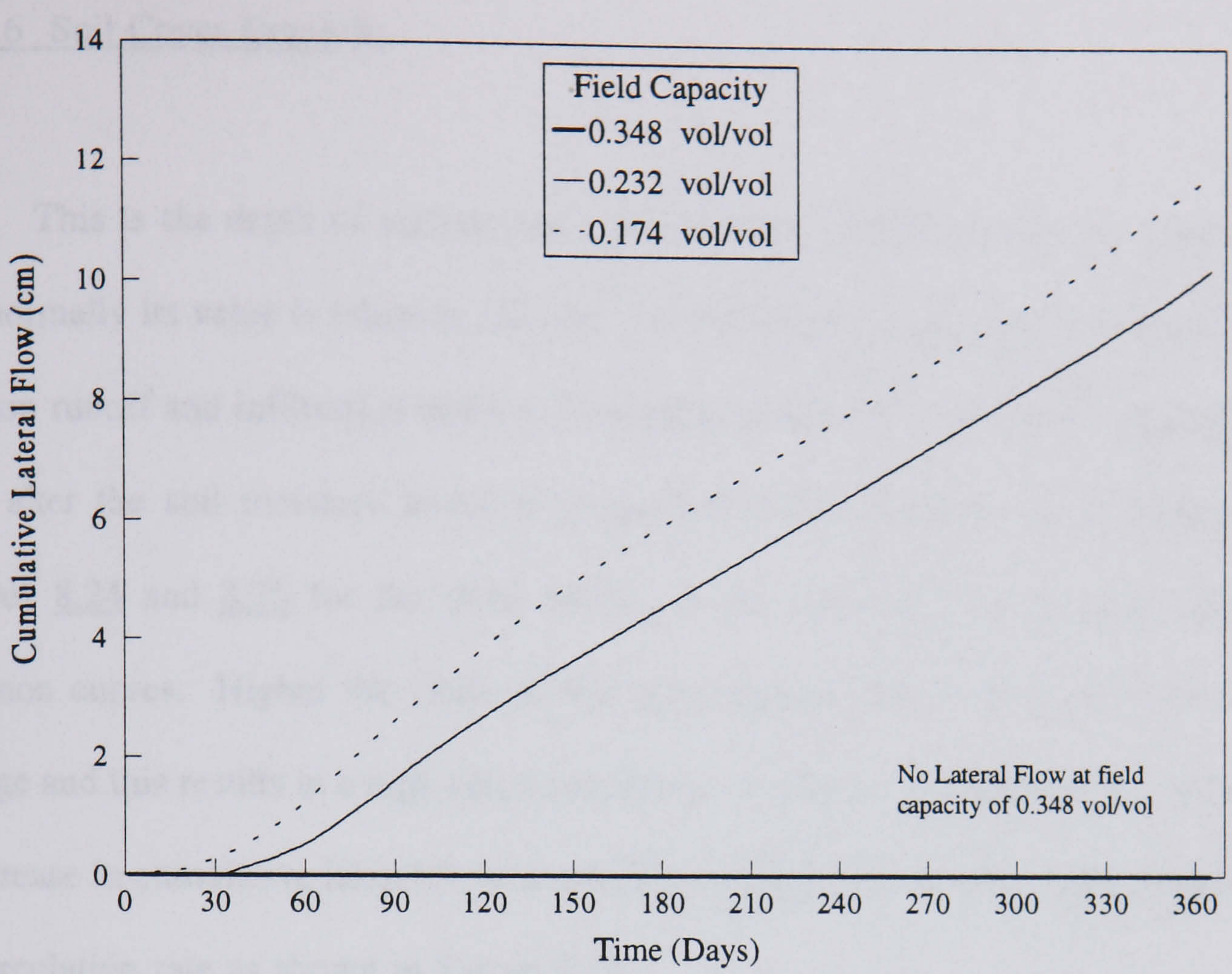


Figure 8.22. Effect of field capacity on cumulative Lateral Flow depth.

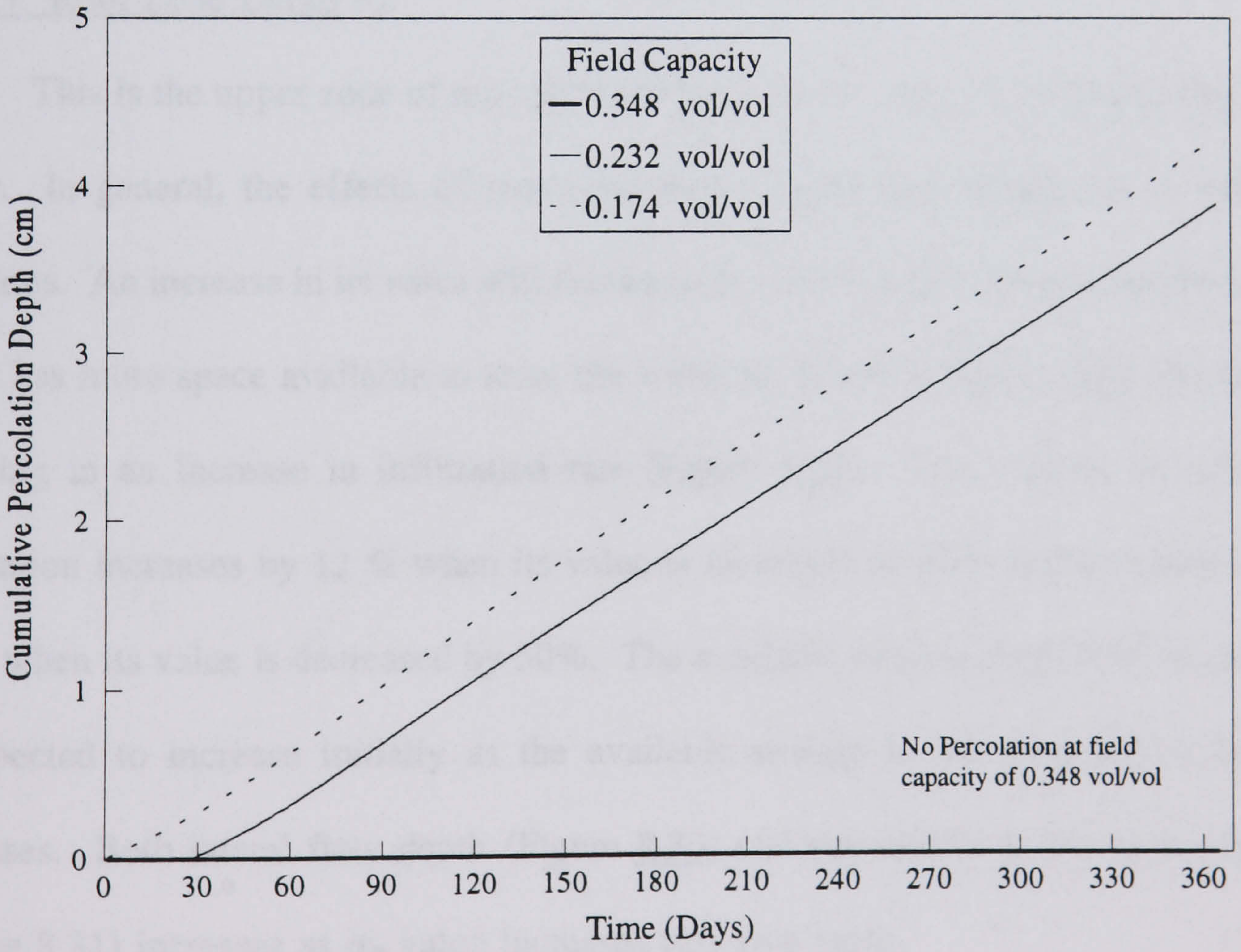


Figure 8.23. Effect of field capacity on cumulative Percolation depth.

8.1.3.6 Soil Cover Depth S_D

This is the depth of surface soil cover to store infiltration water temporally and normally its value is taken as 100 cm. Its effect was found not to be detectable both on runoff and infiltration under a 50% increase and 25 % decrease, although it does alter the soil moisture levels in proportion to the changes. It is shown in Figures 8.24 and 8.25 for the three depths of 1.5, 1.0 and 0.75 m, with almost common curves. Higher the value of soil cover means greater space for moisture storage and this results in a high saturation depth. A greater saturation depth yielded a decrease in cumulative lateral flow depth (Figure 8.26) and to some extent increase in percolation rate as shown in Figure 8.27.

8.1.3.7 Root Zone Depth R_D

This is the upper zone of top soil cover from where most of the plants extract water. In general, the effects of root zone depth would vary greatly as its value increases. An increase in its value will decrease the runoff, which means that the soil cover has more space available to store the water as shown in Figure 8.28 and thus resulting in an increase in infiltration rate (Figure 9.29). The volume of annual infiltration increases by 12 % when its value is increased by 50% and decreases by 39 % when its value is decreased by 50%. The available evapotranspiration demand is expected to increase initially as the available storage in the evaporative zone increases. Both lateral flow depth (Figure 8.30) and cumulative percolation depth (Figure 8.31) increases as its value increases and vice versa.

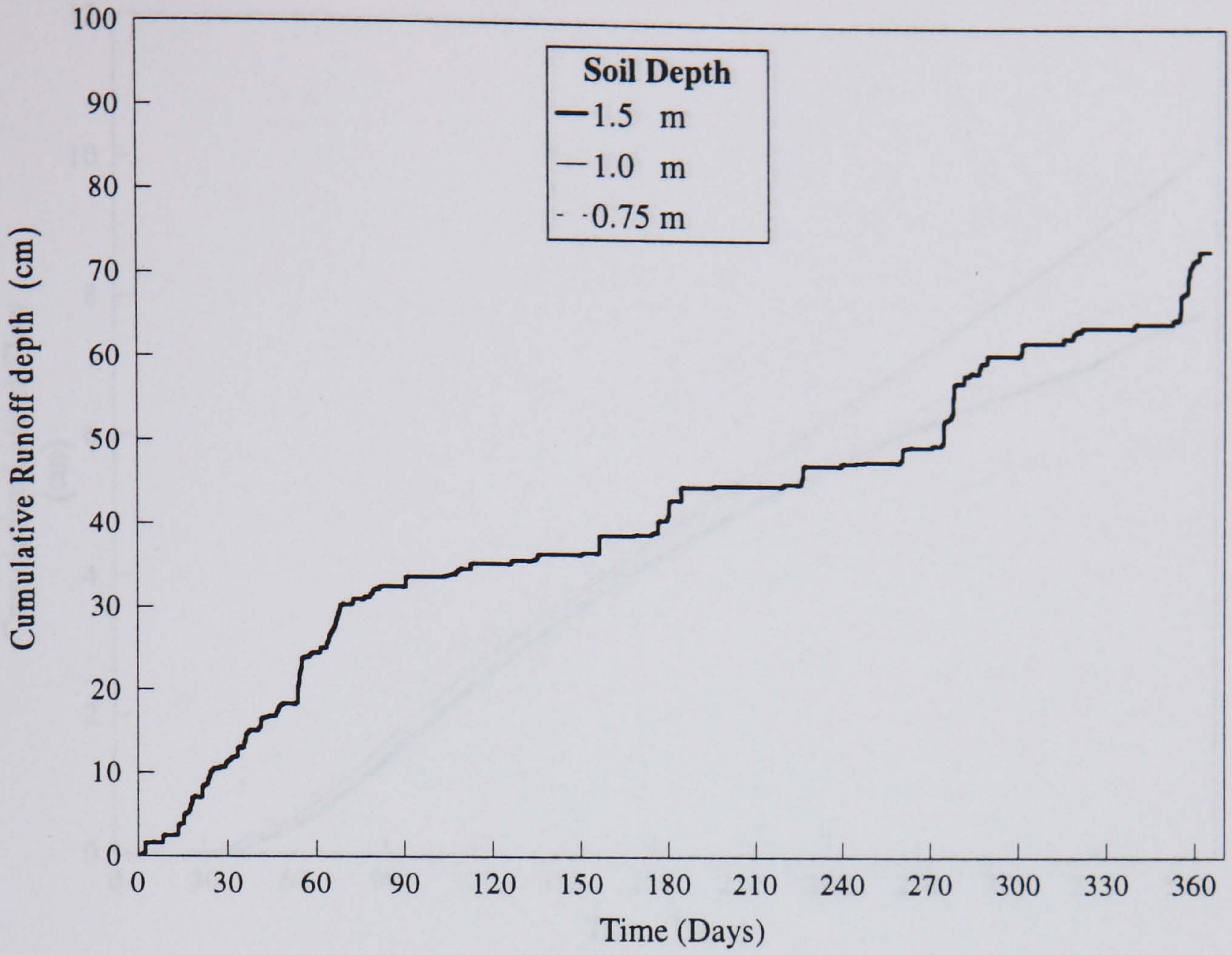


Figure 8.24. Effect of soil depth on cumulative runoff depth.

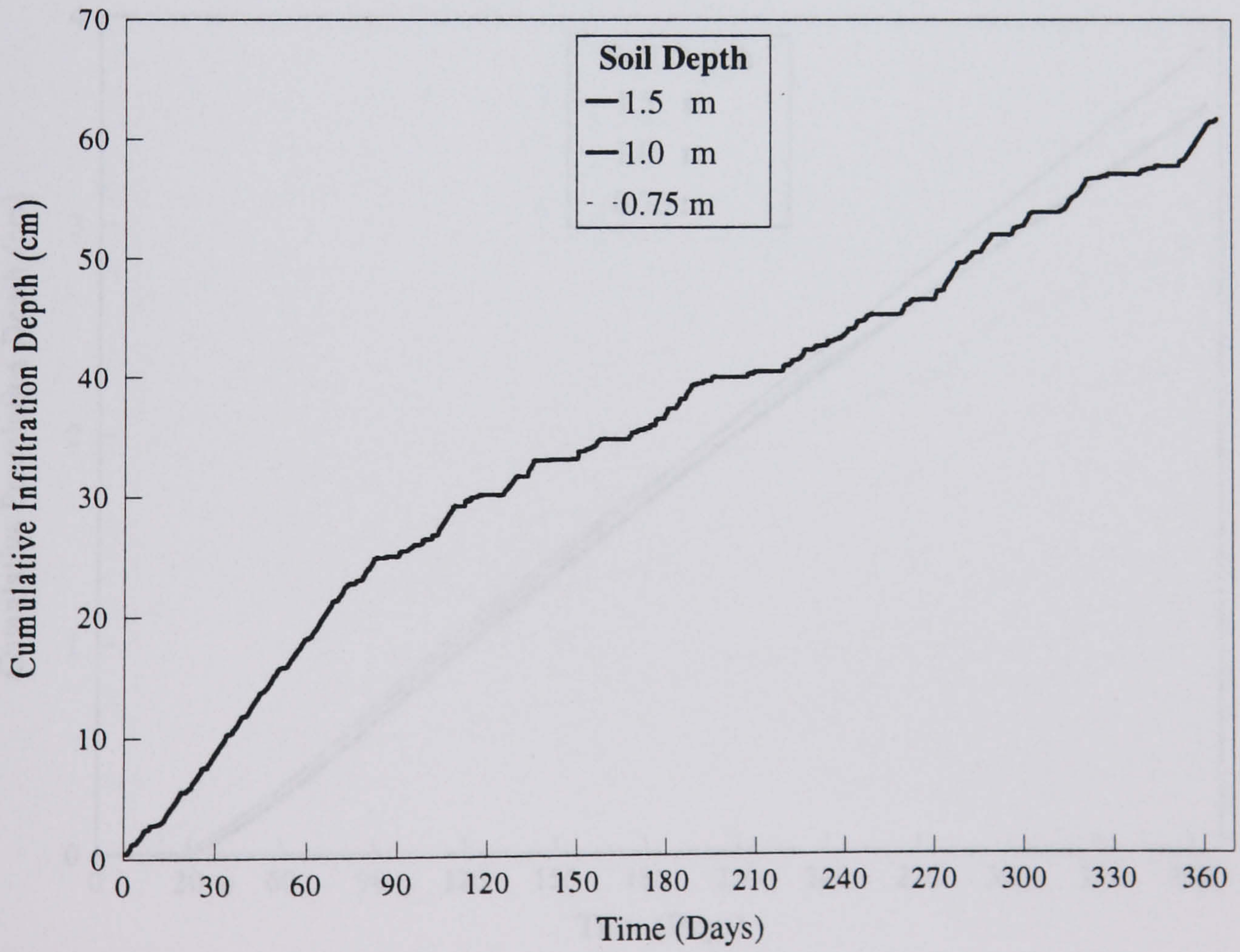


Figure 8.25. Effect of soil depth on cumulative infiltration depth.

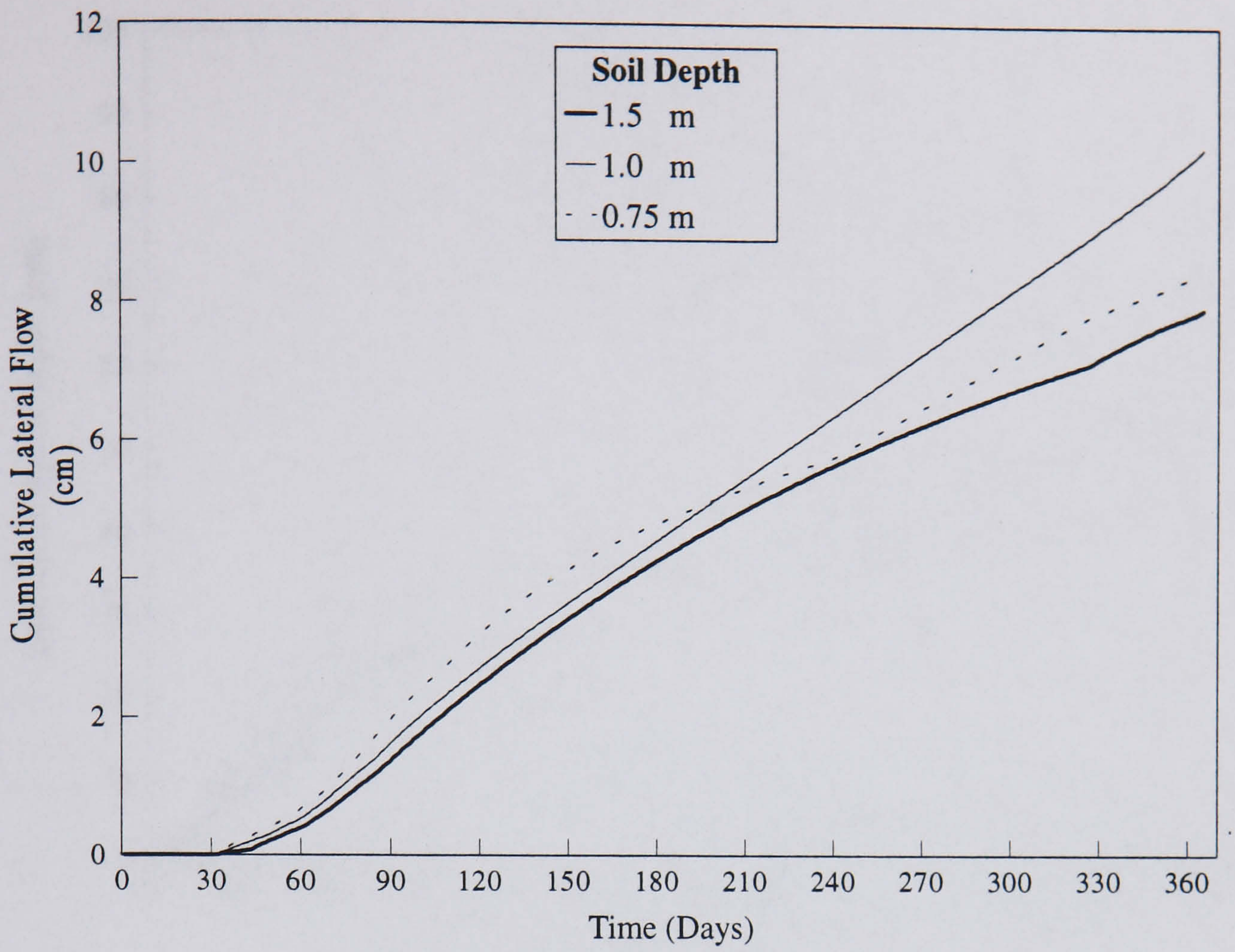


Figure 8.26. Effect of soil depth on cumulative Lateral Flow depth.

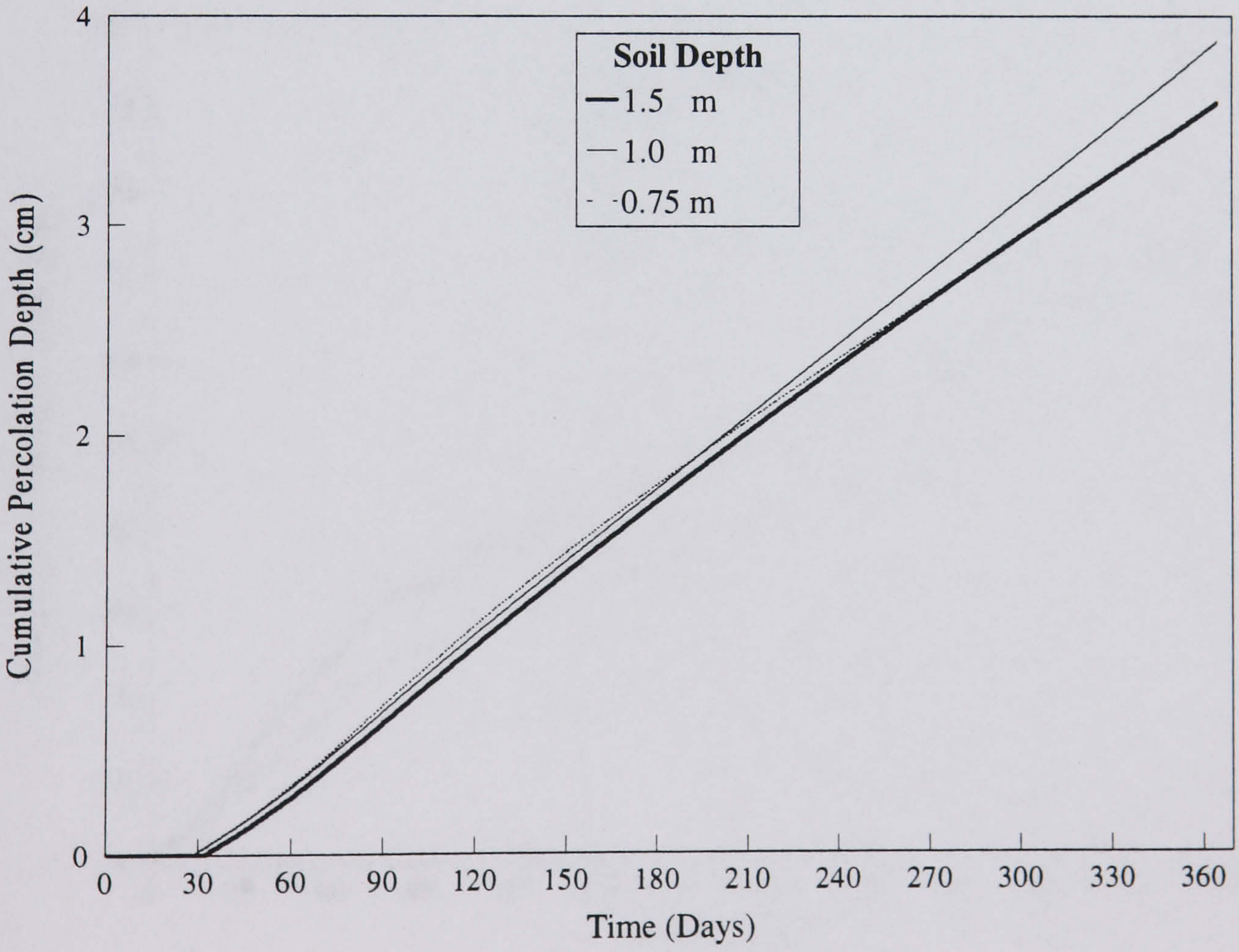


Figure 8.27. Effect of soil depth on cumulative Percolation depth.

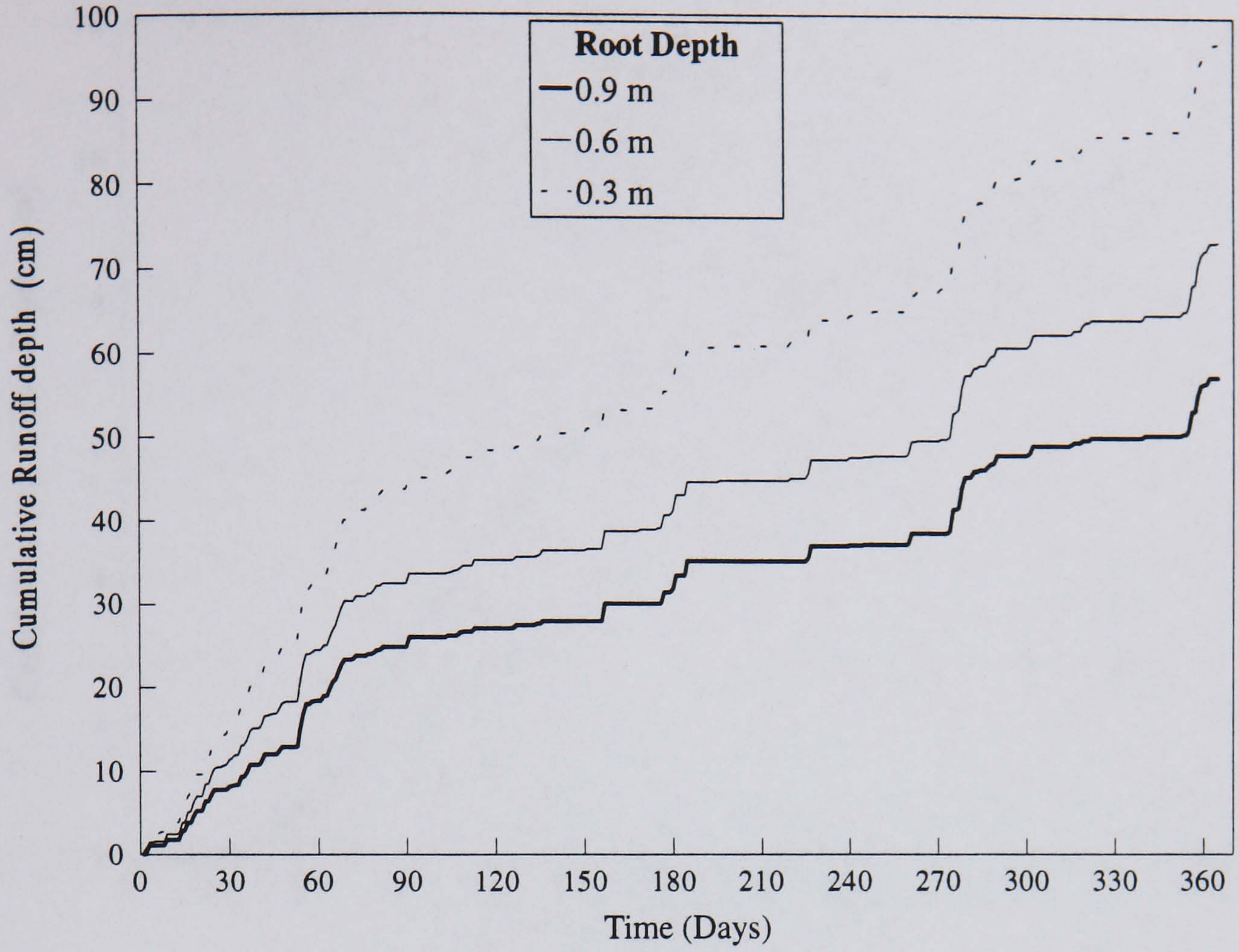


Figure 8.28. Effect of root depth on cumulative runoff depth.

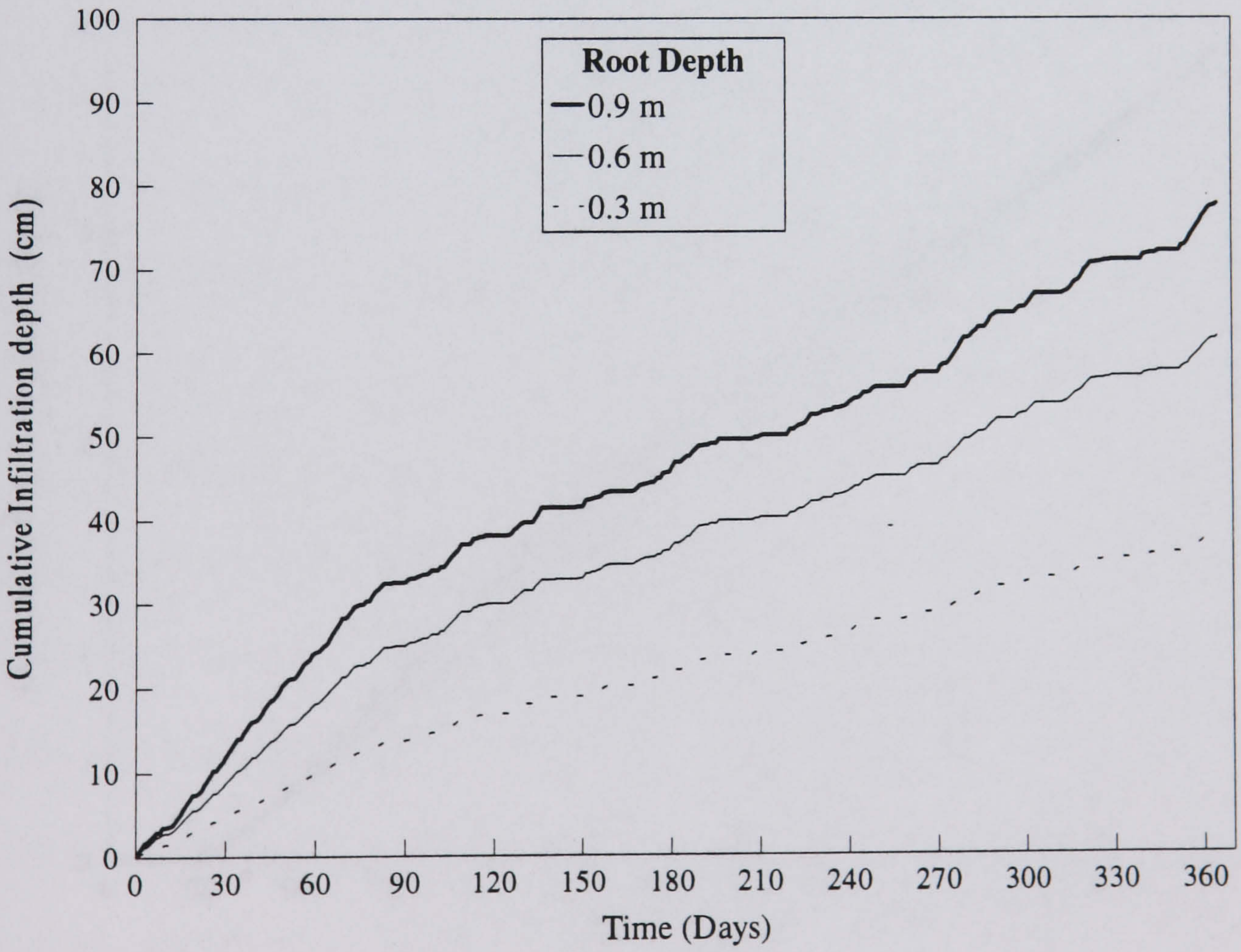


Figure 8.29. Effect of root depth on cumulative infiltration depth.

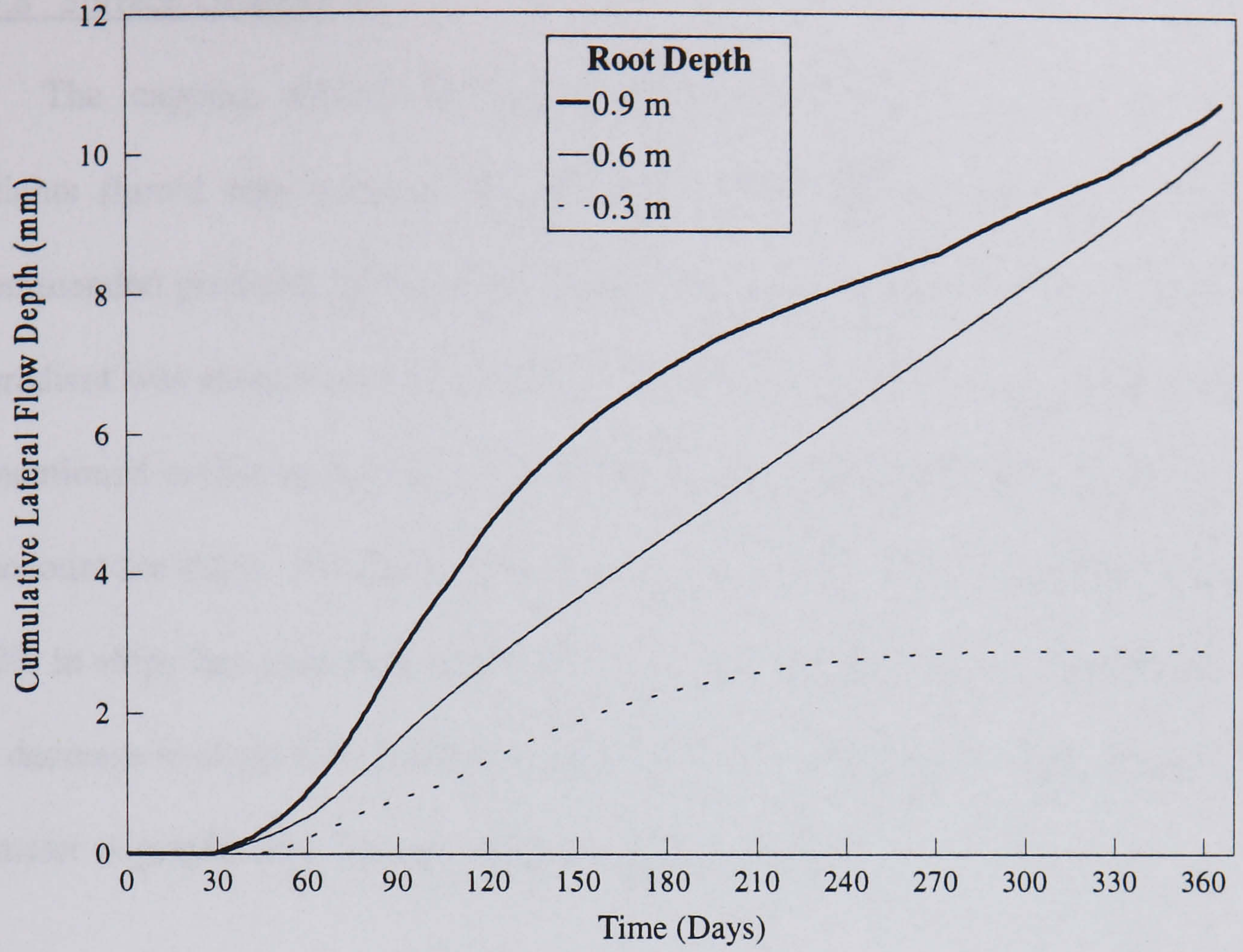


Figure 8.30. Effect of root depth on cumulative Lateral Flow depth.

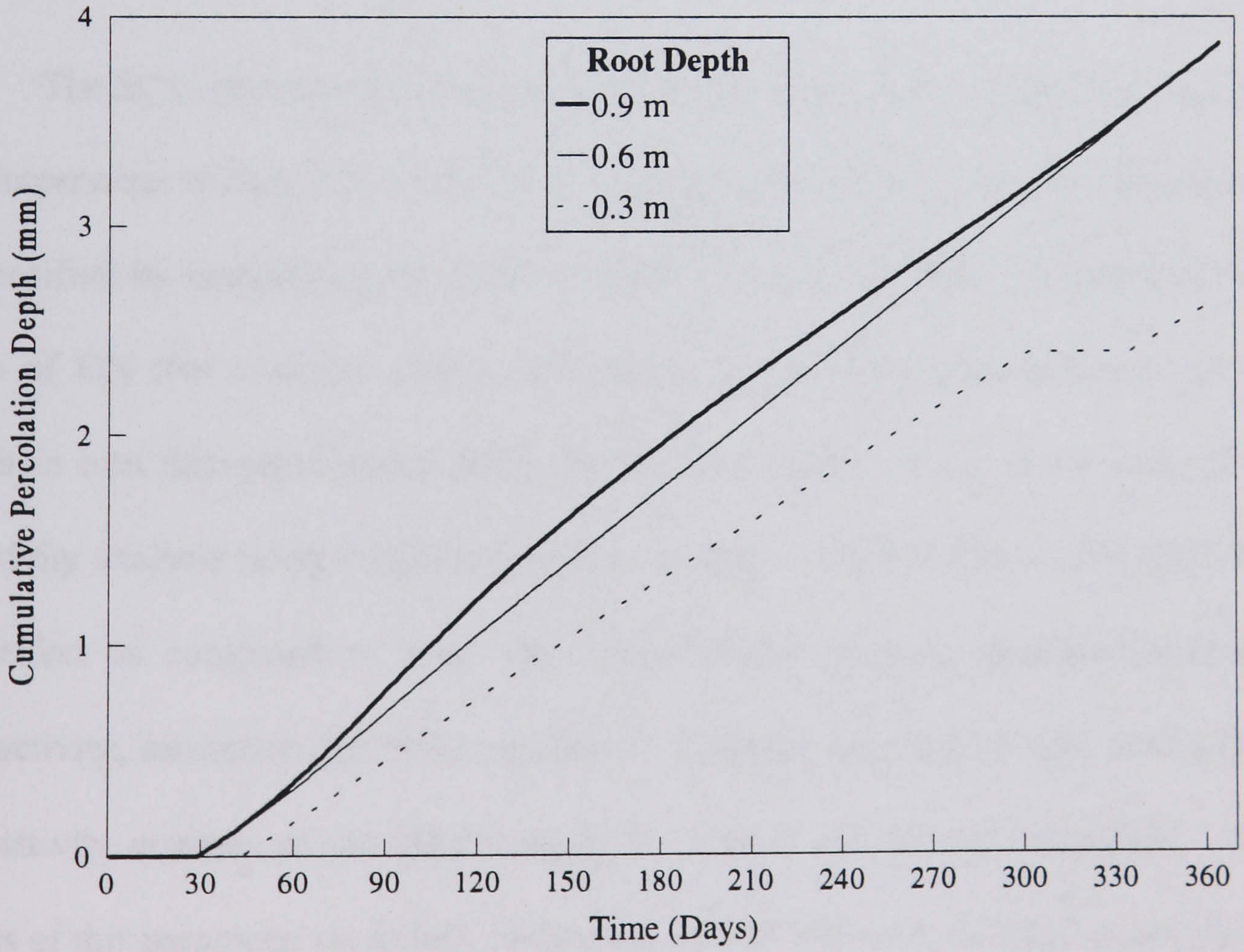


Figure 8.31. Effect of root depth on cumulative Percolation depth.

8.1.3.8 Surface Gradient S_G

The capping should be laid to adequate gradients to promote runoff. Gradients should take account of settlement as the waste continues to degrade. Recommended gradients lie between 1 in 30 and 1 in 6 (DoE, 1986). A base value for gradient was chosen as 1 in 10 which is the average of the recommended range. As mentioned earlier in the theory of model development that the SCS method did not account for slope. Therefore, variation in slope has no effect on runoff. Increase of 50% in slope has increased in lateral flow from 102 mm to 158 mm annually and 50% decrease in slope has resulted in 55 mm depth of lateral flow. The effect of this parameter is graphically shown in Figures 8.32 to 8.35.

8.1.3.9 SCS Curve Number CN

The SCS curve number is a dimensionless quantity with a range from 0 to 100 (for impervious surface CN = 100; for a natural surface CN < 100). Its value should be specified by considering the surface condition of the landfill. Generally a high value of CN (for example clayey soil) significantly increased volumetric runoff, which in turn decreased lateral drainage and percolation. From the results of the sensitivity analysis being conducted, when its value was altered by ± 15% there was less effect as compared to other soil characteristics such as saturated hydraulic conductivity, saturation and field capacities. The same conclusion was drawn from a sensitivity analysis of the HELP model by Peyton and Schroeder (1987). The effects of this parameter on runoff, infiltration, lateral flow and percolation are shown in Figures 8.36 to 8.39.

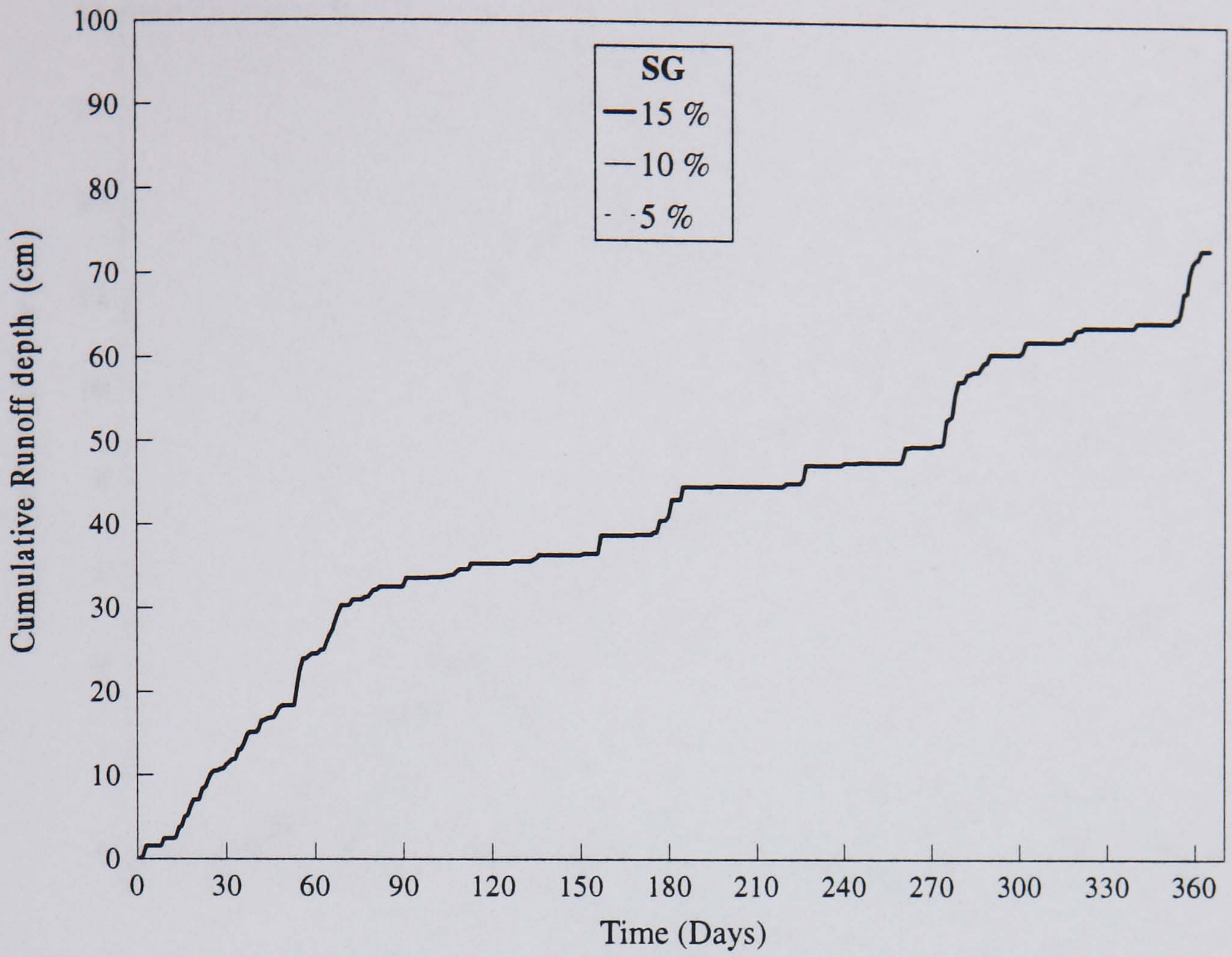


Figure 8.32. Effect of surface gradient on cumulative runoff depth.

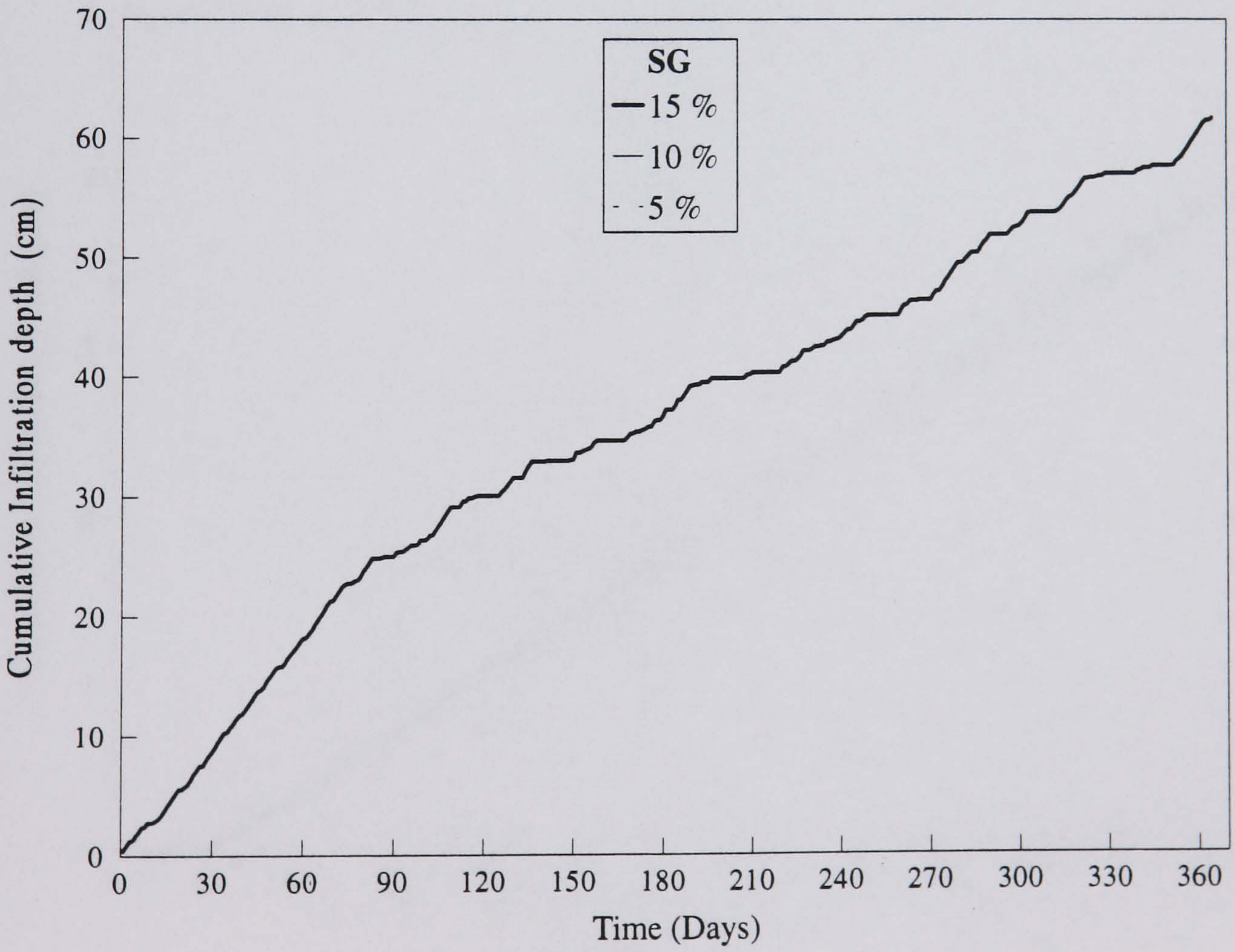


Figure 8.33. Effect of surface gradient on cumulative infiltration depth.

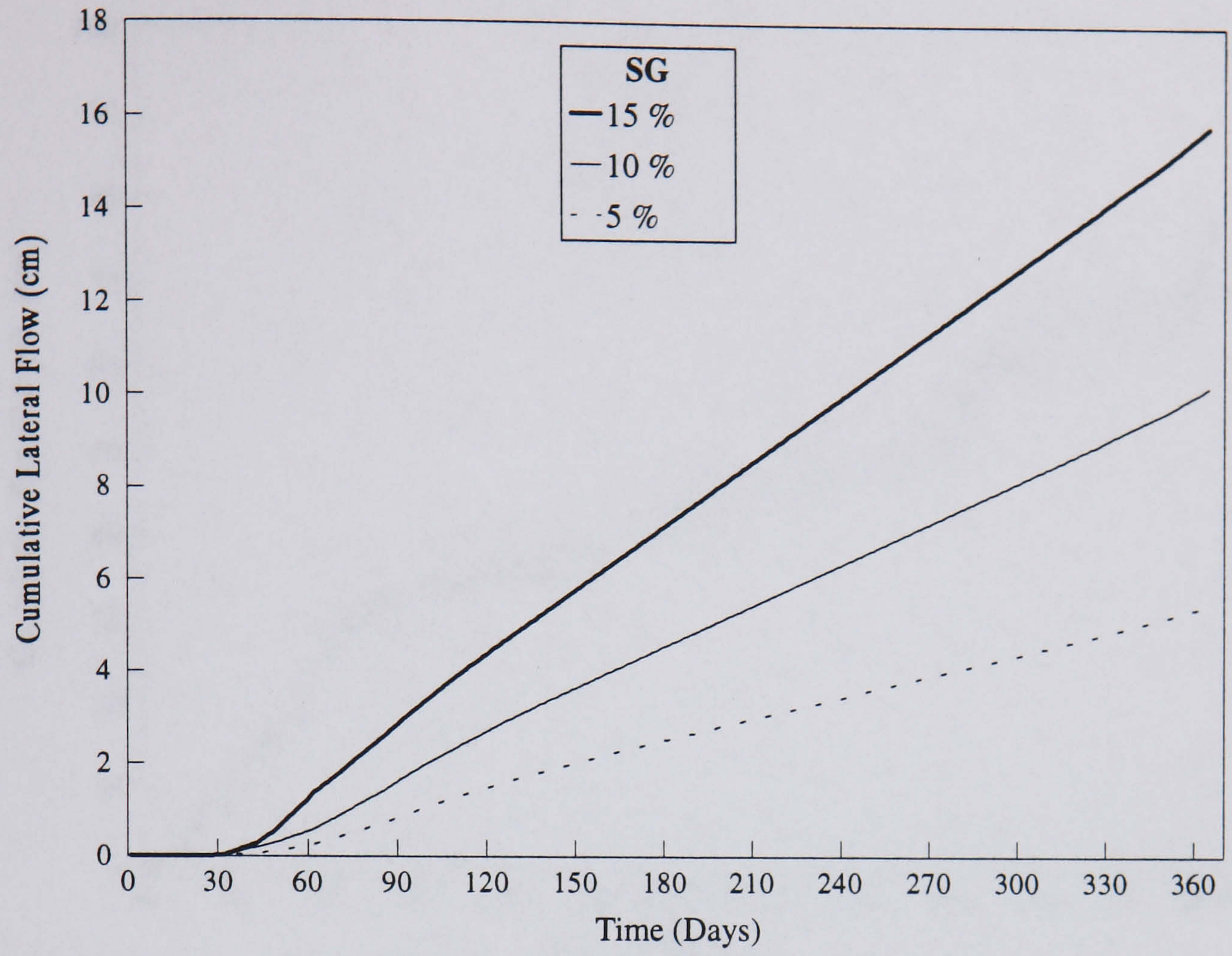


Figure 8.34. Effect of surface gradient on cumulative Lateral Flow depth.

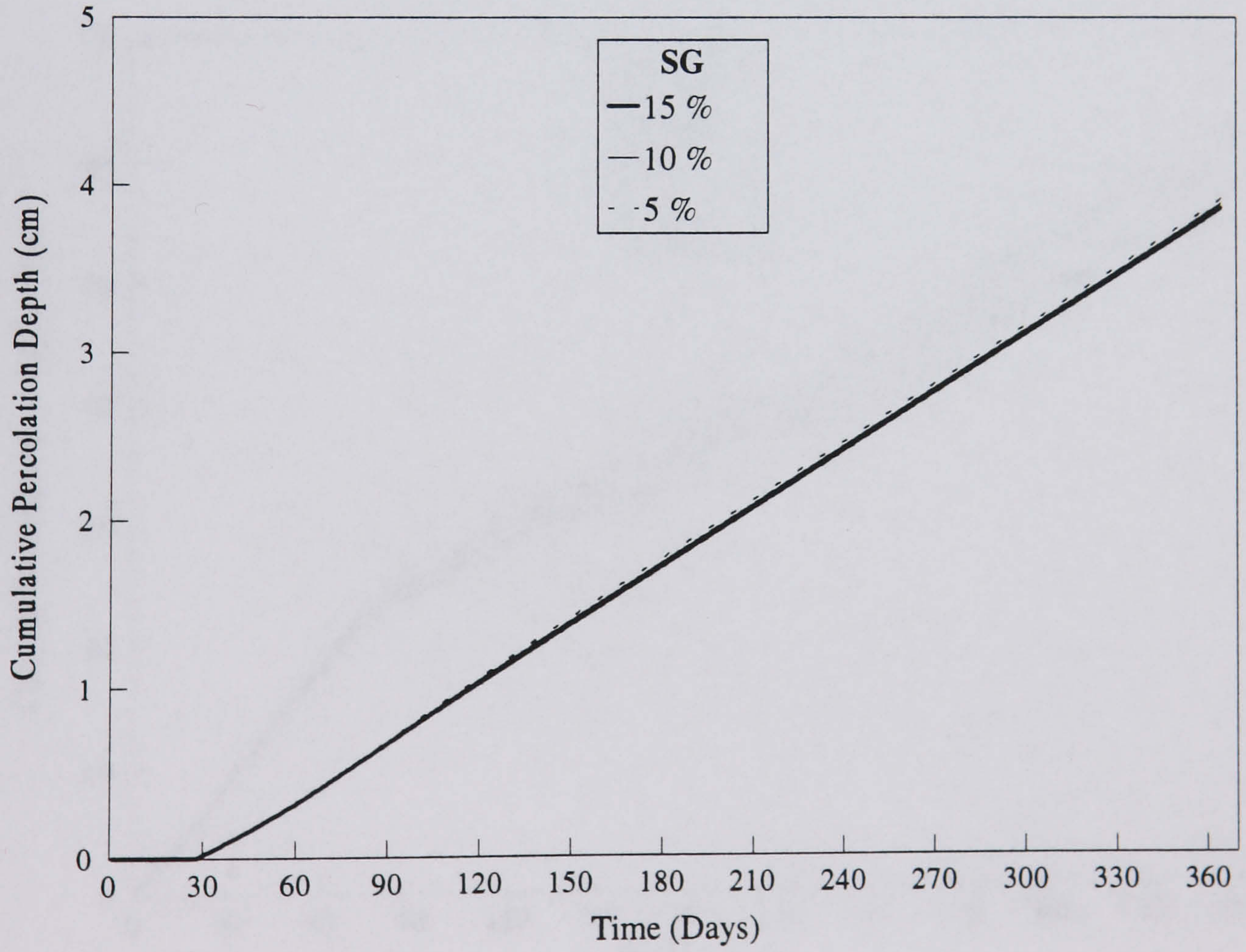


Figure 8.35. Effect of surface gradient on cumulative Percolation depth.

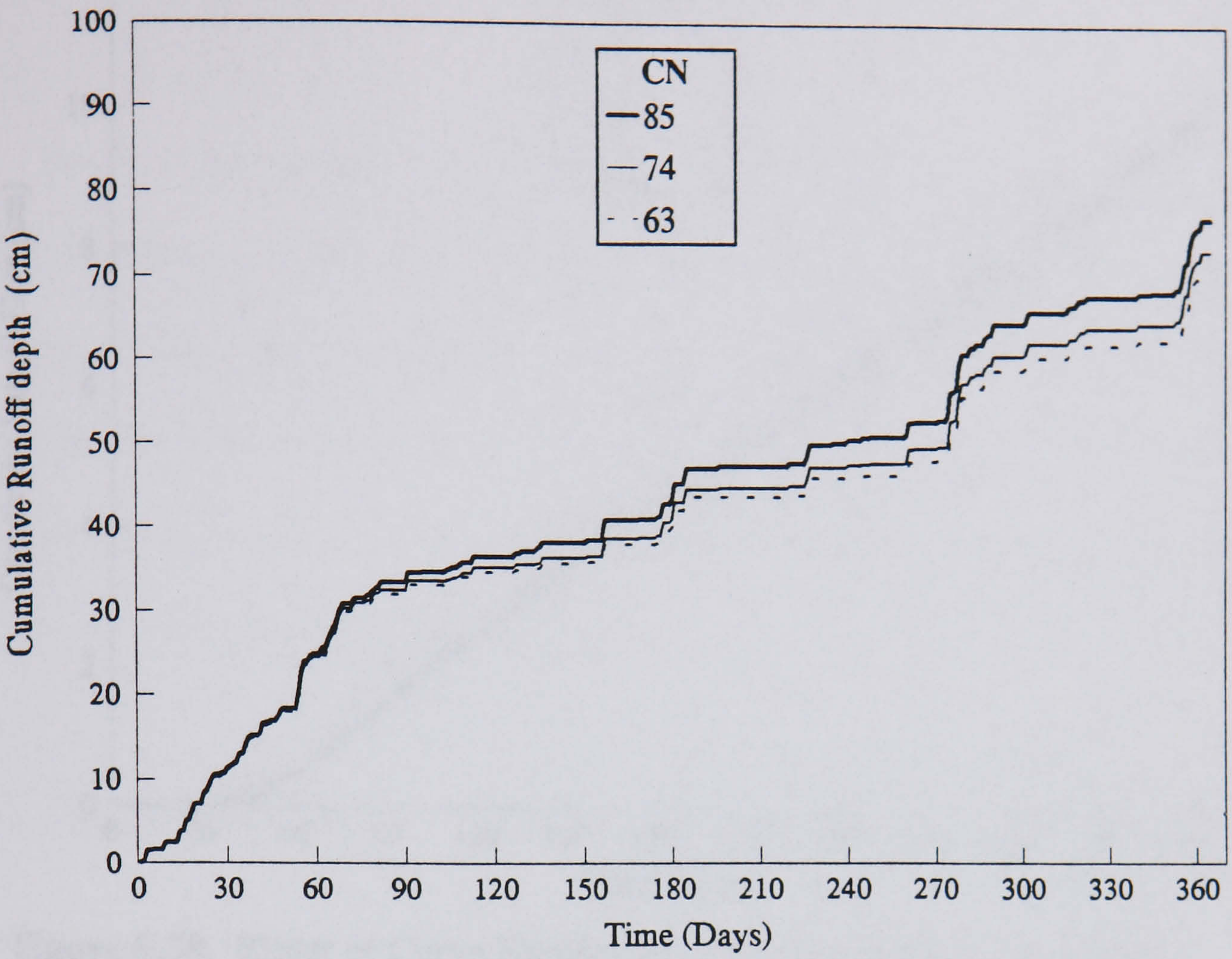


Figure 8.36. Effect of Curve Number on cumulative runoff depth.

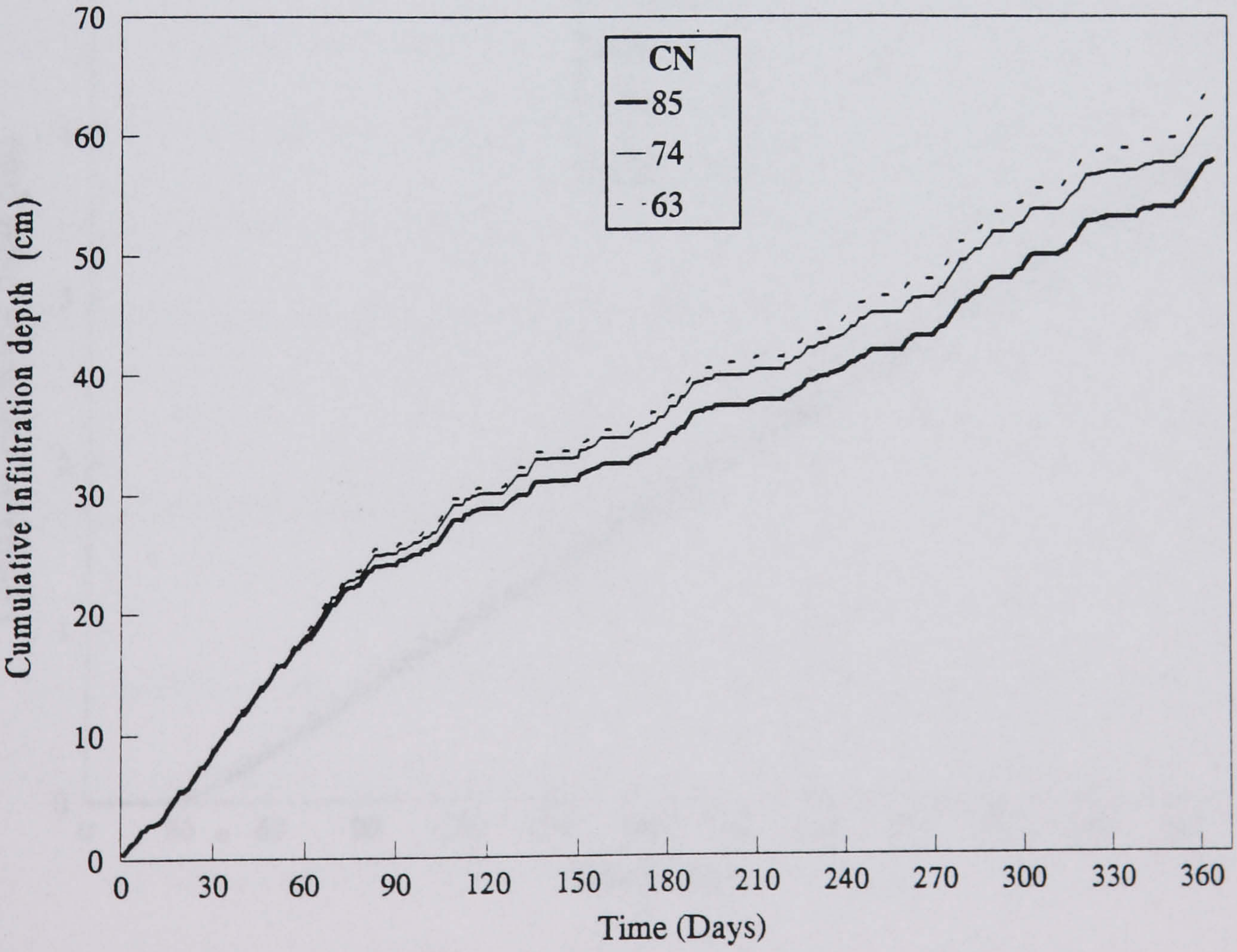


Figure 8.37. Effect of Curve Number on cumulative infiltration depth.

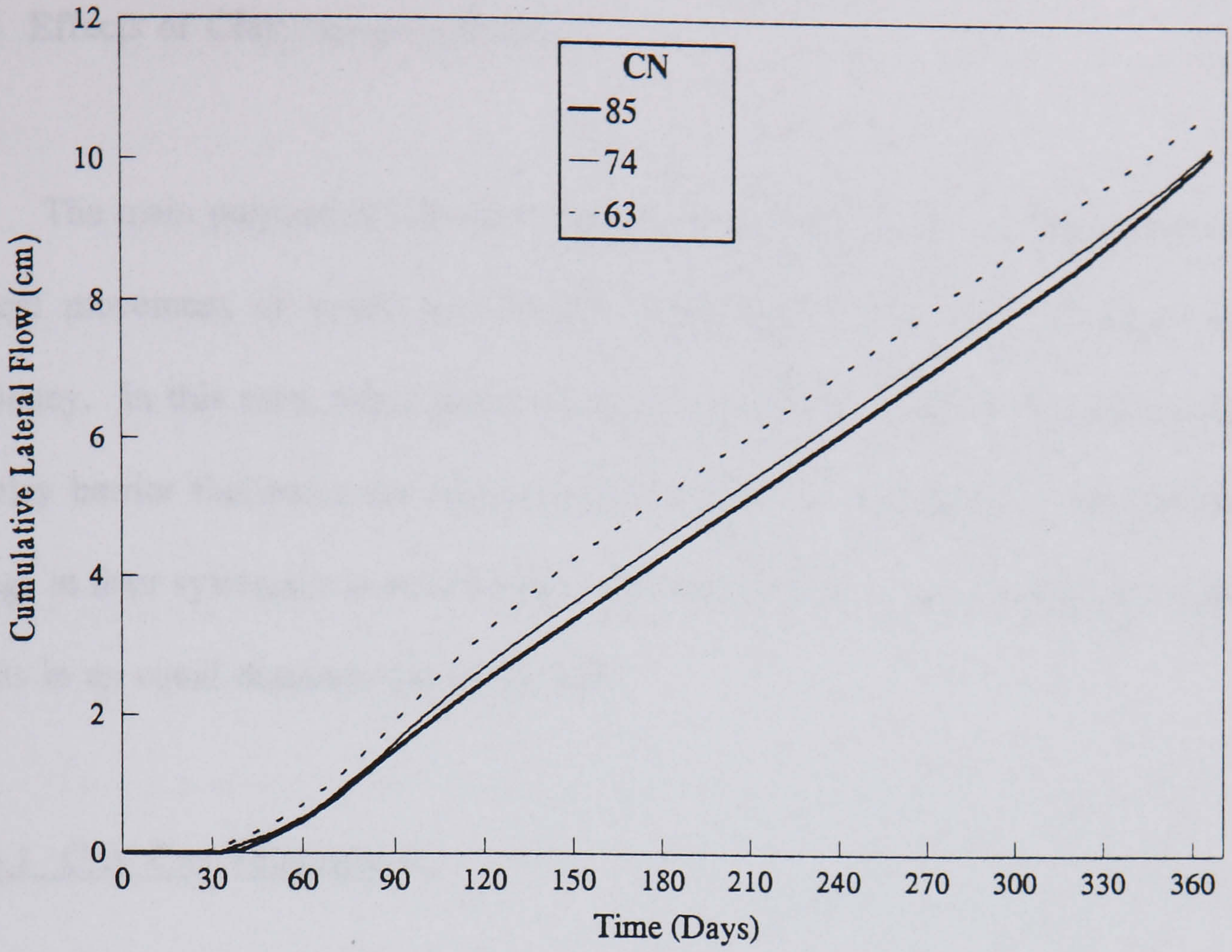


Figure 8.38. Effect of Curve Number on cumulative Lateral Flow depth.

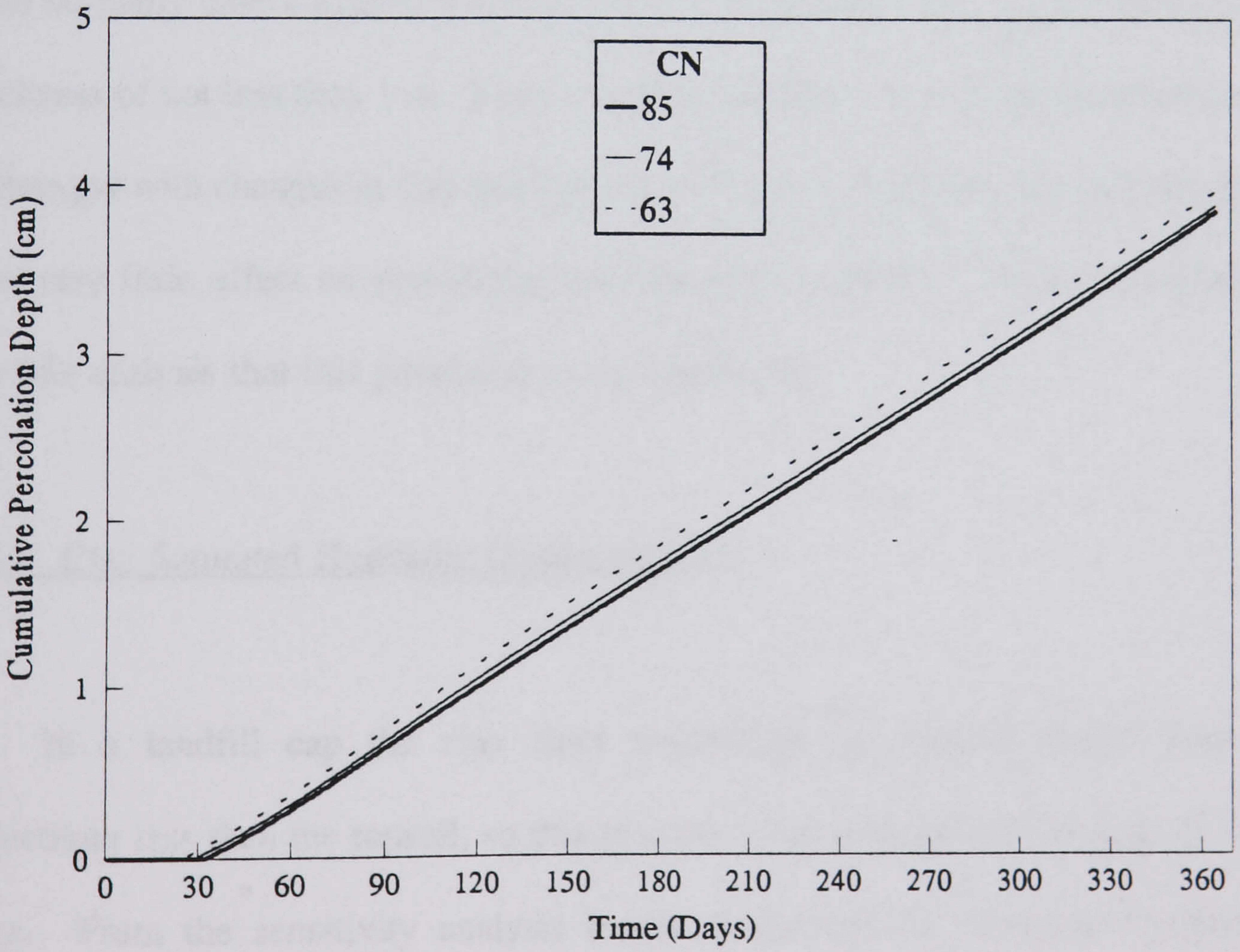


Figure 8.39. Effect of Curve Number on cumulative Percolation depth.

8.1.4 Effects of Clay cap parameters

The main purpose of the liners placed below the topsoil are to minimize the vertical movement of water into landfill depending on the cap's thickness and efficiency. In this case, when lateral drainage is allowed from the soil cover, then the clay barrier facilitates the subsurface flow into the side drains. The moisture storage in liner systems is assumed to be constant; therefore, any drainage into a liner results in an equal drainage out of the liner.

8.1.4.1 Clay Cap Thickness C_D

Capping should incorporate a low permeability layer which, in case of clay, should normally have a hydraulic conductivity of not greater than 1 x 10^{-7} cm/sec and a thickness of not less than 1 m. The cumulative depths of runoff and infiltration do not changed with changes in clay thickness by + 50 and -15 %, as given in Table 8.4. It has very little effect on percolation and lateral flow depths. So it is concluded from this analysis that this parameter is not significant.

8.1.4.2 Clay Saturated Hydraulic Conductivity C_K

In a landfill cap the clay liner underlying the topsoil should have a conductivity less than the topsoil, so this parameter has a significant bearing on cap design. From the sensitivity analysis it was found that the saturated hydraulic conductivity of the liner is the primary control of leakage through a clay liner. It has no effect on cumulative infiltration and runoff, but cumulative depth of lateral drainage varies little with changes in its value under both steady and unsteady inflows. When value of C_K was increased by 10 times, the cumulative percolation was increased by 700% on a yearly basis and the percolation rate decreases when its value was decreased by 10 times as shown graphically in Figure 8.40.

8.1.4.3 Liner Leakage C_L

The clay liners, installed to minimize the infiltration water, may suffer a certain degree of failure to allow water to flow through. This is mainly due to cracking which is partially due to the settlement and overburden pressure. A zero value indicates no leakage at all. An increase in its value has a direct effect on percolation. So a reasonable value depending on the age of the landfill should be assigned to this parameter.

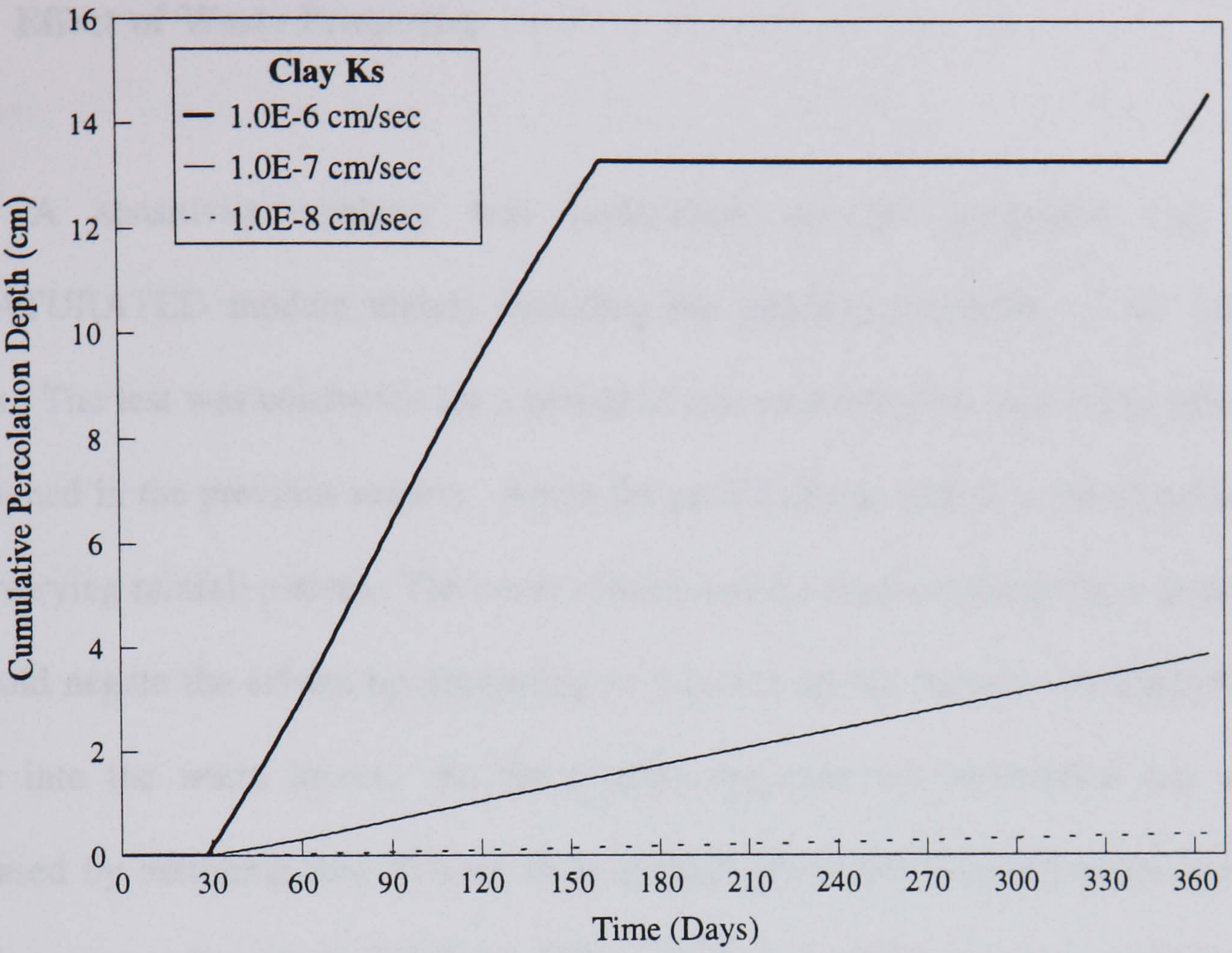


Figure 8.40. Effect of Clay Conductivity on cumulative Percolation depth.

8.1.5 Effect of Waste Properties

A sensitivity analysis was undertaken on the parameters of the UNSATURATED module mainly including the physical properties of the waste layers. The test was conducted for a period of one year using the input data already mentioned in the previous section. Again the period of one year is a good indicator for a varying rainfall pattern. The cover system was not used in this analysis because it would negate the effects by preventing or minimizing the intrusion of infiltration water into the waste layers. So for a quick response the percolation rate was increased by assuming that 27% of daily rainfall percolated into the waste layers, which agrees well with the Dickson (1987) assumption of 1 mm/day percolation.

The basic parameter set is given in Tables 8.1 and 8.2. The input data is based on the results of the experimental models described in Chapter 6. Other design parameters required are either measurable or estimable with varying degrees of accuracy. The results from the basic control run for the period of fifteen months are given in Table 8.5. A total inflow of 32.7 m^3 was infiltrated into the cell with a result of 5.93 m^3 of leachate being produced during the simulation period. The wide discrepancy between the cumulative inflow and leachate discharged is an indication of the amount of inflow which the material has absorbed. The leachate mound starts to build-up from the 11th month and also the leachate starts by the same month. Volumetric moisture levels at the end of each month for different modelling layers are also given in Table 8.5.

The different physical parameters have a direct effect on leachate flow which indicates the influence of these parameters on the model output. In this context, density of the waste material has a significant effect on leachate production and also indirect effect on other physical properties of the waste material. Table 8.6 contains the results of all the sensitivity trials of the NUMMOL model including the variations in leachate levels, cumulative leachate outflow and final average moisture contents of the different modelling layers. This table is referred to during the following discussion for each individual parameter.

Table 8.5. Results of sensitivity control run on the UNSATURATED Module.

Month	Cumulative Percolation (m^3)	Cumulative Leachate (m^3)	Leachate Level (cm)	Layer Moisture Content (vol/vol)			
				1	2	3	4
0	0	0	0	0.25	0.25	0.25	0.25
1	5.0	0	0	0.32	0.25	0.25	0.25
2	10.3	0	0	0.36	0.29	0.25	0.25
3	14.0	0	0	0.35	0.35	0.25	0.25
4	15.9	0	0	0.35	0.36	0.28	0.25
5	17.1	0	0	0.36	0.35	0.29	0.25
6	19.5	0	0	0.37	0.36	0.32	0.25
7	20.7	0	0	0.35	0.35	0.35	0.25
8	22.2	0	0	0.36	0.36	0.36	0.26
9	23.5	0	0	0.36	0.36	0.36	0.28
10	28.1	0	0	0.36	0.36	0.36	0.34
11	29.3	1.20	2.07	0.35	0.35	0.35	0.36
12	32.7	3.79	3.72	0.36	0.36	0.36	0.36
13	32.7	5.57	1.25	0.35	0.35	0.35	0.35
14	32.7	5.81	0.90	0.35	0.35	0.35	0.35
15	32.7	5.93	0.72	0.35	0.35	0.35	0.35

Table 8.6. Results of sensitivity trials on UNSATURATED Module.

Physical Property % variation	Leachate Level (cm)	Cumulative Leachate (m^3)	Final Volumetric Moisture Content
Initial Moisture Content			
40% increase	0.72	20.93	0.34
50% decrease	0	0	0.15
Field Capacity			
20% increase	0	0	0.37
15% decrease	0.86	29.62	0.27
Saturation Capacity			
10% increase	0.85	5.64	0.34
15% decrease	0.36	6.35	0.34
Saturated Conductivity			
50% increase	0.57	6.03	0.34
50% decrease	1.07	5.69	0.34
Dry density			
10% increase	4.70	2.89	0.35
10% decrease	0	6.41	0.34
Modelling layers			
2 layers	1.51	5.84	0.34
6 layers	0.44	5.97	0.34

8.1.5.1 Effect of initial moisture content

The sensitivity of this parameter is very important to model operation in the unsaturated zone since it is very susceptible to an estimation error. Once the waste moisture level reaches field capacity then there is practically no chance that waste will drop to the initial moisture level. Normally its value is assumed near or equal to field capacity. Figure 8.41 shows the variation in leachate level caused by a change in the value of the initial capacity. It is important to note that when this parameter is decreased by 50%, the leachate level has not established over the period of 15 months. As would be expected a lower initial capacity of 50% has led to no leachate flow and a higher initial capacity would lead to increase in leachate flow, as shown in Figure 8.42.

8.1.5.2 Effect of field capacity

If the initial moisture content of waste is less than field capacity, infiltrating water must wet and build up moisture content to the point where downward flow occurs. The moisture content at which free drainage, beginning from saturation and following the saturation curve, just stops, is the field capacity. Channelling will result in a much lower practical field capacity for waste. The variations caused by altering the field capacity by +20 % and -15 % are shown in Figures 8.43 and 8.44 for leachate level and cumulative leachate flow respectively. An increase in its value led to very substantial reduction in leachate levels and leachate volumes, which in this case are observed to be zero over 15 months. A reduction in field capacity has increased effect on leachate levels and leachate flow, while a 25 % decrease occurred in the final moisture content. The leachate flow commenced after one month.

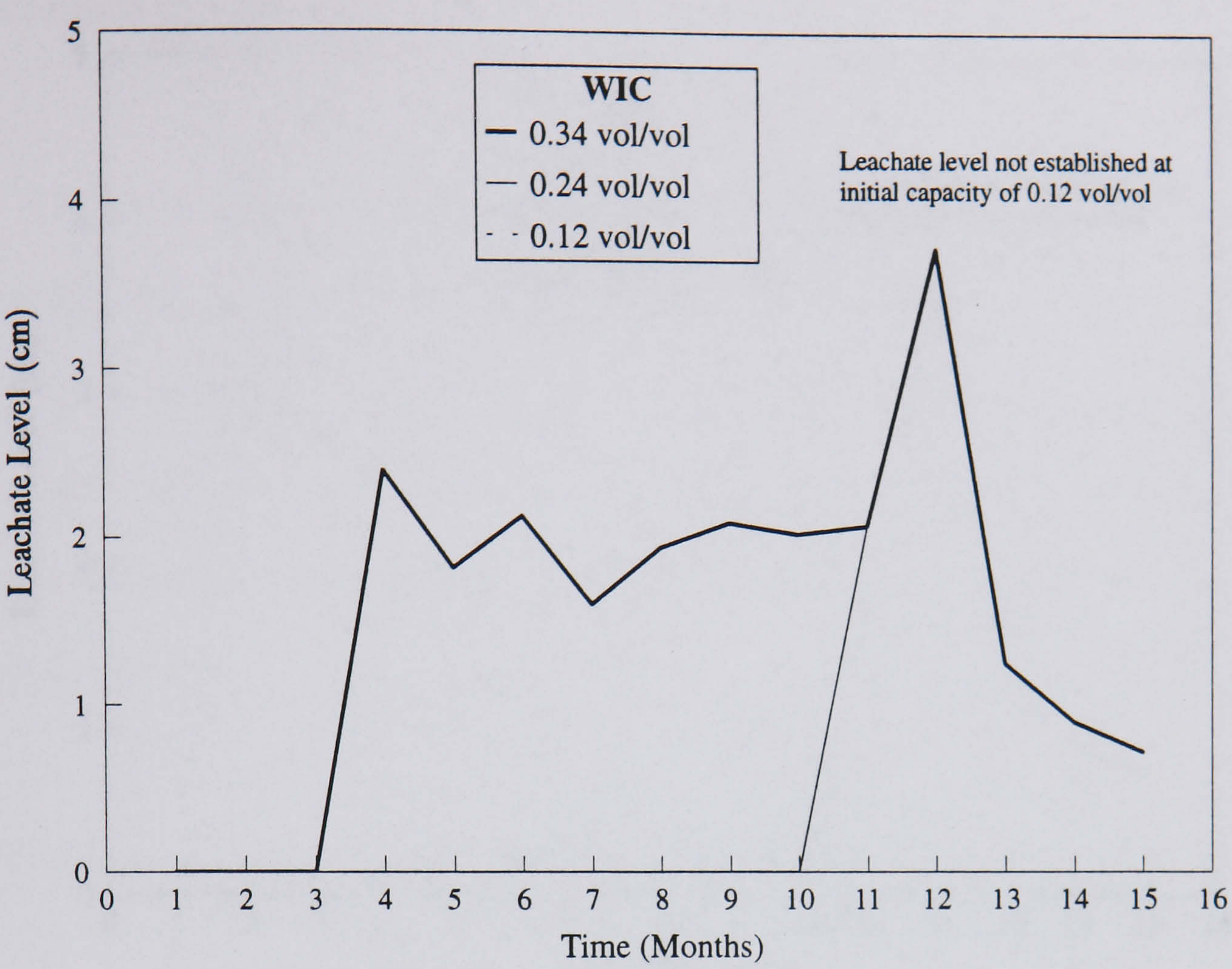


Figure 8.41. Effect of waste initial capacity on leachate level.

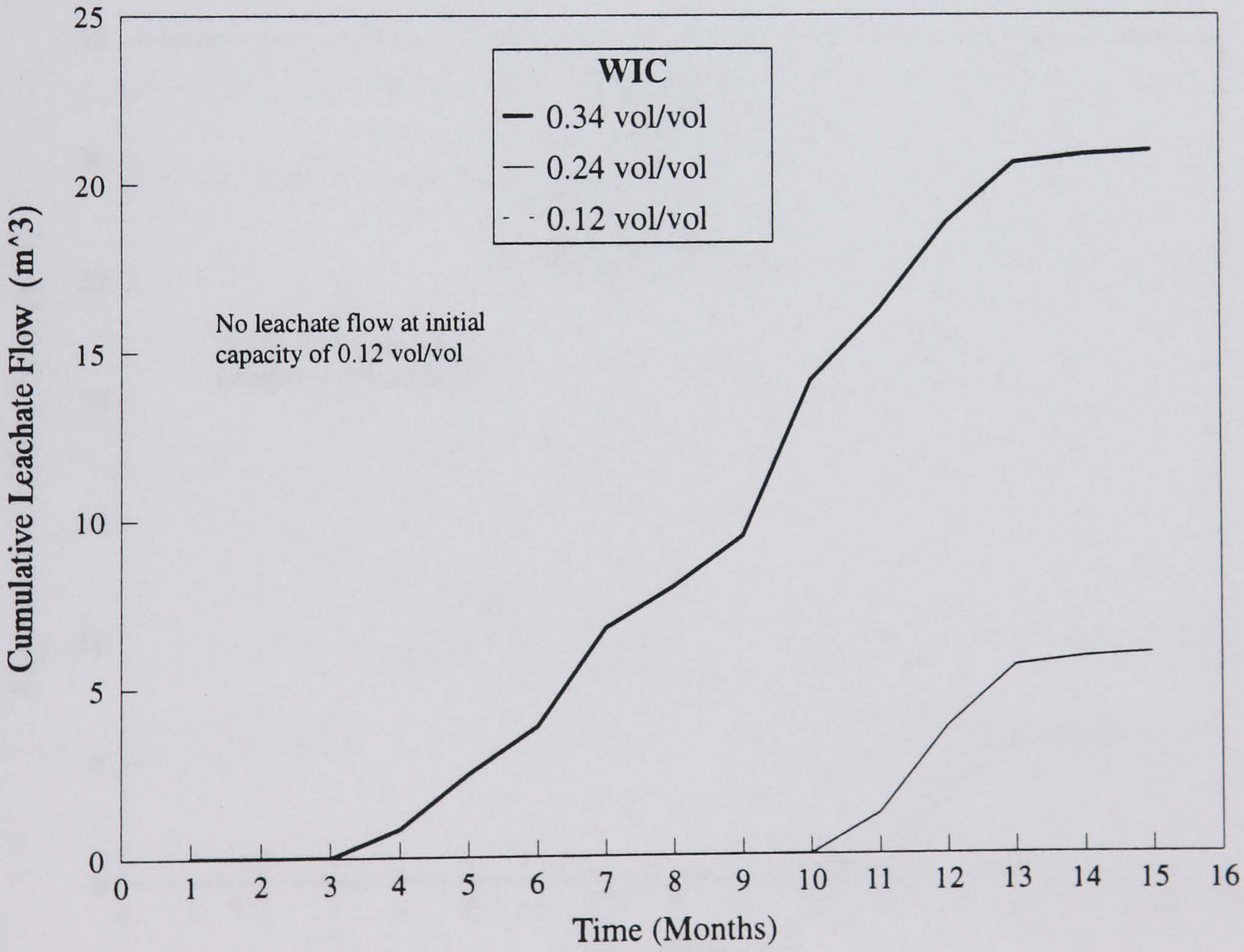


Figure 8.42. Effect of waste initial capacity on cumulative leachate flow.

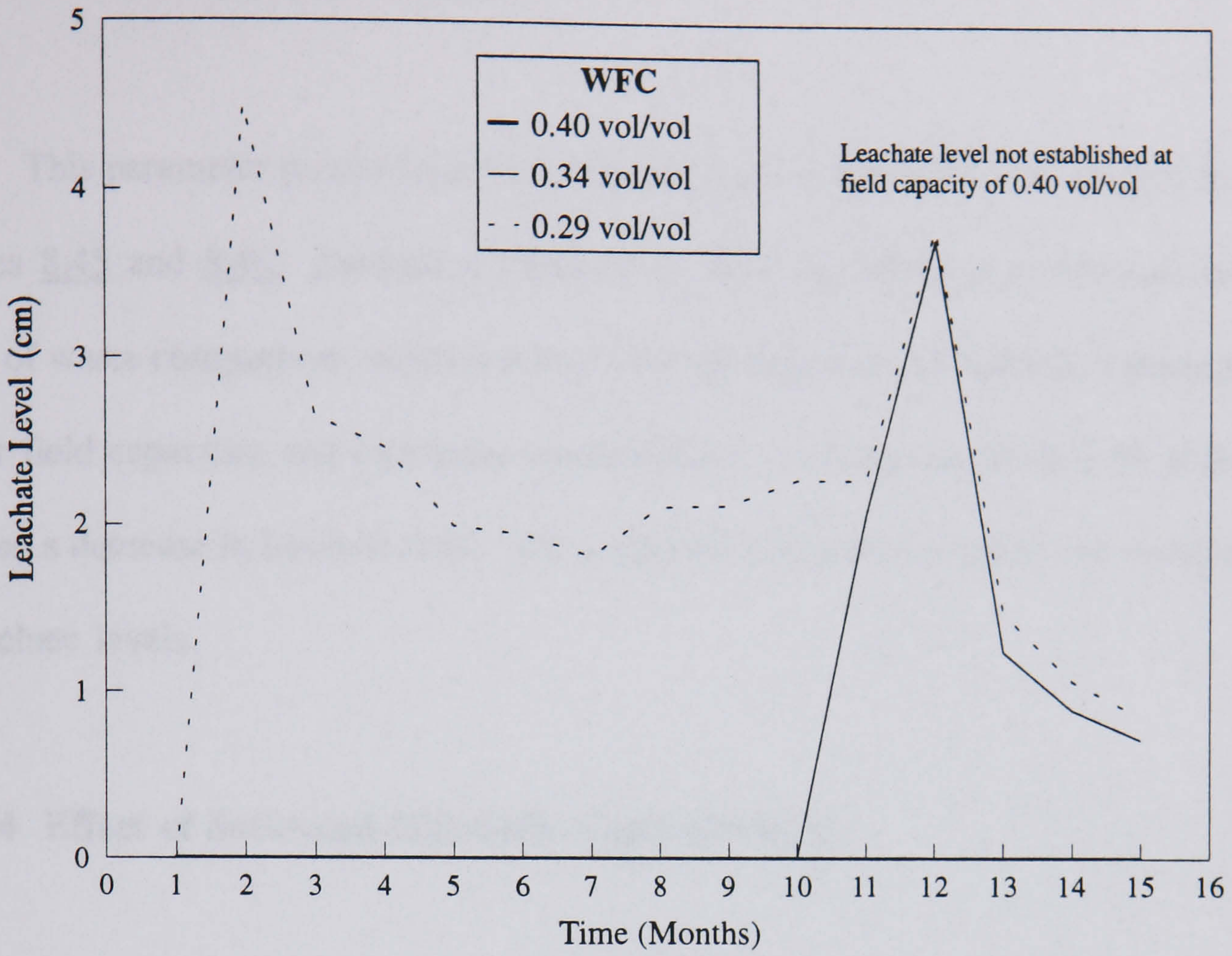


Figure 8.43. Effect of waste field capacity on leachate level.

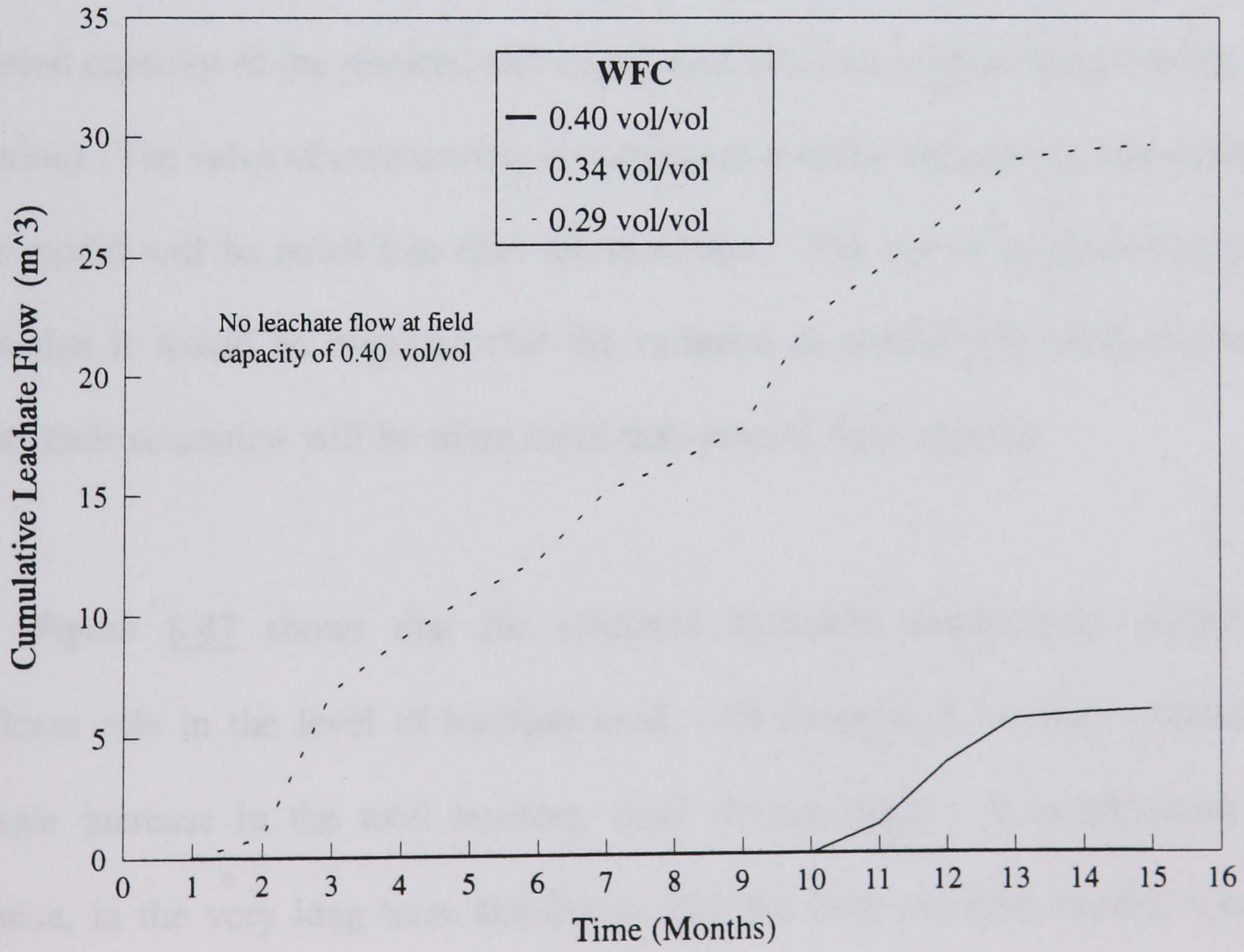


Figure 8.44. Effect of waste field capacity on cumulative leachate flow.

8.1.5.3 Effect of saturation capacity

This parameter proved to be the most sensitive in the trials as is evident from Figures 8.45 and 8.46. Saturation capacity of waste is expected to decrease as a result of waste compaction, settlement and biodegradation in the landfill, resulting in higher field capacities and hydraulic conductivities. An increase from 0.40 to 0.44 resulted a decrease in leachate flow. The same effect was also noted in the variations in leachate levels.

8.1.5.4 Effect of Saturated Hydraulic Conductivity K_s

The saturated hydraulic conductivity of the porous material controls the velocity at which water will pass through it. The velocity mainly depends on saturation capacity of the material and varies with moisture content from 0 to K_s (at saturation). The value of conductivity (unsaturated) actually used during calculations in the model will be much less than the maximum. The use of a power function means that it would be expected that the variation in conductivity with moisture content near saturation will be more rapid than around field capacity.

Figure 8.47 shows that the saturated hydraulic conductivity played a significant role in the level of leachate head. An increase in its value yielded a moderate increase in the total leachate value (Figure 8.48). It is important to recognise, in the very long term simulation, that the final moisture content would become the same regardless of the conductivity assigned.

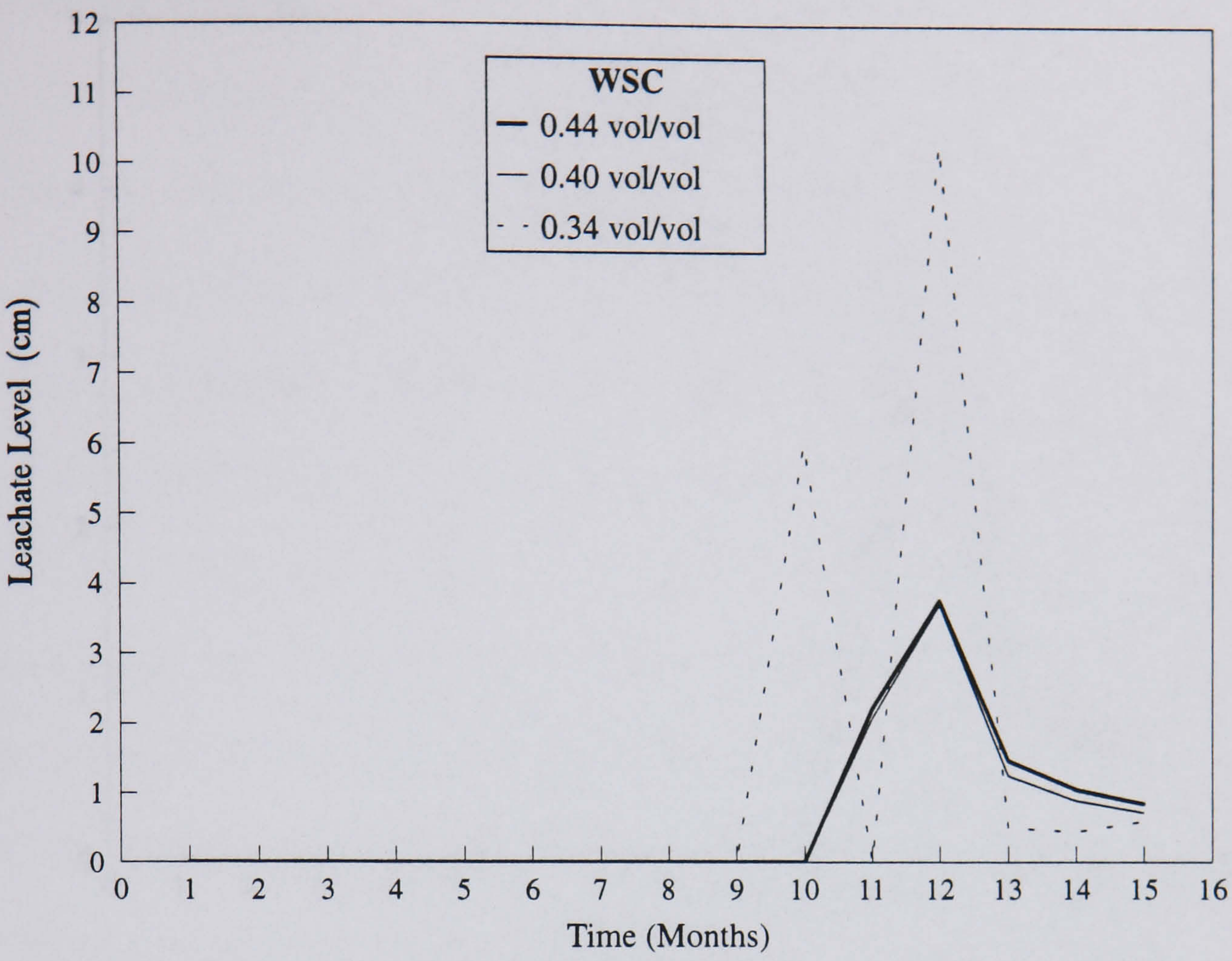


Figure 8.45. Effect of waste saturation capacity on leachate level.

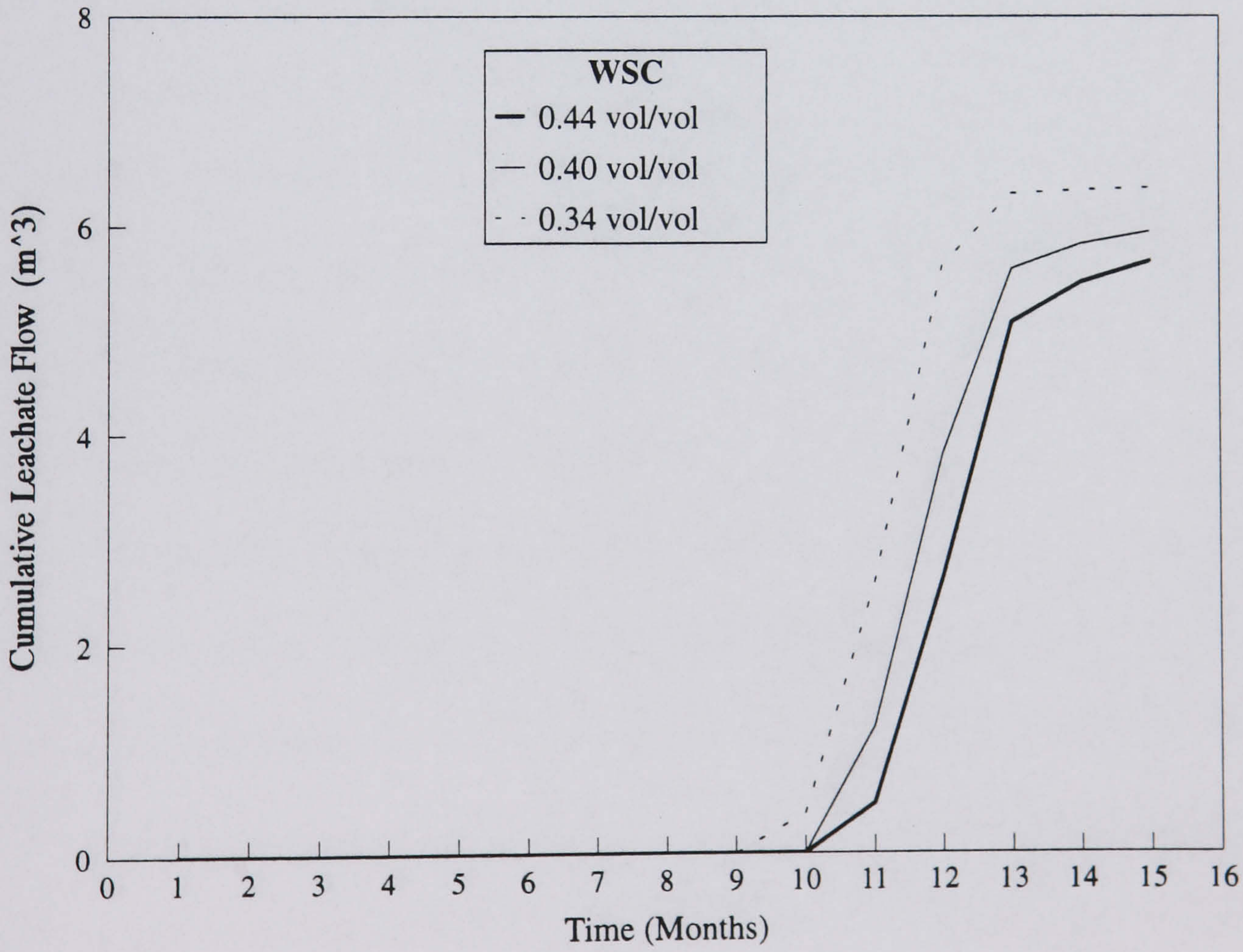


Figure 8.46. Effect of waste saturation capacity on cumulative leachate flow.

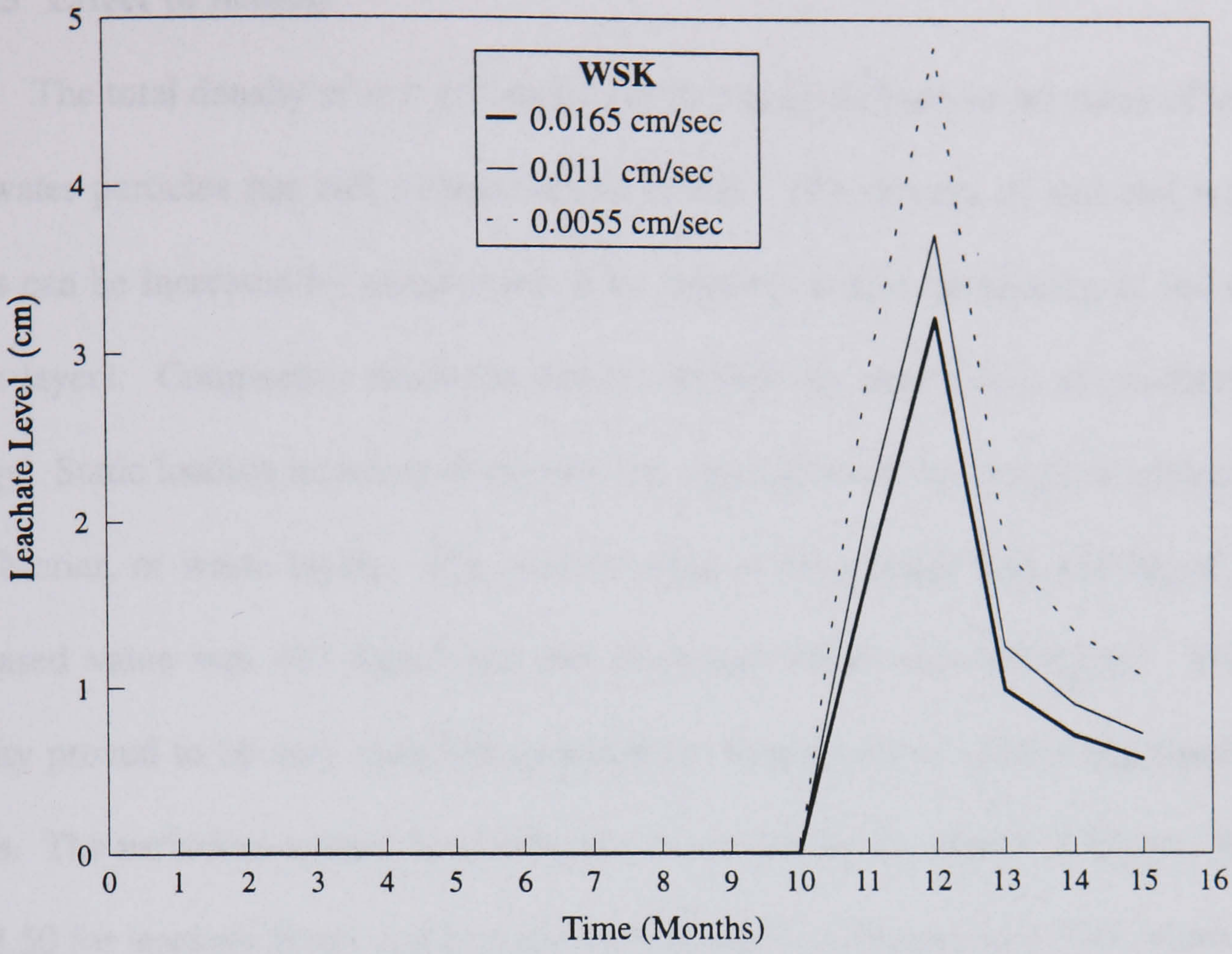


Figure 8.47. Effect of waste saturated conductivity on leachate level.

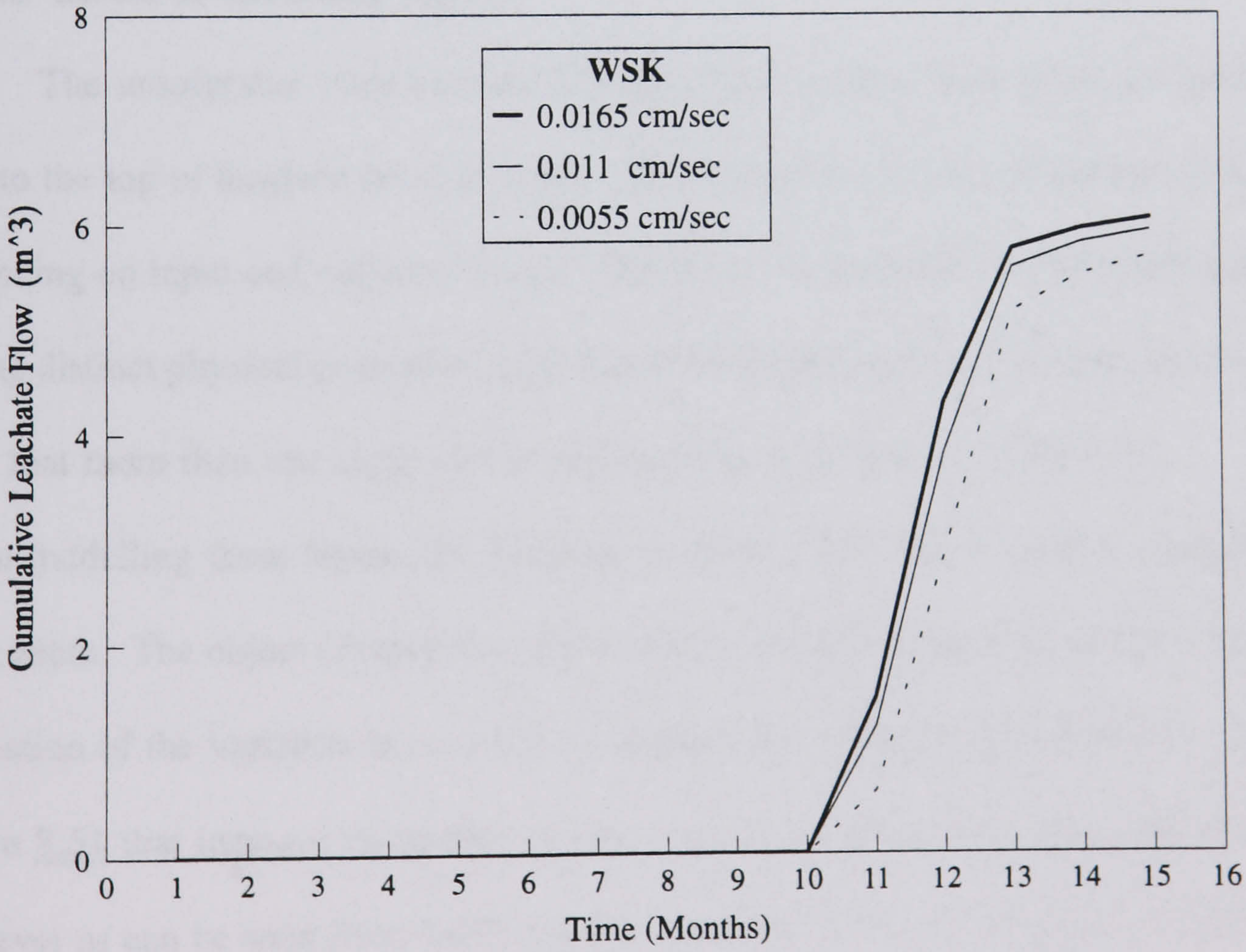


Figure 8.48. Effect of waste saturated conductivity on cumulative leachate flow.

8.1.5.5 Effect of density

The total density of soil and waste layers can be defined as the mass of solid and water particles per unit volume of the media. The density of soil and waste layers can be increased by compaction, static loading, and/or dewatering of soil and waste layers. Compaction increases density through the application of mechanical energy. Static loading increases density by the application of the weight of additional soil, barrier, or waste layers. The control value of dry density was 450 kg/m^3, an increased value was 495 kg/m^3 and the decreased value was 405 kg/m^3. Waste density proved to be very sensitive parameter to both leachate volume and leachate levels. The variations caused by altering the waste density are shown in Figures 8.49 and 8.50 for leachate levels and cumulative leachate flow respectively. The increased value of dry density led to decrease in cumulative leachate flow and vice versa.

8.1.5.6 Effect of modelling layers

The unsaturated zone extends from the land surface (here from the landfill cap) to the top of leachate level in a cell. This distance will vary from time to time depending on input and output of a cell. The lifts in unsaturated and saturated zones having distinct physical properties, which must be determined on a site-specific basis. Note that more than one layer can be assigned the same material properties.

When modelling these layers, the program redefines these layers using a modelling layer depth. The object of modelling the waste in discrete layers is to enable a better evaluation of the variation in moisture throughout the material. It can be seen from Figure 8.51 that increase in number of layers has led to decrease in leachate levels. However as can be seen from Table 8.6 and Figure 8.52 the use of different number of modelling layers has contributed to a slight variation in the total leachate flow.

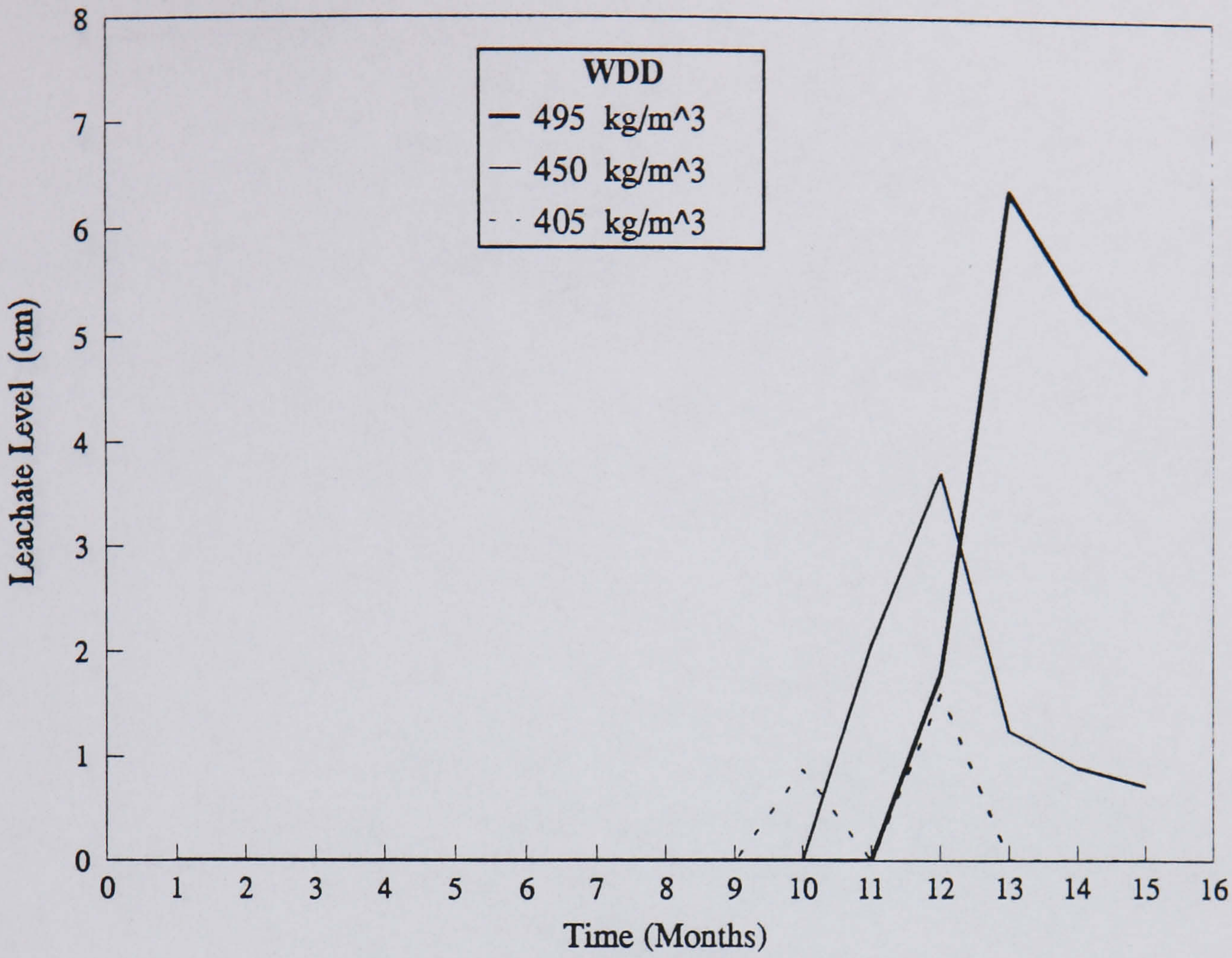


Figure 8.49. Effect of waste dry density on leachate level.

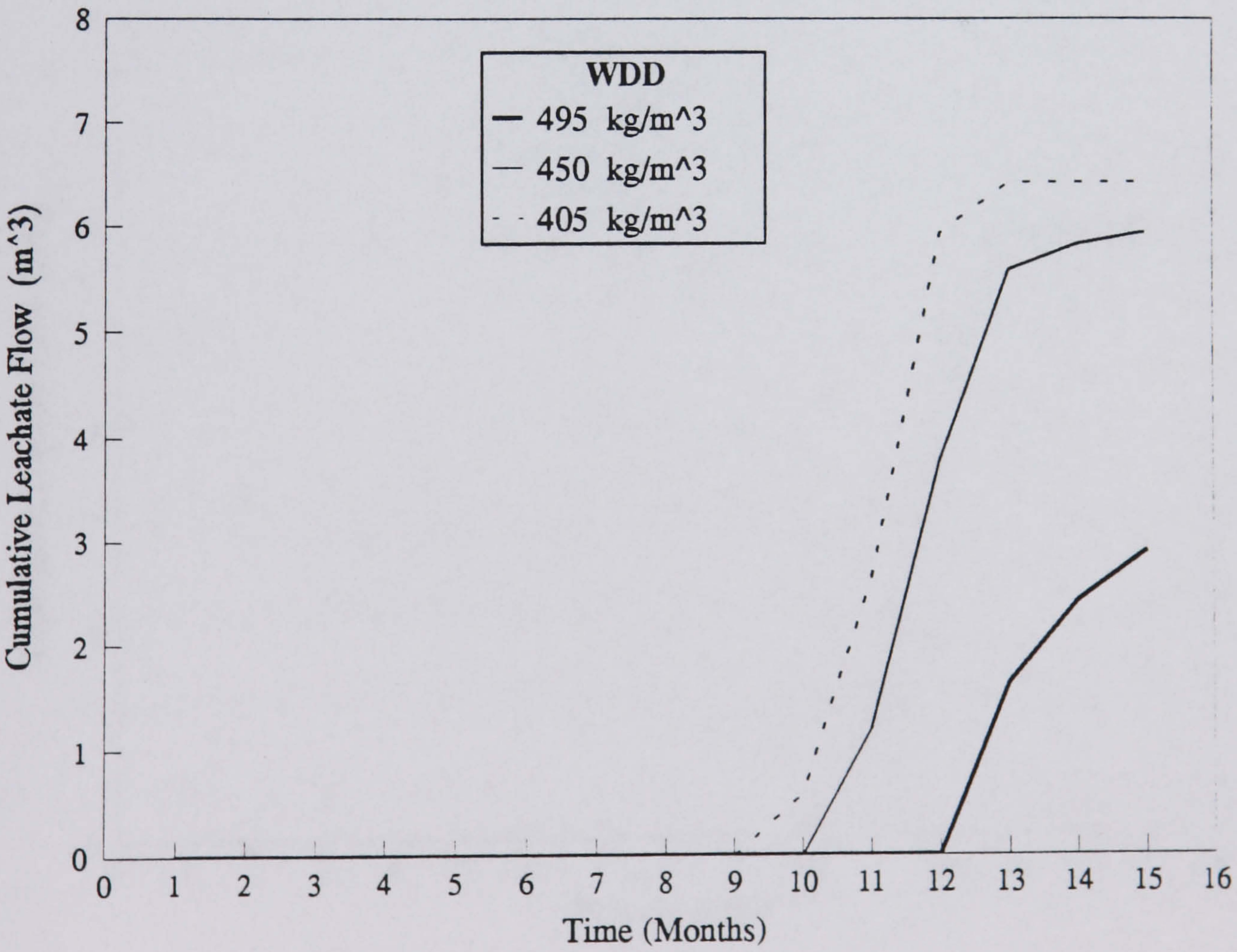


Figure 8.50. Effect of waste dry density on cumulative leachate flow.

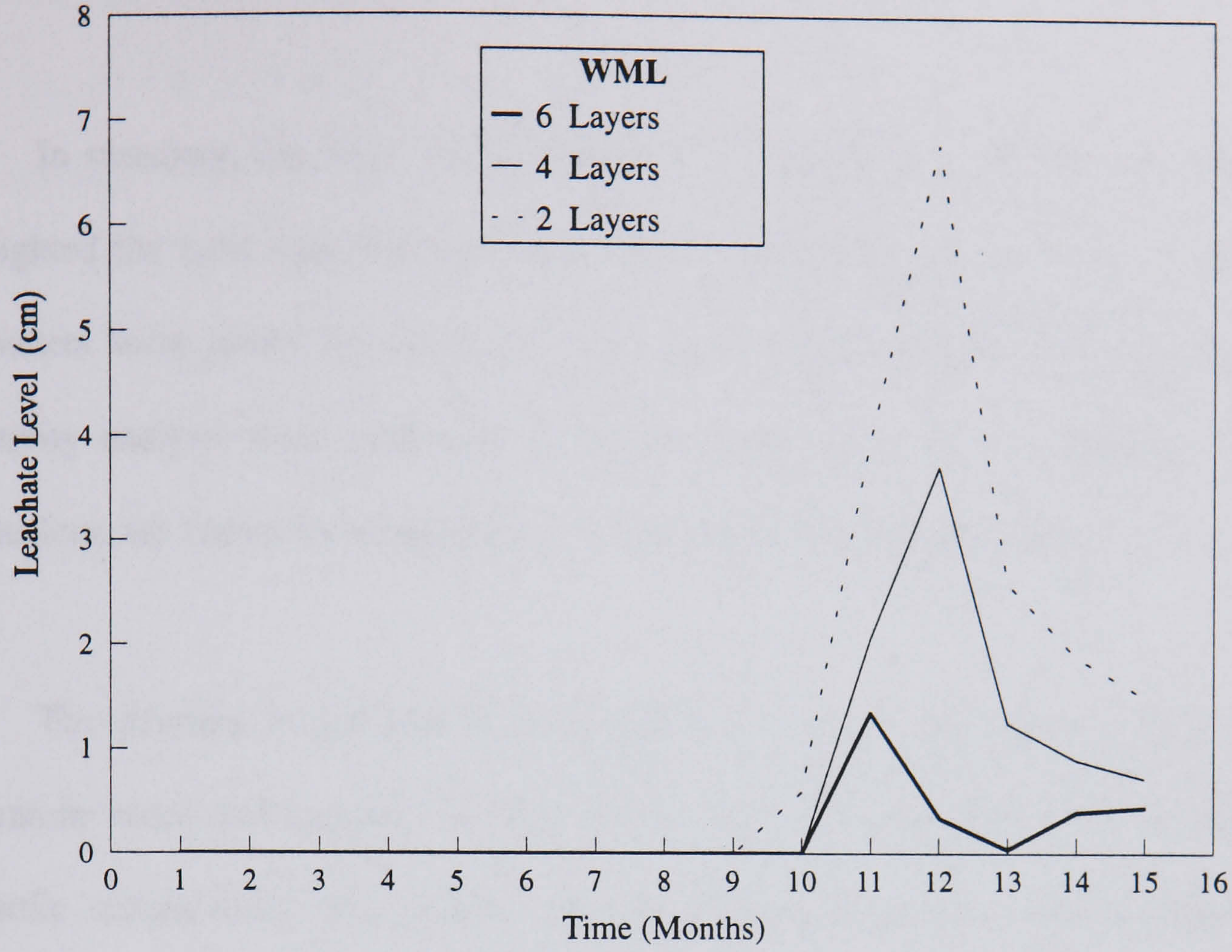


Figure 8.51. Effect of waste modelling layers on leachate level.

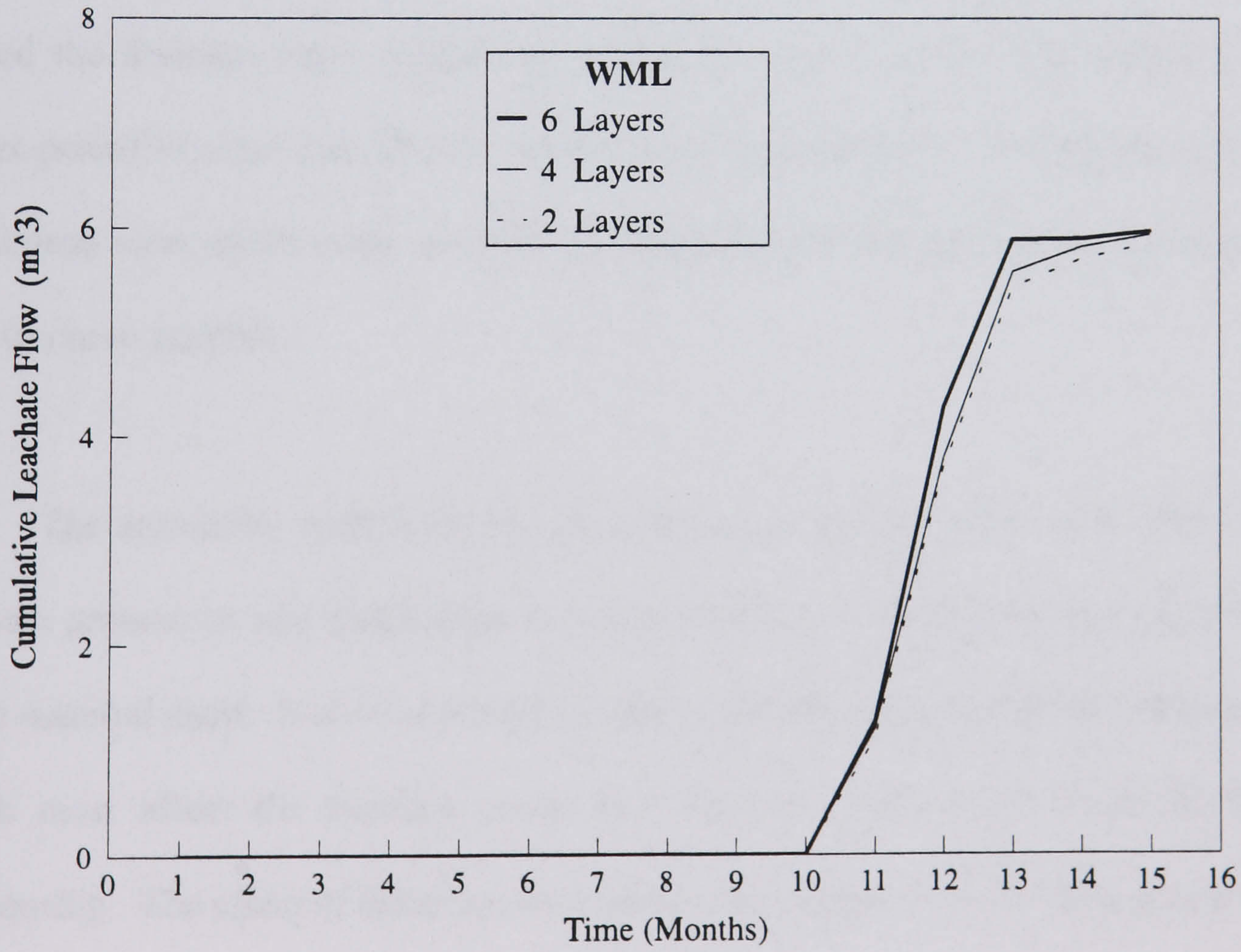


Figure 8.52. Effect of waste modelling layers on cumulative leachate flow.

8.1.6 Conclusions

In summary, the daily sensitivity trials have proved very useful. They have highlighted the most sensitive parameters under control conditions. Various input parameters were tested for soil cover, liner and waste materials. The results of sensitivity analysis were presented in tabular form and as well in graphs. The conclusions are drawn by comparing with the results from control runs.

The primary importance of the topsoil cover is to provide a storage for infiltration water and presence of liner allows it to drain laterally. The saturated hydraulic conductivity (K_s) of the soil has been confirmed, under unsaturated conditions, as the most sensitive of the input parameters; with a marked effect on runoff, infiltration and percolation. The lower hydraulic conductivity of the clay soil slowed the drainage rate, maintaining moisture contents above field capacity for longer period of time and allowing greater evapotranspiration. The runoff volume predictions were much more sensitive to evapotranspiration and soil characteristics than to curve number.

The sensitivity trials have shown that the parameters which most affect the leachate production and distribution in waste materials were the physical properties of the material itself. It is concluded from this sensitivity analysis that the parameters which most affect the leachate production were the ones which form the K-θ relationship. The effect of density contributes to the variations to all waste properties and hence has a marked influence on the model outputs. The saturated hydraulic conductivity of waste material has been proved under unsaturated conditions to be the most sensitive of the input parameters; with a marked effect on total leachate flow and leachate levels.

8.2 Case Study

To assess the predictive ability of the NUMMOL model, it was applied to the experimental landfill cells. The new planned landfill experimental sites at Mid Auchencarroch are situated on a piece of open upland moor, facing south west across the Vale of Leven (Wingfield-Hayes, 1994). The geometrical description of the experimental cells is given in Table 8.7.

Two different scenarios are considered by comparing the production and distribution of leachate within cells. In scenario one, a cell of 5 m depth is to be filled with a pulverized waste matrix with no intermediate soil layers, while in scenario two, a cell is to be filled with four waste layers with intermediate soil layers. The physical properties of materials used in cells are given in Table 8.8.

There was no measurement of precipitation on site, therefore Gartlea Farm data was used. The annual precipitation at Gartlea from August 1993 to July 1994 was 1312 mm. This compares very closely with the long term average annual precipitation at Killearn which is 1270 mm. The precipitation data for Gartlea for the 12 month period mentioned is shown in Figure 8.53, with evapotranspiration data (495 mm per annum). With the objective of reaching the critical moisture levels quickly, rather than trying to simulate real cap percolation conditions, high quantities of water were used for percolation in the simulation. A value of 1 mm/day was chosen to be used for percolation into a cell.

Table 8.7. Model Parameters for Experimental Cells.

Parameters	Scenario 1	Scenario 2
Landfill Data :		
Number of cells	1	1
Cell depth [m]	6.7	6.7
Top area of cell [m^2]	840	840
Bottom area of cell [m^2]	840	840
Leachate level in cell [m]	0	0
Soil Cover Data :		
Soil type	Loam	Loam
SCS Curve Number	74	74
Soil cover thickness [m]	0.5	0.5
Cover Lateral Drainage :		
Surface slope [ratio]	0.025	0.025
Drainage length [m]	30	30
Barrier soil :		
Clay cap thickness [m]	1.2	1.2
Sat. con. of clay cap [cm/sec]	10^{-7}	10^{-7}
Waste Material Data:		
Number of waste layers	4	1
Thickness of waste layers [m]	1.1	5
Density of waste layers [kg/m^3]	450	450
Thickness of soil layer [m]	0.15	-

Table 8.8. Physical Properties of Experimental Cell Materials.

Material	Physical Property				
	θ_w vol/vol	θ_f vol/vol	θ_s vol/vol	θ_i vol/vol	K_s cm/sec
Soil	0.116	0.232	0.464	0.200	3.7×10^{-4}
Waste	-	0.340	0.400	0.240	1.1×10^{-2}
Liner	-	-	0.480	0.480	2.3×10^{-7}

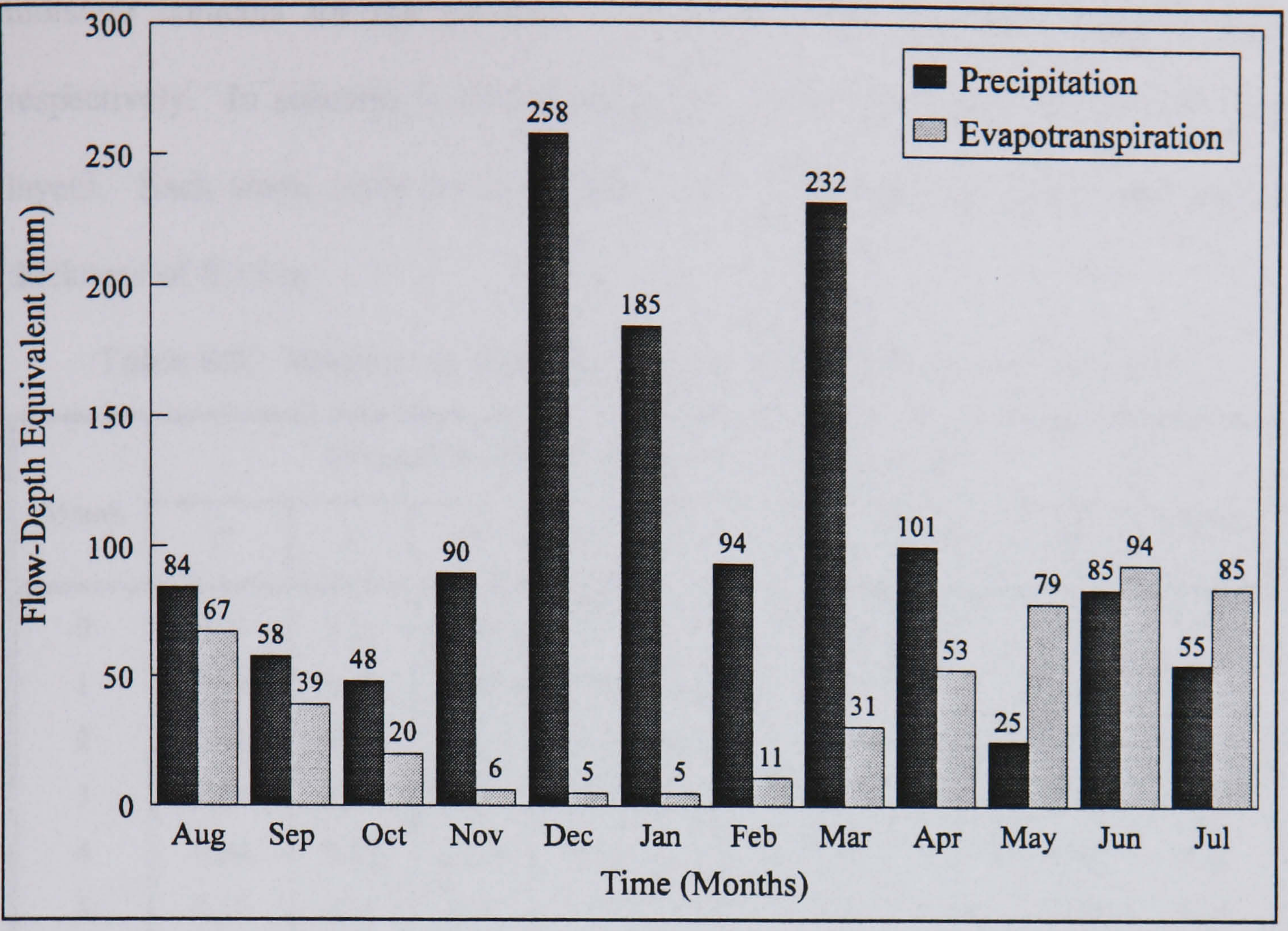


Figure 8.53. Monthly Precipitation and Evapotranspiration Data at Gartlea, 1993-94.

It is assumed that no seepage is occurring from the cell boundary and no leachate discharged from the cell bottom. A 3 mm quantity of leachate was recirculated from the bottom of a cell into the top waste layer on weekly basis. This was mainly done in order to distribute moisture evenly within cell and to accelerate the process of degradation. However, the program first checks the amount of leachate produced at the bottom of landfill, and then deduced the amount of leachate to be recirculated.

The NUMMOL model was run for the two different scenarios for a period of two years. The output results of the model including the final moisture contents of the different layers and leachate levels are compared. The monthly variation of moisture contents for the scenario 1 & 2 are given in Tables 8.9 and 8.10, respectively. In scenario 1, modelling layers consists of four waste and four soil layers. Each waste layer has a thickness of 1.1 m, while the soil layers have a thickness of 0.15 m.

Table 8.9. Monthly moisture contents in different layers of scenario 1.

Month	Volumetric moisture contents in modelling layers								Average
	1^w	2^s	3^w	4^s	5^w	6^s	7^w	8^s	
0	0.24	0.22	0.24	0.20	0.24	0.20	0.24	0.20	0.22
1	0.29	0.20	0.24	0.20	0.24	0.20	0.24	0.20	0.23
2	0.31	0.20	0.24	0.20	0.24	0.20	0.24	0.20	0.23
3	0.34	0.27	0.25	0.20	0.24	0.20	0.24	0.20	0.24
4	0.34	0.26	0.28	0.20	0.24	0.20	0.24	0.20	0.25
5	0.34	0.24	0.29	0.20	0.24	0.20	0.24	0.20	0.24
6	0.34	0.25	0.31	0.20	0.24	0.20	0.24	0.20	0.25
7	0.34	0.25	0.32	0.20	0.24	0.20	0.24	0.20	0.25
8	0.34	0.25	0.34	0.22	0.24	0.20	0.24	0.20	0.25
9	0.34	0.25	0.34	0.23	0.25	0.20	0.24	0.20	0.26
10	0.34	0.25	0.34	0.25	0.26	0.20	0.24	0.20	0.26
11	0.35	0.25	0.34	0.25	0.28	0.20	0.24	0.20	0.26
12	0.35	0.26	0.35	0.28	0.33	0.20	0.24	0.20	0.28
13	0.34	0.27	0.34	0.24	0.35	0.23	0.28	0.20	0.28
14	0.35	0.27	0.34	0.25	0.34	0.25	0.30	0.20	0.29
15	0.34	0.27	0.34	0.23	0.34	0.23	0.34	0.37	0.31
16	0.34	0.26	0.34	0.26	0.34	0.26	0.35	0.46	0.33
17	0.34	0.24	0.34	0.25	0.34	0.25	0.36	0.46	0.32
18	0.34	0.25	0.34	0.26	0.34	0.27	0.38	0.46	0.33
19	0.34	0.25	0.34	0.26	0.34	0.26	0.39	0.46	0.33
20	0.34	0.25	0.34	0.25	0.34	0.35	0.40	0.46	0.34
21	0.34	0.25	0.34	0.23	0.34	0.46	0.40	0.46	0.35
22	0.34	0.25	0.34	0.25	0.35	0.46	0.40	0.46	0.36
23	0.35	0.25	0.34	0.25	0.37	0.46	0.40	0.46	0.36
24	0.35	0.26	0.35	0.45	0.40	0.46	0.40	0.46	0.39

^{w} waste layer ^{s} soil layer

Table 8.10. Monthly moisture contents in different layers of scenario 2.

Month	Volumetric moisture contents in modelling layers				Average
	1	2	3	4	
0	0.24	0.24	0.24	0.24	0.24
1	0.28	0.24	0.24	0.24	0.25
2	0.30	0.24	0.24	0.24	0.26
3	0.34	0.25	0.24	0.24	0.27
4	0.34	0.27	0.24	0.24	0.27
5	0.34	0.28	0.24	0.24	0.27
6	0.34	0.30	0.24	0.24	0.28
7	0.34	0.31	0.24	0.24	0.28
8	0.34	0.33	0.24	0.24	0.29
9	0.34	0.34	0.24	0.24	0.29
10	0.34	0.34	0.25	0.24	0.29
11	0.35	0.34	0.26	0.24	0.30
12	0.34	0.34	0.32	0.24	0.31
13	0.34	0.34	0.34	0.26	0.32
14	0.35	0.34	0.34	0.28	0.33
15	0.34	0.34	0.34	0.33	0.34
16	0.34	0.34	0.34	0.35	0.34
17	0.34	0.34	0.34	0.36	0.35
18	0.34	0.34	0.34	0.38	0.35
19	0.34	0.34	0.34	0.39	0.35
20	0.34	0.34	0.35	0.40	0.36
21	0.34	0.34	0.36	0.40	0.36
22	0.34	0.34	0.37	0.40	0.36
23	0.35	0.34	0.39	0.40	0.37
24	0.34	0.38	0.40	0.40	0.38

The results obtained from the model's simulation are compared with the results/predictions using a mass balance approach to check the model accuracy. The depth of water which infiltrates in two years time is equal to 72.8 cm. As it is already mentioned that there is no leakage of leachate from the boundaries of cell, so the change in moisture content after two years will be equal to the input of water that is infiltrated. From Table 8.11, the amount of water stored in a cell is equal to 70.75 cm. An error of 2.05 cm depth of water in two years is a result from rounding errors and an increase in number of modelling layers.

Table 8.11. Calculation Sheet for leachate distribution in scenario 1.

Layer # - Type	Initial θ vol/vol	Final θ vol/vol	Δθ vol/vol	Depth of water cm
1 - waste	0.24	0.34	0.10	11.0
2 - soil	0.20	0.26	0.06	0.9
3 - waste	0.24	0.35	0.11	12.1
4 - soil	0.20	0.45	0.25	3.75
5 - waste	0.24	0.40	0.24	17.6
6 - soil	0.20	0.46	0.26	3.9
7 - waste	0.24	0.40	0.16	17.6
8 - soil	0.20	0.46	0.26	3.9
Total				70.75

In the case of scenario 2, the change in moisture content is 0.142 vol/vol after two years, which is equivalent to 71 cm depth of water. So the difference between total infiltration and amount of water stored in a cell is 1.8 cm, which is less than the previous case. This is because the number of modelling layers is less and equal to four. However, it is not a significant in respect of cumulative leachate volume. It is concluded that by increasing the number of modelling layers, the rounding error becomes more.

The monthly leachate levels are shown in Figure 8.54, indicating that leachate levels in both cells have established after 10 month. In scenario 1, the soil layers provide a barrier to reduce the water flow rate. In scenario 2, the material used is only waste, so the movement of leachate has a uniform pattern. Also the leachate mound will be high in this case, because no intermediate soil layers are present.

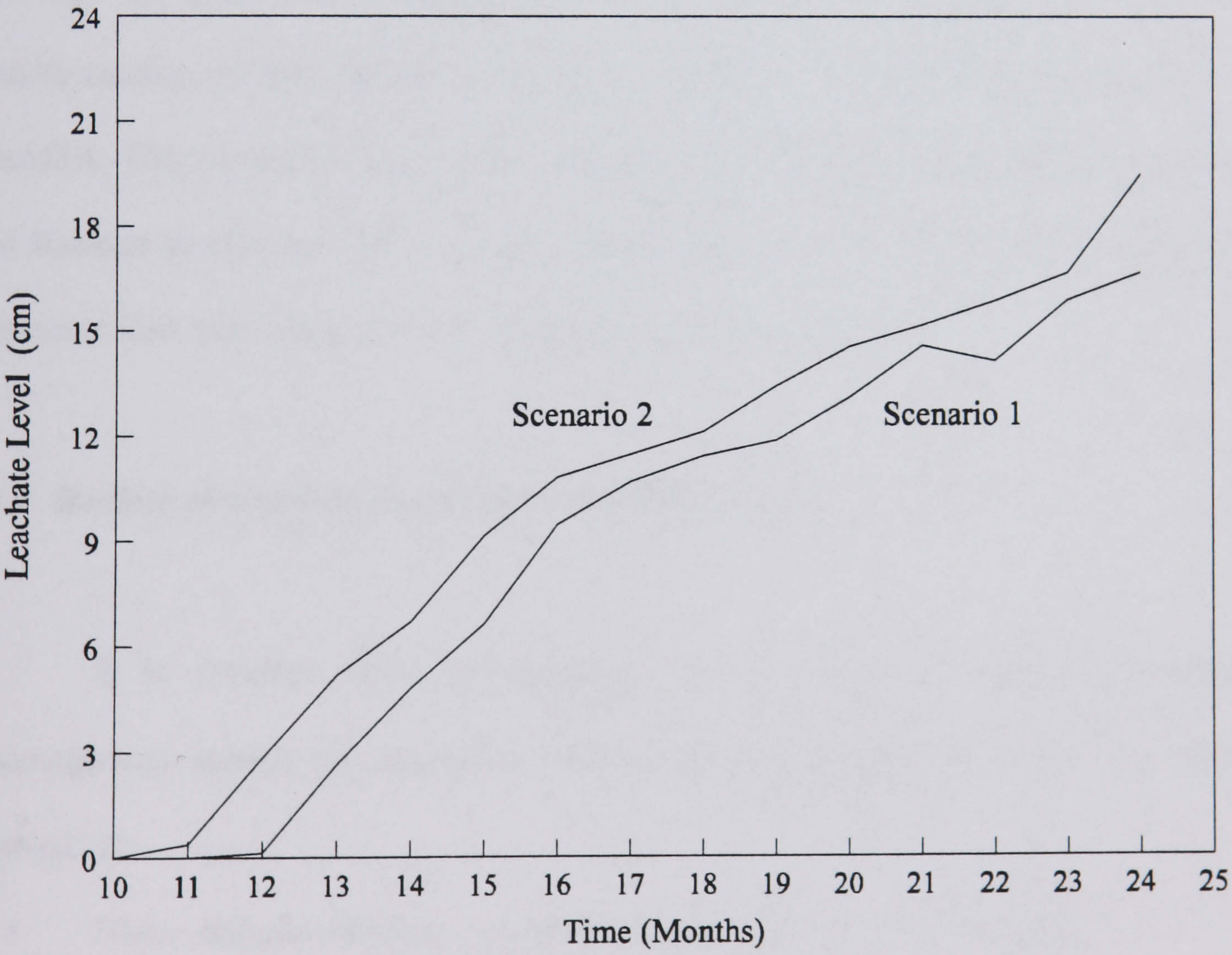


Figure 8.54. Leachate levels in two different scenarios.

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 General

One of the aims of the research project was to investigate the significance of placement density on the hydraulic characteristics of waste material such as: moisture retention capacities, drainage and saturated hydraulic conductivity. Mathematical models have been developed describing the relationship between density and those parameters describing the retention and movement of water in waste. These basic individual models are then utilised in the development of an applied numerical model (NUMMOL) for simulating leachate production and movement within landfill sites. Perhaps the greatest benefit derived from this work is the insight and increased understanding of the physical processes controlling the quantity of leachate in a landfill. This research work is a step towards standardisation in numerical modelling of leachate production from landfill sites. The findings of the research project are grouped into three parts and are discussed separately below.

9.2 Review of Existing Leachate Production Models

It is revealed from the literature that a number of landfill leachate management models are available. These models are categorised into two main groups as:

- *Water Balance Models* - using the conservation of mass principle.
- *Porous Media Models* - using Richard's equation.

An evaluation of these models identifies a number of deficiencies and limitations. The conclusions drawn from the review of these models are outlined below:

- The porous media models are complex and sophisticated because of Richard's equation, which is a non-linear partial differential equation and can only be solved using complex numerical schemes. Furthermore, these models require a large number of parameters, thus making them impractical to apply in real situations.

- The input data required for a water balance model are considerably less than those required for porous media models.

- The most fundamental deficiency in the existing models (especially in water balance models), is the lack of understanding of moisture flow processes in the waste matrix.

- Most of the existing models are based on the SCS method for surface runoff because it is computationally efficient and the required inputs are generally available.

- Following are some of the limitations in the existing models:
    - No consideration is given for the settlement of a landfill.
    - Waste and intermediate soil layers are modelled as one layer.
    - No consideration is given to leachate recirculation.

- None of the models visually draws landfill and its components.
- No model allows for changing conditions of waste hydraulic properties during the simulation period.

9.3 Experimental Investigation

The following conclusions have been drawn from the experimental investigation carried out in order to determine the effect of density on hydraulic properties of waste material:

- ★ Waste density is identified as a fundamental parameter governing the different hydraulic properties describing the retention and movement of water in the waste matrix.

- ★ It is verified that Darcy's law generally holds for pulverised waste for hydraulic gradients ranging from 0 to 4.

- ★ The saturated hydraulic conductivity (both vertical and horizontal) follows the Log-normal distribution.

- ★ The saturated hydraulic conductivity varies exponentially with the density of waste material.

- ★ A significant difference was found between vertical and horizontal saturated hydraulic conductivities.

9.4 Model Theory and Development

The NUMMOL (NUMerical Modelling of Leachate) model developed in this study consists of simulation and interface modules. The simulation module includes four sub-modules SURFACE, UNSATURATED, RESERVOIR and COLLECTOR. Each of these modules individually simulates the hydrologic response associated with it by using input data and/or using output data of other modules. The user friendly interface module controls all the different scenarios via pop-up windows.

The SURFACE module is based on a modified CREAMS model (option-1) approach which takes into account the hydrological processes in landfill cover which are precipitation, evapotranspiration, infiltration, runoff, soil moisture storage, percolation and saturated subsurface flow. The SCS method is used to partition the daily precipitation into runoff and infiltration. Soil moisture storage is updated using CREAMS model approach and the vertical drainage from a soil segment is computed by Campbell's equation. Saturated lateral drainage (subsurface flow) is modelled by an analytical approximation to the steady-state solution of the Boussinesq equation. Percolation through the clay liner is computed by Darcy's law using the effective saturation depth over the liner.

The UNSATURATED module distributes the percolating water (i.e. output from SURFACE Module) and leachate recirculation (if specified), into the unsaturated zone of a cell. The module is based on LPM (Lumped Parameter Model), incorporating mathematical flow models, developed through experimental investigation. This unsaturated zone comprises of waste layers with intermediate soil layers, which are further divided into discrete layers named 'modelling layers'. The leachate mound head in a cell is updated on a daily basis, by comparing segment moisture contents with their corresponding porosities.

The RESERVOIR module distributes the leachate among different cells of a landfill. In case of disperse site, the COLLECTOR module computes the amount of leachate that is discharged through the drainage system. Finally, it calculates leachate which seeps from the bottom of a cell.

The sensitivity analysis of the model has proved very useful, in highlighting the most sensitive parameters under control conditions. The saturated hydraulic conductivity (K_s) of the soil cover has been confirmed, under unsaturated conditions, as being most sensitive of the input parameters; with a marked effect on runoff, infiltration and percolation.

It is also concluded from sensitivity trials that the parameters which mostly affected the leachate production and distribution in waste materials are the physical properties of the material itself. The effect of density contributes to the variations of all waste properties and hence has a marked influence on the model outputs. The saturated hydraulic conductivity of the waste material has been proved under unsaturated conditions as being the most sensitive of the input parameters, with a marked effect on total leachate flow and leachate levels.

9.5 Recommendations

This research has led to the development of an applied numerical leachate management model using some of the existing modelling techniques for landfill covers water balance and mathematical models, describing the retention and movement of water in waste material, which were developed through experimentation. However, as we acquire a greater understanding of the hydrological behaviour of landfills, the number and complexity of the questions which face us tend to increase rather than decrease. In other words, research often tends to raise more questions than it answers. In many respects this is true for the research effort on the continued development and refinement of the NUMMOL model developed in this research. Some questions have been answered while new problems have been uncovered. The following recommendations are suggested for future study:

- The different hydraulic processes describing the water retention and movement in waste material reported in this study are limited to pulverized waste. Further, the conclusions are drawn from laboratory experimentation and need to be extended under field conditions and other types of waste material such as crude and baled waste.
- One of the major limitations in modelling leachate management is the limited availability of sufficient landfill data, which results in uncertainty in any model predictions. One of the methods to overcome this problem is to generate data utilizing Monte Carlo technique.
- The NUMMOL model can further be enhanced by applying it to the real situation.
- It is recommended that field data be collected in order to compare it with model prediction.

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APPENDIX

A-1 Regression and Correlation Analysis

The term "regression analysis" refers to the methods by which estimates are made of the values of a variable from a knowledge of the values of one or more other variables, and to the measurement of the errors involved in the estimation process. The term "correlation analysis" refers to methods for measuring the strength of the association (correlation) among these variables.

The equation of a straight line is $Y = a + b X$, where 'a' is called Y intercept, and 'b' is the slope of the line. The coefficients 'a' and 'b' are given by,

$$a = \bar{Y} - b\bar{X}$$

$$b = \frac{\Sigma XY - n\bar{X}\bar{Y}}{\Sigma X^2 - n\bar{X}^2} \qquad \text{(A-1)}$$

The coefficient of correlation is given by

$$R^2 = 1 - \frac{\Sigma(Y - Y_c)^2}{\Sigma(Y - \bar{Y})^2} \qquad \text{(A-2)}$$

where Y_c is a computed value of the independent variable and Y is an observed value.

The model with zero intercept is given by

$$Y = bX \qquad \text{(A-3)}$$

The model of Equation A-3 can be calibrated using the principle of least squares by substituting Equation A-3 into Equation A-4 as

$$F = \min \sum_{i=1}^{n} \left(\hat{Y}_i - Y_i\right)^2 \tag{A-4}$$

$$F = \min \sum_{i=1}^{n} \left(b X_i - Y_i\right)^2 \tag{A-5}$$

Differentiating Eq. A-5 with respect to b and setting the result equal to zero yields

$$b = \frac{\sum_{i=1}^{n} X_i Y_i}{\sum_{i=1}^{n} X_i^2} \tag{A-6}$$

The value of b computed will result in the minimum error variance for any solution of Equation A-3.

The alternate method for calculating R^2 for the regression through the origin, suggested by Gordon (1981), is

$$R^2 = 1 - \frac{Residual\ SS}{Corrected\ Total\ SS} \tag{A-7}$$

where Residual SS is the residual sum of squares based on the model being fitted (in this case Residual SS = $\Sigma y_i^2 - [(\Sigma x_i y_i)^2 / \Sigma x_i^2]$), and the Corrected Total SS = $\Sigma(y_i - \bar{y})^2$.

A-2 Kolmogorov-Smirnov Test (K-S Test)

There are various techniques for measuring the discrepancy between empirical and theoretical distributions. The *Cramér-von Mises* statistic "discrepancy" as an average of the squared difference; the ***Kolmogorov-Smirnov*** statistic measures discrepancy as the maximum absolute difference. The K-S statistic is given by (Kolmogorov, 1933)

$$D_n = \max \left| P_s(x) - P_t(x) \right| \tag{A-8}$$

The sample continuous distribution function (P_s) is a step function, whereas, the theoretical distribution function P_t is continuous. The largest discrepancy between the two functions will occur at one of the sample values, say, at the mth smallest, $X_{(m)}$. Then D_n is either

$$a_m = \left| P_s(X_m) - P_t(X_m) \right| \tag{A-9}$$

$$b_m = \left| P_s(X_m) - P_t(X_{m-1}) \right| \tag{A-10}$$

The K-S statistic is then compared with the critical values of the statistic which depends on the significance level and number of data points. The larger the value of D_n the greater the evidence against the null hypothesis with rejection if D_n is larger than the prescribed critical value. The critical values of D for the K-S test are given in Table A-1.

Table A-1. Critical Values of D for the Kolmogorov-Smirnov Goodness of Fit Test.

Degrees of freedom	Significance level				
	0.20	0.15	0.10	0.05	0.01
1	0.900	0.925	0.950	0.975	0.995
2	0.684	0.726	0.776	0.842	0.929
3	0.565	0.597	0.642	0.708	0.829
4	0.494	0.525	0.564	0.624	0.734
5	0.446	0.474	0.510	0.563	0.669
6	0.410	0.436	0.470	0.521	0.618
7	0.381	0.405	0.438	0.486	0.577
8	0.358	0.381	0.411	0.457	0.543
9	0.339	0.360	0.388	0.432	0.514
10	0.322	0.342	0.368	0.409	0.486
11	0.307	0.326	0.352	0.391	0.468
12	0.295	0.313	0.338	0.375	0.450
13	0.284	0.302	0.325	0.361	0.433
14	0.274	0.292	0.314	0.349	0.418
15	0.266	0.283	0.304	0.338	0.404
16	0.258	0.274	0.295	0.328	0.391
17	0.250	0.266	0.286	0.318	0.380
18	0.244	0.259	0.278	0.309	0.370
19	0.237	0.252	0.272	0.301	0.361
20	0.231	0.246	0.264	0.294	0.352
25	0.210	0.220	0.240	0.264	0.320
30	0.190	0.200	0.220	0.242	0.290
35	0.180	0.190	0.210	0.230	0.270
40	0.170	0.180	0.190	0.210	0.250
50	0.150	0.160	0.170	0.190	0.230
60	0.140	0.150	0.160	0.170	0.210
70	0.130	0.140	0.150	0.160	0.190
80	0.120	0.130	0.140	0.150	0.180
90	0.110	0.120	0.130	0.140	0.170
100	0.110	0.110	0.120	0.140	0.160
> 100	$1.07/n^{1/2}$	$1.14/n^{1/2}$	$1.22/n^{1/2}$	$1.36/n^{1/2}$	$1.63/n^{1/2}$

Source: Kolmogorov (1933)

A-3 Regula Falsi Method

Regula falsi is a method for calculating zero of continuous function. Suppose that a zero α of a continuous function f(x) is contained in [a,b]; let x_0, x_1 be different points of this interval. The iteration formula of the *Regula Falsi* method is

$$x_{k+1} = x_k - \frac{f(x_k)\,(x_{k-1} - x_k)}{f(x_{k-1} - f(x_k)} \qquad k = 1,2,\cdots \qquad \textbf{(A-11)}$$

If the sequence $\{x_k\}$ converges, then it must converge to a zero of f. This method is faster than the bisection method and its convergent is also guaranteed (Atkinson, 1978).

A-4 National Waste Analysis Categories

Table A-2. National Waste Analysis Categories.

11 Main Categories	33 Minor Categories	Identification No.
Paper / Card	Newspapers	1
	Magazines	2
	Other paper	3
	Liquid cartons	4
	Card packaging	5
	Other card	6
Plastic film	Refuse sacks	7
	Other plastic film	8
Dense plastic	Clear beverage bottles	9
	Coloured bev. bottles	10
	Other bottles	11
	Food packaging	12
	Other dense plastic	13
Textiles	Textiles	14
Misc. Combustibles	Disposable nappies	15
	Other MC	16
Misc. Non-Combustibles	MNC	17
Glass	Brown bottles	18
	Green bottles	19
	Clear bottles	20
	Clear jars	21
	Broken glass	22
Putresibles	Garden putresibles	23
	Other putresibles	24
Ferrous	Beverage cans	25
	Food cans	26
	Batteries	27
	Other cans	28
	Other Fe	29
Non-Ferrous	Beverage cans	30
	Foil	31
	Other non Fe	32
Fines	< 10 mm category	33

Source: Warren Spring Laboratory (1993)

NUMMOL MODEL SOURCE CODE

MAIN PROGRAM NUMMOL

Subroutine	**Filename**
WINDOWMAIN	W-MAIN.FOR
WINDOW3	W-MAIN.FOR
WINDOW5	W-MAIN.FOR
NEW_FILE	NEW.FOR
INPUTG	NEW.FOR
EDITOR	EDITOR2.FOR
DIREDIT	EDITOR2.FOR
DIRLIS	EDITOR2.FOR
SWIN0	WIN-0N-S.FOR
SWIN1	WIN-1N-S.FOR
SWIN2	WIN-2N-S.FOR
SWIN3	WIN-3N-S.FOR
WIN_HELP	WIN-HELP.FOR
SPLAN	PLAN2-S.FOR
SECTION	PLAN2-S.FOR
SIMULATION	SIMULT-S.FOR
CHECKDATE	SIMULT-S.FOR
NODAYSA	SIMULT-S.FOR
STARTER	SIMULT-S.FOR
GRAPHM	GRAPH-S.FOR
GRAPH	GRAPH-S.FOR
SURFACE	SURFACE.FOR
UNSATURATED	UNSAT.FOR
RESERVOIR	RESERV-N.FOR
COLLECTOR	COLLEC.FOR
RUNOFF	OTHER.FOR
LATFLO	OTHER.FOR
AREAPOLY	OTHER.FOR

```
      PROGRAM WINDOWMAIN
      PARAMETER (NL=1000, NW = 5)
      IMPLICIT INTEGER*2 (A-Z)

      CHARACTER Hline(NW, NL)*80
      integer*2  Nrows(NW)
      common/hlp/Nrows, Hline

c  window handles
      COMMON/Winhand/ Win_h, Win_0, Win_1, Win_2, Win_3

      INCLUDE 'COLOURS.INS'
      INCLUDE 'KEYS.INS'

      CHARACTER  A(7)*76, ITEM_2(4)*20

      A(1)='  █▄  █ █   █ █▄ ▄█ █▄ ▄█ █▀▀▀▀▀█
     &  █'
      A(2)='  ██  █ █   █ ██ ██ ██ ██ █   █
     &  █'
      A(3)='  █ █  █ █   █ █ ██ █ █ ██ █ █   █
     &  █'
      A(4)='  █ █ █ █   █ █ █ █ █ █ █ █   █
     &  █'
      A(5)='  █  █ █ █   █ █   █ █   █ █   █
     &  █'
      A(6)='  █  ██ █   █ █   █ █   █ █   █
     &  █'
      A(7)='  █  ▀█ █▄▄▄▄▄█ █  █ █   █ █▄▄▄▄▄█

     &  █▄▄▄▄▄▄'

      DATA ITEM_2/' 1. Define Problem', ' 2. Simulation',
     & ' 3. Results', ' 4. Exit'/

      CALL CLEAR_SCREEN@
      CALL HIDE_CURSOR@

      BORDER1=5
      SHADOW1=0
      HP1=1
      VP1=1
      HS1=78
      VS1=23
      CALL WCREATE@(HP1,VP1,HS1,VS1,RED+INVERSE_CYAN,H1)
      CALL WBORDER@(H1,BORDER1)
C      CALL WSHADOW@(H1,SHADOW1)
      CALL WTITLE@(H1,' N U M M O L',WHITE+INVERSE_BLUE+INTENSE)
      CALL POPW@(H1)

      DO M=1,7
        CALL WCOUP@(A(M),BLUE+INVERSE_CYAN+INTENSE,HP1,M+2,H1)
      END DO

*......................Help File reading .................*
c   NW  window number 5
```

```
c  Nrows(4)  number of lines
c  Hline is two dimentional character array (Wnumber, 4)

     OPEN (12, FILE='NUMMOL.HLP')
      DO I = 1, NW
       J = 0
  10   J = J + 1
       READ (12,'(A80)', end=20) Hline(I,J)
       IF(Hline(I,J)(1:1) .NE. '@') goto 10

  20   Nrows(I) = J - 1
      END DO
     CLOSE(12)
*...............................................*

******************** WINDOW-2 *************************
     BORDER2=0
     SHADOW2=3
     NITEM_2=4
     HP2=20
     VP2=10
     VS2=NITEM_2+1
     HS2=20
     CALL WCREATE@(HP2,VP2,HS2,VS2,BLACK+INVERSE_WHITE,2)
     CALL WBORDER@(2,BORDER2)
     CALL WSHADOW@(2,SHADOW2)
     CALL WTITLE@(2,' MAIN PROGRAM',WHITE+INVERSE_BLUE)
     CALL POPW@(2)


     IAT=BLACK+INVERSE_WHITE
     VP=1
     HP=0

  3  DO K=1,NITEM_2
      CALL WCOUP@(ITEM_2(K),IAT,HP,K,2)
     END DO

     CALL WCOUP@(ITEM_2(VP),WHITE+INVERSE_RED+INTENSE,HP,VP,2)

  9  CALL GET_KEY@(K)

c Down arrow
     IF(K.EQ.DOWN_KEY)THEN
      IF (VP .NE. NITEM_2) THEN
       VP=VP+1
      ELSE
       VP=1
      ENDIF

c Up arrow
     ELSEIF(K.EQ.UP_KEY)THEN
      IF (VP .NE. 1) THEN
       VP=VP-1
      ELSE
       VP=NITEM_2
```

```
      ENDIF

c Enter Key
     ELSEIF(K.EQ.ENTER_KEY) THEN
      IF(VP .EQ. 1) THEN
        CALL CONCEALW@(2)
        CALL WINDOW3(H1)
        CALL POPW@(2)
      ELSEIF(VP .EQ. 2) THEN
C         START SIMULATION
        CALL CONCEALW@(2)
        CALL SIMULATION
        CALL POPW@(2)
      ELSEIF(VP .EQ. 3) THEN
        CALL CONCEALW@(2)
        CALL WINDOW5(H1)
        CALL POPW@(2)
      ELSE
        GOTO 5
      ENDIF

c Home key
     ELSEIF(K.EQ.HOME_KEY) THEN
       VP=1

c End key
     ELSEIF(K.EQ.END_KEY) THEN
       VP=NITEM_2

c Esc key
     ELSEIF(K.EQ.ESC_KEY) THEN
       GOTO 5

C For other keys: respond with BEEP
     ELSE
       CALL BEEP@
       GOTO 9
     ENDIF
     GOTO 3

 5   CALL KILLW@(2)
     CALL KILLW@(H1)
     CALL RESTORE_CURSOR@
     END


***************** WINDOW-3 *******************
     SUBROUTINE WINDOW3(H1)
     IMPLICIT INTEGER*2 (A-Z)
     INCLUDE 'COLOURS.INS'
     INCLUDE 'KEYS.INS'
     CHARACTER ITEM_3(5)*20,FILENAME*80
     FILENAME='EDITOR2.FOR'
     DATA ITEM_3/' 1. New  File ', ' 2. Open File... ',
    & ' 3. View File... ', ' 4. View Plan ',' 5. Quit '/
```

```
      BORDER3=0
      SHADOW3=3
      NITEM3=5
      HP3=42
      VP3=10
      VS3=NITEM3+1
      HS3=20
      CALL WCREATE@(HP3,VP3,HS3,VS3,BLACK+INVERSE_WHITE,3)
      CALL WBORDER@(3,BORDER3)
      CALL WSHADOW@(3,SHADOW3)
      CALL WTITLE@(3,' INPUT WINDOW',WHITE+INVERSE_BLUE)
      CALL POPW@(3)

      IAT=BLACK+INVERSE_WHITE
      VP=1
      HP=0

 3    DO K=1,NITEM3
       CALL WCOUP@(ITEM_3(K),IAT,HP,K,3)
      END DO

      CALL WCOUP@(ITEM_3(VP),WHITE+INVERSE_RED+INTENSE,HP,VP,3)

 9    CALL GET_KEY@(K)

      IF(K.EQ.DOWN_KEY)THEN
        IF (VP .NE. NITEM3) THEN
          VP=VP+1
        ELSE
          VP=1
        ENDIF
      ELSEIF(K.EQ.UP_KEY)THEN
        IF (VP .NE. 1) THEN
          VP=VP-1
        ELSE
          VP=NITEM3
        ENDIF
      ELSEIF(K.EQ.ENTER_KEY) THEN

        IF(VP .EQ. 1 .OR. VP .EQ. 2)  THEN
          FileState = VP - 1
          CALL CONCEALW@(3)

          CALL NEW_FILE (FileState)

          CALL POPW@(3)

        ENDIF

        IF(VP .EQ. 3) THEN
           CALL EDITOR(FILENAME)
C           CALL EDITOR('EDITOR2.FOR ')
        ENDIF

        IF(VP .EQ. 4) THEN
```

```
          CALL CONCEALW@(H1)
C           CALL CONCEALW@(2)
          CALL CONCEALW@(3)
            CALL SPLAN
          CALL POPW@(H1)
C           CALL POPW@(2)
          CALL POPW@(3)
        ENDIF

        IF(VP .EQ. NITEM3) GOTO 5

      ELSEIF(K.EQ.HOME_KEY) THEN
        VP=1
      ELSEIF(K.EQ.END_KEY) THEN
        VP=NITEM3
      ELSEIF(K.EQ.ESC_KEY) THEN
        GOTO 5
      ELSE
        CALL BEEP@
        GOTO 9
      ENDIF
      GOTO 3

  5   CALL KILLW@(3)
      END
********************************************

**************** WINDOW-5 *****************
      SUBROUTINE WINDOW5(H1)
      IMPLICIT INTEGER*2 (A-Z)
      INCLUDE 'COLOURS.INS'
      INCLUDE 'KEYS.INS'
      CHARACTER ITEM_5(4)*20,FILENAME*80
      FILENAME='RESERV.OUT'
      DATA ITEM_5/' 1. View  File ', ' 2. Print File ',
     & ' 3. View Graph ',' 4. Quit '/

      BORDER5=0
      SHADOW5=3
      NITEM5=4
      HP5=42
      VP5=10
      VS5=NITEM5+1
      HS5=20
      CALL WCREATE@(HP5,VP5,HS5,VS5,BLACK+INVERSE_WHITE,5)
      CALL WBORDER@(5,BORDER5)
      CALL WSHADOW@(5,SHADOW5)
      CALL WTITLE@(5,' OUTPUT WINDOW-5',WHITE+INVERSE_BLUE)
      CALL POPW@(5)

      IAT=BLACK+INVERSE_WHITE
      VP=1
      HP=0

3     DO K=1,NITEM5
        CALL WCOUP@(ITEM_5(K),IAT,HP,K,5)
```

```
      END DO

      CALL WCOUP@(ITEM_5(VP),WHITE+INVERSE_RED+INTENSE,HP,VP,5)

    9 CALL GET_KEY@(K)

      IF(K.EQ.DOWN_KEY)THEN
        IF (VP .NE. NITEM5) THEN
          VP=VP+1
        ELSE
          VP=1
        ENDIF
      ELSEIF(K.EQ.UP_KEY)THEN
        IF (VP .NE. 1) THEN
          VP=VP-1
        ELSE
          VP=NITEM5
        ENDIF
      ELSEIF(K.EQ.ENTER_KEY) THEN
        IF(VP .EQ. 1) THEN
             CALL EDITOR(FILENAME)
C             CALL EDITOR('RESERV.OUT  ')
        ELSEIF(VP .EQ. 3) THEN
           CALL CONCEALW@(H1)
C            CALL CONCEALW@(2)
           CALL CONCEALW@(5)
             CALL GRAPHM
           CALL POPW@(H1)
C            CALL POPW@(2)
           CALL POPW@(5)

        ELSEIF(VP .EQ. NITEM5) THEN
          GOTO 5
        ENDIF
      ELSEIF(K.EQ.HOME_KEY) THEN
        VP=1
      ELSEIF(K.EQ.END_KEY) THEN
        VP=NITEM5
      ELSEIF(K.EQ.ESC_KEY) THEN
        GOTO 5
      ELSE
        CALL BEEP@
        GOTO 9
      ENDIF
      GOTO 3

    5 CALL KILLW@(5)
      END
*******************************************

      SUBROUTINE NEW_FILE (FileState)

      IMPLICIT INTEGER*2 (A-Z)
      INCLUDE 'COLOURS.INS'
      INCLUDE 'KEYS.INS'
```

```
      CHARACTER OUTPUT*13
C       , EXT*5

      IF (FileState .EQ. 1) THEN
        CALL DIREDIT( '*.NUM', OUTPUT)
        GOTO 21
      ENDIF

      FileState = 0

      BORDER6 = 2
      SHADOW6 = 3
      HP6 = 60
      VP6 = 10
      VS6 = 2
      HS6 = 15
      CALL WCREATE@(HP6,VP6,HS6,VS6,BLACK+INVERSE_WHITE,HANDLE)
      CALL WBORDER@(HANDLE,BORDER6)
      CALL WSHADOW@(HANDLE,SHADOW6)
      CALL WTITLE@(HANDLE,' FILE NAME',WHITE+INVERSE_BLUE)
      CALL POPW@(HANDLE)

      CALL INPUTG(HANDLE, OUTPUT)
      CALL KILLW@(HANDLE)

 21   IF (OUTPUT .NE. ' ') THEN
        CALL SWIN0(OUTPUT, FileState)   ! call data editing window 0
      ENDIF

      RETURN
      END

      SUBROUTINE INPUTG(HANDLE,INPUT)
      IMPLICIT INTEGER*2 (A-Z)
C       INTEGER*2 PTR,K,ERROR_CODE,HANDLE,OUTPUT
      CHARACTER INPUT*13,BLANKS*13,SEND*13,EXT*4
      INCLUDE 'KEYS.INS'

      CALL FILL@(BLANKS,13,0)
      EXT='.NUM'
    5 INPUT=' '
    1 PTR=LENG(INPUT)
      IF(PTR.EQ.0) THEN
        PTR=1
      ELSEIF(PTR.EQ.10) THEN
        PTR=9
      ENDIF
C Wipe area uder the string
      CALL WCOUP@(BLANKS,-1,1,1,HANDLE)
C Add the .PCX extension to the input
      SEND=INPUT(:PTR)//EXT
C Write current filename.PCX
     CALL WCOUP@(SEND(:LENG(SEND)),-1,1,1,HANDLE)

C Fetch a key
     CALL GET_KEY@(K)
```

```
      IF(K.EQ.ESC_KEY) THEN
       OUTPUT=0
        GOTO 9
      ENDIF

      IF(K.GT.0)THEN
        IF(K.EQ.13)THEN
C If <CR> update input name and exit
          INPUT(PTR+1:)=EXT
          GOTO 2
        ELSEIF(K.EQ.8.OR.K.EQ.255)THEN
C Backspace and DEL key
          INPUT(PTR:)=' '
        ELSEIF(K.LT.255)THEN
C Add character to string
          INPUT(PTR+1:)=CHAR(K)
        ENDIF
      ENDIF
      GOTO 1

c Check name of file
  2   CALL OPENW@(INPUT,HANDLE1,ERROR_CODE)
      IF(ERROR_CODE.NE.0) THEN
C        PRINT*,'FILE NAME IS WRONG'
       GOTO 5
      ENDIF
      OUTPUT=1
      CALL DOSERR@(ERROR_CODE)
      CALL ERR77(INPUT,ERROR_CODE)
      CALL CLOSEF@(HANDLE1,ERROR_CODE)
  9   RETURN
      END

        SUBROUTINE EDITOR(FILENAME)
        PARAMETER (NL=1000)
        IMPLICIT INTEGER*2(A-Z)
        CHARACTER*80 CENTRE@,LINEA(NL)*80,FILENAME*13,PAT*80
        CHARACTER CR*5
        CHARACTER*50 CURDIR@

        INCLUDE 'KEYS.INS',NOLIST
        INCLUDE 'COLOURS.INS',NOLIST

        COUNTER = 1
        CALL RESTORE_CURSOR@


C     FILENAME = 'LIST.OUT'

C     CALL COMMAND_LINE(PAT)

 1   OPEN(12,FILE=FILENAME)
          READ (12,'(A80)', end=20)(LINEA(I),I=1,NL)
       CLOSE(12)
```

```
 20  N = I - 1

        PAT = CURDIR@()

        CALL APPEND_STRING@(PAT,'\')
        CALL APPEND_STRING@(PAT,FILENAME)


C  OPEN THE WINDOW DISPLAY
        IF (COUNTER .EQ. 1) THEN
         HP=1
         VP=1
         HS=78 ! SOME FUNCTION OF DIRECTORY LENGTH
         VS=23
         WCOLOR = BLACK+INVERSE_CYAN
         TCOLOR = BLUE +INVERSE_WHITE
         CALL WCREATE@(HP,VP,HS,VS,WCOLOR,WINDOW)
         CALL POPW@(WINDOW)
         COUNTER = 2
        ENDIF

         CALL WCOUP@(CENTRE@(PAT,HS),TCOLOR,0,0,WINDOW)

         CALL WCOUP@('   Files',TCOLOR,70,0,WINDOW)
         CALL WCOUP@('F5',RED+INVERSE_WHITE,70,0,WINDOW)

         CALL WCOUP@(CENTRE@('Use cursor keys, ESC when finished',HS),
     + TCOLOR,0,22,WINDOW)

        LN = 1
        K  = 1
        IF (N .GT. VS) THEN
          NOLINES = VS-3
        ELSE
          NOLINES = N - 1
        ENDIF

  6  M = 1
        DO J = LN, NOLINES+LN
          CALL WCOUP@(LINEA(J),-1,0,M,WINDOW)
          M = M+1
        END DO

  5  CALL SET_CURSOR_POSW@(WINDOW,0,K)


        WRITE(CR,'(I5)') LN + K - 1
        CALL WCOUP@(CR,WHITE+INVERSE_BLUE+INTENSE,1,22,WINDOW)

C  WAIT FOR THE USER TO PRESS A KEY
  9  CALL GET_KEY@(KEY)

        IF(KEY.EQ.ESC_KEY)THEN
          FILE= ' '
          GOTO 17
```

```
      ELSEIF(KEY .EQ. F5_KEY) THEN
         CALL DIREDIT('*.*  ', FILENAME)
         IF (FILENAME .NE. ' ') THEN
          CALL WCLEAR@(WINDOW)
          GOTO 1
         ENDIF

      ELSEIF(KEY.EQ.DOWN_KEY)THEN
        IF (K.LT.21)THEN
          K = K + 1
          GOTO 5
        ELSEIF (LN+NOLINES .LT. N) THEN
          LN = LN+1
        ENDIF

      ELSEIF(KEY.EQ.PGDOWN_KEY)THEN
        LN=LN+NOLINES
        IF(LN+NOLINES .GE. N) LN=N-NOLINES

      ELSEIF(KEY.EQ.UP_KEY)THEN
        IF (K.GT.1)THEN
          K=K-1
          GOTO 5
        ELSEIF(LN .GT. 1) THEN
          LN=LN-1
        ENDIF

      ELSEIF (KEY .EQ. PGUP_KEY) THEN
        LN = LN - NOLINES
        IF (LN .LE. 1)   THEN
         LN = 1
         K = 1
        ENDIF
      ELSEIF (KEY .EQ. END_KEY) THEN
        LN = N - NOLINES
        K = 21

      ELSEIF (KEY .EQ. HOME_KEY) THEN
        LN = 1
        K = 1
      ELSE
        GOTO 9
      ENDIF
      GOTO 6

17  CALL KILLW@(WINDOW)
      RETURN
      END


      SUBROUTINE DIREDIT(EXT, FILE1)

      IMPLICIT INTEGER*2(A-Z)
      INCLUDE 'KEYS.INS'   , NOLIST
      INCLUDE 'COLOURS.INS', NOLIST
```

```
      PARAMETER (NN=1000)
      CHARACTER*80 CENTRE@,FILES(NN)*41,FILE*41,PAT*120,EXT*5,BLK*41
      CHARACTER*50 CURDIR@, FILE1*13
      BLK='                                         '

c    CALL HIDE_CURSOR@

C  OPEN THE WINDOW DISPLAY
      HP=32
      VP=1
      HS=47 ! SOME FUNCTION OF DIRECTORY LENGTH
      VS=23
      WCOLOR=WHITE+INVERSE_BLUE
      TCOLOR=BLUE+INVERSE_WHITE
      CALL WCREATE@(HP,VP,HS,VS,WCOLOR,WINDOW)
      CALL WCOUP@(CENTRE@('Use cursor keys, ESC when finished',HS),
     +TCOLOR,0,22,WINDOW)
      CALL POPW@(WINDOW)

**********
C     EXT='*.*'
      CALL COMMAND_LINE(PAT)
      CALL APPEND_STRING@(PAT,EXT)

* Call Subroutine DIRLIS for listing and sorting of current dirctory files
 29  CALL DIRLIS(PAT,N,FILES)

      LN = 1
      K  = 1

      IF (N .LT. 20) THEN
       NOLINES = N - 1
       RN = N
      ELSE
       NOLINES = VS - 3
       RN = 21
      ENDIF

      CALL WCOUP@(CENTRE@(CURDIR@(),HS),TCOLOR,0,0,WINDOW)

  6  M=1
      DO J = LN, NOLINES+LN
       CALL WCOUP@(FILES(J),-1,0,M,WINDOW)
       M=M+1
      END DO

      VPL=LN+K-1
      CALL WCOUP@(FILES(VPL),WHITE+INVERSE_RED+INTENSE,0,K,WINDOW)

C  WAIT FOR THE USER TO PRESS A KEY
  9  CALL GET_KEY@(KEY)

      IF(KEY .EQ. ESC_KEY)THEN
        FILE= ' '
        GOTO 17
```

```
      ELSEIF(KEY .EQ. ENTER_KEY) THEN
        FILE=FILES(VPL)
        IF(FILE(1:1) .EQ. '\') THEN
                CALL ATTACH@(FILE(2:14),ERROR_CODE)
          DO I=1,21
                CALL WCOUP@(BLK,-1,0,I,WINDOW)
          END DO
          GOTO 29
        ENDIF
        GOTO 17

      ELSEIF(KEY .EQ. DOWN_KEY)THEN
        IF (K.LT.RN)THEN
           K=K+1
        ELSEIF(LN+NOLINES .LT. N) THEN
           LN=LN+1
        ELSE
           GOTO 9
        ENDIF

      ELSEIF(KEY .EQ. PGDOWN_KEY)THEN
         LN=LN+NOLINES
         IF(LN+NOLINES .GE. N) LN=N-NOLINES
C     IF(N .EQ. NOLINES) LN=N

      ELSEIF(KEY .EQ. UP_KEY)THEN
         IF (K.GT.1)THEN
           K=K-1
         ELSEIF(LN .GT. 1) THEN
           LN=LN-1
         ELSE
           GOTO 9
         ENDIF

      ELSEIF(KEY .EQ. PGUP_KEY)THEN
         LN = LN-NOLINES
         IF (LN .LE. 1) LN = 1

      ELSEIF(KEY .EQ. END_KEY)THEN
         IF(LN .EQ. (N-NOLINES) .AND. K .EQ. RN) THEN
           GOTO 9
         ELSE
           LN = N-NOLINES
           K  = RN
         ENDIF

      ELSEIF(KEY .EQ. HOME_KEY)THEN
         IF(LN .EQ. 1 .AND. K .EQ. 1) THEN
           GOTO 9
         ELSE
           LN = 1
           K  = 1
         END IF

      ELSE
```

```
         GOTO 9
        ENDIF
        GOTO 6

 17   CALL KILLW@(WINDOW)
        CALL RESTORE_CURSOR@
        FILE1 = FILE(1:13)
        RETURN
        END

        SUBROUTINE DIRLIS (PAT,N,Y)
        IMPLICIT INTEGER*2(A-Y)
        PARAMETER(NMAX=1000)
        CHARACTER*120 FILES(NMAX),PAT,Y(NMAX)*41,TEMP*41
        CHARACTER*13 FILES1(NMAX),TEMPF
        CHARACTER*2 CY,CM,CD, CH, CMI ,CT,F_SC*9,DATEC*9,TIMEC*6

        INTEGER*2 ATTR(NMAX),DATE(NMAX),TIME(NMAX)
        INTEGER*4 FILE_SIZE(NMAX)
        LOGICAL SORTED

        ND = 0
C      L = LENG(PAT) - 2
        L = 1
        CALL FILES@(PAT,N,1000,FILES,ATTR,DATE,TIME,FILE_SIZE)

* TO REMOVE HIDDEN FILES
        NM = 0
        DO 14 I = 1, N
         IF(ATTR(I) .EQ. 7 ) GOTO 14
         NM = NM + 1
         FILES(NM) = FILES(I)
         ATTR (NM) = ATTR (I)
         DATE (NM) = DATE (I)
         TIME (NM) = TIME (I)
         FILE_SIZE (NM) = FILE_SIZE (I)
 14   CONTINUE
        N = NM
*******************************


        DO I = 1, N
         FILES1(I)=FILES(I)(L:L+12)

*   Search for a sub-directory to add back slash in the start
         IF(ATTR(I) .EQ. 16) THEN
          TEMPF='\'//FILES1(I)
          FILES1(I)=TEMPF
          F_SC='  <DIR>  '
          ND=ND+1
         ELSE
          WRITE(F_SC,'(I9)') FILE_SIZE(I)
         ENDIF

*   Convert the date from DOS COMPRESSED FORMAT
         YEAR = DATE(I)/512
         MONTH= (DATE(I)-YEAR*512)/32
```

```
          DAY  = DATE(I)-YEAR*512-MONTH*32
          YEAR = YEAR + 80

          WRITE(CY,’(I2)’) YEAR
          WRITE(CM,’(I2)’) MONTH
          WRITE(CD,’(I2)’) DAY

          IF(MONTH .LT. 10) THEN
                CT= ’0’//CM(2:2)
                CM=CT
          ENDIF

          IF(DAY .LT. 10) THEN
                CT= ’0’//CD(2:2)
                CD=CT
          ENDIF

        DATEC=’ ’ //CD//’-’//CM // ’-’ // CY

*    Convert the time from DOS COMPRESSED FORMAT

        IF(TIME(I) .GE. 0) THEN
                HOUR = TIME(I)/2048
                MIN  = (TIME(I)-HOUR*2048)/32
        ELSE
                HOUR = TIME(I)/2048 + 32  - 1
                ZM = ( (REAL(TIME(I))/2048. + 32.) - HOUR) *2048./32.
                MIN = INT(ZM)
        ENDIF

        WRITE(CH,’(I2)’)  HOUR
        WRITE(CMI,’(I2)’) MIN

        IF(HOUR .LT. 10) THEN
         CT= ’0’//CH(2:2)
         CH=CT
        ENDIF

        IF(MIN .LT. 10) THEN
         CT= ’0’//CMI(2:2)
         CMI=CT
        ENDIF

        TIMEC=’ ’ //CH//’:’//CMI

*
        Y(I)=FILES1(I)//’ ’//F_SC//’ ’//DATEC//’ ’//TIMEC
       END DO

*****************************************************
       SORTED = .FALSE.
       LAST=N-1
 15 IF (.NOT. SORTED) THEN
              SORTED = .TRUE.
              DO 20 I=1, LAST
                IF(Y(I)(1:13) .GT. Y(I+1)(1:13)) THEN
```

```
                    TEMP = Y(I)
                    Y(I) = Y(I+1)
                    Y(I+1) = TEMP
                    SORTED = .FALSE.
               ENDIF
  20      CONTINUE
              LAST=LAST-1
              GOTO 15
         ENDIF
***********************
         DO I = N, 1, -1
           Y(ND+I)=Y(I)
         END DO

         DO I = 1, ND
           Y(I)=Y(N+I)
         END DO
*****************************************************

         RETURN
         END



C     PROGRAM WIN0
      SUBROUTINE SWIN0(FileName, FileState)

      IMPLICIT INTEGER*2 (A-Z)
      PARAMETER (TC=10)
      INCLUDE 'COLOURS.INS',NOLIST
      INCLUDE 'KEYS.INS'   ,NOLIST

      COMMON/Winhand/ Win_h, Win_0, Win_1, Win_2, Win_3

      CHARACTER LineV(4)*6,MSG(20)*80,LINE*2,LINE1*2,SiteName*40
      CHARACTER LLC(4)*5,ULC(4)*5,Control(4)*4,F_help(4)*40,Blank*40
      CHARACTER FileName*13

      REAL DC(TC), HD(TC), LL(TC), LR(TC)
      REAL LLV(4), ULV(4), VALUE(4)

      LOGICAL*2 LOG                                           -
      CALL SET_SUFFIX@(FileName, 'LDF', LOG)

c  NCELL    number of cell
c  DC       depth of cell
c  HS       height from datun
c  LL       leachate level in a cell
c  LR       leachate recirculation

     DATA  LLV/  1,   0,   0,  0/
     DATA  ULV/ 999, 300,  10, 30/

     DATA LLC/'  1' ,'0','0','0'/
     DATA ULC/'999','100','10','30'/
```

```
      DATA CONTROL/'Edit','^P^P^P^P','Help','Exit'/
      DATA F_help/'Edits an existing window',
     &'Saves file & moves to Next window','Help about window',
     &'Exits to the Main Menu'/

      SiteName = 'Site Name'
      VPNAME = 1
      Blank ='                    '

      HELPCOL = BLUE+INVERSE_CYAN

*.................... WINDOW DEFINITION .................*
      BORDER = 2
      SHADOW = 0
      HP1 = 2
      VP1 = 2
      WHS = 61
      WVS = 21
      WCOLOUR = BLACK+INVERSE_CYAN
      TCOLOUR = WHITE+INVERSE_BLUE+INTENSE
      RCOLR   = YELLOW+INVERSE_CYAN
      CALL WCREATE@(HP1,VP1,WHS,WVS,WCOLOUR,Win_0)
      CALL WBORDER@(Win_0,BORDER)
      CALL WSHADOW@(Win_0,SHADOW)
      CALL WTITLE@(Win_0,' WINDOW-1',TCOLOUR)
      CALL POPW@(Win_0)

      L = 17
      MSG(1)=' Site Name  : '
      MSG(2)=' No of Cells = '

 MSG(3)=' ┌──────┬──────────────┬──────────────────┬──────
──────────┬────────────┐ '
      MSG(4)=' | Cell | Cell Depth | Height from | Leachate Level |  q_l  | '
      MSG(5)=' |  #   |     m      | Datum m     |       m        | mm/day | '

 MSG(6)=' ├──────┼──────────────┼──────────────────┼──────
──────────┼────────────┤ '
      MSG(7)=' |      |            |             |                |        |'

 MSG(L)=' └──────┴──────────────┴──────────────────┴──────
──────────┴────────────┘ '
c          12345678901234567890123456789012345678901234567890123456789012345678
*               *         *         *
      DO Im = 8, L-1
        MSG(Im) = MSG(7)
      END DO

      DO Im = 1, L
        CALL WCOUP@(MSG(Im),WCOLOUR,0,Im,Win_0)
      END DO

      Advance = 0

*.....................................................*
```

```
* Window control parameters ...........
     LINE = ' '
     NITEM = 4   ! Number of Commands Edit Back etc

     HP_R = 2    ! Horizontal Position of Range
     VP_R = L+1  ! Vertical   Position of Range
     HPC = 1     ! Horizontal Position of Command
     VPC = L+2   ! Vertical   Position of Command
     LHPC = 1
     HP_H = 2    ! Horizontal Position of Help
     VP_H = L+3  ! Vertical   Position of Help
     CM_TAB = 10 ! Command Tab
* ................

*  Data initialization ........
c     NCELL = 10  ! Number of Cells used in a file
     DATA DC/10*1.0/
     DATA HD/10*0.0/
     DATA LL/10*0.0/
     DATA LR/10*0.0/
*...........

     HP = 1
     VP = 1

c..... If file exists then change all values

     IF(FileState .EQ. 1) THEN
       OPEN(10, FILE=FileName)
         Read(10,'(A40)') SiteName
         Read(10,*) NCELL
         DO I = 1, NCELL
           Read(10,*) n, DC(I), HD(I), LL(I), LR(I)
         END DO
       CLOSE(10)
     ELSE
       GOTO 3
     ENDIF
*
     CALL WCOUP@(SiteName,-1,18,VPNAME,Win_0)
     WRITE(LINE,'(I2)') NCELL
     CALL WCOUP@(LINE, -1,18,2,Win_0)

     DO I = 1, NCELL
       WRITE(LINE1,'(I2)') I
       CALL WCOUP@(LINE1,WCOLOUR,3,I+6,Win_0)
     END DO

     VP = 7
     DO I = 1, NCELL

       HP = 8

      DO J = 1, 4
       IF(J .EQ. 1) THEN
         WRITE(LineV(J),'(F6.2)') DC(I)
```

```
        ELSEIF(J .EQ. 2) THEN
          WRITE(LineV(J),'(F6.2)') HD(I)
        ELSEIF(J .EQ. 3) THEN
          WRITE(LineV(J),'(F6.2)') LL(I)
        ELSEIF(J .EQ. 4) THEN
          WRITE(LineV(J),'(F6.2)') LR(I)
        ENDIF

       CALL WCOUP@(LineV(J),-1,HP,VP,Win_0)
       HP = HP+14
      END DO
       VP = VP+1
     END DO
*..................................................*

*................ Window control section ...........*
  3  KHPC = 1
     DO K = 1, NITEM
       CALL WCOUP@(Control(K),WCOLOUR,KHPC,VPC,Win_0)
       KHPC = KHPC + CM_TAB
     END DO

 13   CALL WCOUP@(Control(HPC),TCOLOUR,LHPC,VPC,Win_0)
     CALL WCOUP@(F_help(HPC),HELPCOL,2,VPC+1,Win_0)

  9  CALL GET_KEY@(KEY)

     IF(KEY.EQ.RIGHT_KEY .OR. KEY .EQ. TAB_KEY)THEN
        HPC = HPC + 1
        IF (HPC .GT. NITEM) HPC = 1

     ELSEIF(KEY.EQ.LEFT_KEY .OR. KEY .EQ. STAB_KEY)THEN
        HPC = HPC - 1
        IF (HPC .LT. 1) HPC = NITEM

     ELSEIF(KEY.EQ.ENTER_KEY) THEN
        IF(HPC.EQ.1)THEN
          CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_0)
          CALL WCOUP@(Blank,WCOLOUR,HP_H,VP_H,Win_0)
          GOTO 26
        ELSEIF(HPC.EQ.2 .AND. Advance .EQ. 1)THEN

         OPEN(11, FILE=FileName)
           WRITE(11,'(A40)') SiteName
           WRITE(11,*) NCELL
           DO I = 1, NCELL
             WRITE (11,131) I, DC(I), HD(I), LL(I), LR(I)
           END DO
 131         FORMAT(1X,I2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2)
         CLOSE(11)

         CALL SWIN1 (FileName, FileState, NCELL, Kill) !Open window 2

c  On return the FileName will be reset
             CALL SET_SUFFIX@(FileName, 'LDF', LOG)
```

```
          IF (Kill .EQ. 1) GOTO 99

        ELSEIF(HPC.EQ.3)THEN
          CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_0)
          CALL WCOUP@(Blank,WCOLOUR,HP_H,VP_H,Win_0)
          Wn = 1
          CALL WIN_HELP(Wn)
          GOTO 13
        ELSEIF(HPC.EQ. 4) THEN
          GOTO 99
        ENDIF

      ELSEIF(KEY.EQ.ESC_KEY) THEN
        HPC = NITEM
      ELSE
        CALL BEEP@
        GOTO 9
      ENDIF

      LHPC = 1+CM_TAB*(HPC-1)
      GOTO 3

*............... Data Editing .....................
 26   CALL WREAD_EDITED_LINE@(SiteName,18,VPNAME,Win_0,-1,IC)
      IF(IC .EQ. -1) GOTO 3
      CALL WCOUP@(SiteName,-1,18,VPNAME,Win_0)

 25   CALL WREAD_EDITED_LINE@(LINE,18,2,Win_0,-1,IC)
      IF(IC.EQ.-1) THEN
        CALL WCOUP@('                         ',-1,HP_R,VP_R,Win_0)
        GOTO 3
      ENDIF
      READ(LINE,*,ERR=10) NCELL
      IF(NCELL .GT. 0 .AND. NCELL .LT. 11) GOTO 6
 10   CALL WCOUP@('0'//' < VALUE < '//'11',RCOLR,HP_R,VP_R,Win_0)
      LINE=' '
      GOTO 25

  6   CALL WCOUP@('                         ',-1,HP_R,VP_R,Win_0)
      CALL WCOUP@(LINE,-1,18,2,Win_0)
      Advance = 0
*.........................................................*

*.... To clear previous values
      DO Im = 7, L
        CALL WCOUP@(MSG(Im),WCOLOUR,0,Im,Win_0)
      END DO

c... Writes new number of sides values
      DO I = 1, NCELL
        WRITE(LINE1,'(I2)')I
        CALL WCOUP@(LINE1,WCOLOUR,3,I+6,Win_0)
      END DO
```

```
*........................Entering Data..................*
    VP = 7
    DO I = 1, NCELL
      HP = 8                    ! Start value position

        J = 1
        WRITE(LineV(J),'(F6.2)') DC(I)
        J = J+1
        WRITE(LineV(J),'(F6.2)') HD(I)
        J = J+1
        WRITE(LineV(J),'(F6.2)') LL(I)
        J = J+1
        WRITE(LineV(J),'(F6.2)') LR(I)


    DO J = 1, 4

 21   CALL WREAD_EDITED_LINE@(LineV(J),HP,VP,Win_0,-1,IC)

        IF(IC.EQ.-1) THEN
          CALL WCOUP@('                    ',-1,HP_R,VP_R,Win_0)
          GOTO 3
        ENDIF
      READ(LineV(J),*,ERR=20) VALUE(J)
      IF(VALUE(J).GE.LLV(J) .AND. VALUE(J).LT. ULV(J)) GOTO 31
 20   CALL WCOUP@(LLC(J)//' < VALUE < '//ULC(J),RCOLR,HP_R,VP_R,Win_0)
      LineV(J) = ' '
      GOTO 21

 31   CALL WCOUP@('                    ',-1,HP_R,VP_R,Win_0)
      CALL WCOUP@('      ',-1,HP,VP,Win_0)

      IF(J .EQ. 1) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        DC(I) = VALUE(J)

        ULC(3) = LineV(J)
        ULV(3) = VALUE(J)

      ELSEIF(J .EQ. 2) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        HD(I) = VALUE(J)

      ELSEIF(J .EQ. 3) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        LL(I) = VALUE(J)

      ELSEIF(J .EQ. 4) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        LR(I) = VALUE(J)
      ENDIF

      CALL WCOUP@(LineV(J),-1,HP,VP,Win_0)
      HP = HP + 14
    END DO
```

```
       VP = VP+1
      END DO

      HPC = 2     ! After finishing entering values, Control at Next
      LHPC = 1 + CM_TAB*(HPC-1)
      Advance = 1
      GOTO 13

  99  CALL KILLW@(Win_0)

      RETURN

      END

C       PROGRAM WIN13
      SUBROUTINE SWIN1(FileName, FileState, NCELL, Kill)
      IMPLICIT INTEGER*2 (A-Z)
      PARAMETER (TC=10, TS=10)
      INCLUDE 'COLOURS.INS',NOLIST
      INCLUDE 'KEYS.INS'   ,NOLIST

      COMMON/Winhand/ Win_h, Win_0, Win_1, Win_2, Win_3

      CHARACTER LineV(5)*7, Msg(20)*80, LINE*2, LINE1*2
      CHARACTER LLC(5)*4,ULC(5)*4,Cell_P(TC)*2,Control(6)*4,F_help(6)*30
      CHARACTER FileName*13

      INTEGER*2 Nsides(TC), BC(TC,TS)
      REAL XC(TC,TS), YC(TC,TS), TB(TC,TS), KB(TC,TS)
      REAL LLV(5), ULV(5), VALUE(5)

c  Nsides  number od sides of a landfill cell
c  XC      X corordinate of cell node
c  YC      Y corordinate of cell node
c  BC      Boundary condition of a cell side
c  TB      Thickness of a barrier between two cells
c  KB      Saturated hydraulic conductivity of a barrier

      LOGICAL*2 LOG
      CALL SET_SUFFIX@(FileName, 'PLN', LOG)

      DATA LLV/  0.0,   0.0,  0.0,  0.0, 1e-7/
      DATA ULV/ 999.0, 999.0, 10.0, 10.0, 1e-4/

      ULV(3) = NCELL

      DATA LLC/  '0',     '0',  '0',  '0', '1e-7'/
      DATA ULC/ '1000', '1000', '10', '10', '1e-4'/

      DATA Control/'Edit','Back','Next','Help','^Q^Q^Q^Q','^P^P^P^P'/
      DATA F_HELP/
     & 'Edits an existing cell','Previous cell','Next cell',
     & 'Help about window','Returns to the previous window',
     & 'Saves data & Moves to the next window'/

      HELPCOL=BLUE+INVERSE_CYAN
```

```
*..................... Window Definition ..............*
      BORDER = 2
      SHADOW = 0
      HP1 = 2
      VP1 = 2
      WHS = 61
      WVS = 21
      WCOLOUR = BLACK+INVERSE_CYAN
      TCOLOUR = WHITE+INVERSE_BLUE+INTENSE
      RCOLR   = YELLOW+INVERSE_CYAN
      CALL WCREATE@(HP1,VP1,WHS,WVS,WCOLOUR,Win_1)
      CALL WBORDER@(Win_1,BORDER)
      CALL WSHADOW@(Win_1,SHADOW)
      CALL WTITLE@(Win_1,' Plan Data',TCOLOUR)
      CALL POPW@(Win_1)

      L=17
      Msg(1)='     Cell # . '
      Msg(2)='  No of Sides = '

Msg(3)=' ┌────────────┬────────────────────────────┬────────────
──┬──────────────┬──────────────────
     1──┐ '
      Msg(4)=' | Side  | Corrdinates      | Boundary | Thickness |     K
     1  | '
      Msg(5)=' |  #   |  X    |  Y     | Conditions |    m    | cm/sec
     1  | '

Msg(6)=' ├────────────┼─────────────┼──────────────┼────────────
──┼──────────────┼──────────────────
     1──┤ '
      Msg(7)=' |      |      |      |      |      |
     1  | '

Msg(L)=' └────────────┴─────────────┴──────────────┴────────────
──┴──────────────┴──────────────────
     1──┘ '
c          12345678901234567890123456789012345678901234567890123456789012345678
      DO Im = 8, L-1
        Msg(Im) = Msg(7)
      END DO

      DO Im = 1, L
        CALL WCOUP@(Msg(Im),WCOLOUR,0,Im,Win_1)
      END DO
        CALL WCOUP@('  Total Cells = ',WCOLOUR,0,0,Win_1)

*... Window Control parameters
      LINE = ' '
      NITEM = 6   ! NUMBER OF COMMANDS Edit Back etc
      HP_R = 2    ! Horizontal Position of Range
      VP_R = L+1  ! Vertical   Position of Range
      HPC = 1     ! Horizontal Position of Command
      VPC = L+2   ! Vertical   Position of Command
      LHPC = 1
      HP_H = 3    ! Horizontal Position of Help
```

```
      VP_H = L+3  ! Vertical   Position of Help
      CM_TAB = 10 ! Command Tab
*........................................

*... Data initialization .......
c      NCELL = 10  ! Number of Cells used in a file
      DATA Nsides/10*0/
      DATA XC/100*1.0/
      DATA YC/100*2.0/
      DATA BC/100*0/
      DATA TB/100*4.0/
      DATA KB/100*1E-6/
*.............

      M = 1
      DO N = 1, NCELL
       WRITE(Cell_P(N),'(I2)')N
      END DO

       IF (FileState .EQ. 1) THEN
          OPEN(10, FILE=FileName)
           READ(10,*) NCELL
            DO N = 1, NCELL
c              READ(10,*)
             READ(10,*) I, Nsides(N)
            DO J = 1, Nsides(N)
            READ(10,*) K, XC(N,J), YC(N,J), BC(N,J), TB(N,J), KB(N,J)
            END DO
           END DO
c 131         FORMAT(1X,I2,3X,F6.2,3X,F6.2,3X,I2,3X,F6.2,3X,E7.1)
          CLOSE(10)
       ENDIF

        WRITE(Line1,'(I2)') NCELL
        CALL WCOUP@(Line1, WHITE+INVERSE_RED+INTENSE,18,0,Win_1)

 33   HP = 1
      VP = 1

      CALL WCOUP@(Cell_P(M),TCOLOUR, 18,VP,Win_1)

c... If file exists then change all values
        WRITE(LINE1,'(I2)') Nsides(M)
        CALL WCOUP@(LINE1,-1,18,2,Win_1)
*.....................................*
*... To clear previous values
      DO I = 7, L
        CALL WCOUP@(Msg(I),WCOLOUR,0,I,Win_1)
      END DO

*...... Displays new values
      VP = 7
      DO I = 1, Nsides(M)
        WRITE(LINE1,'(I2)')I
        CALL WCOUP@(LINE1,WCOLOUR,3,I+6,Win_1)
        HP = 9
```

```
      DO J = 1, 5
       IF(J .EQ. 1) THEN
         WRITE(LineV(J),'(F6.2)') XC(M,I)
       ELSEIF(J .EQ. 2) THEN
         WRITE(LineV(J),'(F6.2)') YC(M,I)
       ELSEIF(J .EQ. 3) THEN
         WRITE(LineV(J),'(I2)') BC(M,I)
       ELSEIF(J .EQ. 4) THEN
         WRITE(LineV(J),'(F6.2)') TB(M,I)
       ELSEIF(J .EQ. 5) THEN
         WRITE(LineV(J),'(E7.1)') KB(M,I)
       ENDIF

      CALL WCOUP@(LineV(J),-1,HP,VP,Win_1)
      HP = HP + 10
     END DO
      VP = VP + 1
    END DO
*............... Window control section .................*
 3  KHPC = 1
    DO K = 1, NITEM
      CALL WCOUP@(Control(K),WCOLOUR,KHPC,VPC,Win_1)
      KHPC = KHPC + CM_TAB
    END DO

13  CALL WCOUP@(Control(HPC),TCOLOUR,LHPC,VPC,Win_1)
    CALL WCOUP@(F_help(HPC),HELPCOL,2,VPC+1,Win_1)

 9  CALL GET_KEY@(KEY)

    IF(KEY.EQ.RIGHT_KEY .OR. KEY .EQ. TAB_KEY)THEN
      HPC = HPC+1
      IF (HPC .GT. NITEM) HPC=1
    ELSEIF(KEY.EQ.LEFT_KEY .OR. KEY .EQ. STAB_KEY)THEN
      HPC = HPC-1
      IF (HPC .LT. 1) HPC=NITEM
    ELSEIF(KEY.EQ.ENTER_KEY) THEN
      IF(HPC.EQ.1)THEN
        CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_1)
    CALL WCOUP@('                              ',WCOLOUR,2,VPC+1,Win_1)
        WRITE(LINE,'(I2)')Nsides(M)
        GOTO 25
      ELSEIF(HPC.EQ.2)THEN
        IF(M.EQ.1) GOTO 9
        M=M-1
        GOTO 33
      ELSEIF(HPC.EQ.3)THEN
        IF(M.EQ.NCELL) GOTO 9
        M=M+1
        GOTO 33
      ELSEIF(HPC.EQ.4)THEN
        CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_1)
    CALL WCOUP@('                              ',WCOLOUR,2,VPC+1,Win_1)
        Wn = 2
```

```
           CALL WIN_HELP(Wn)
           GOTO 3

         ELSEIF(HPC.EQ.6)THEN   ! Saves File and advances

           DO K1 = 1, NCELL
              IF(Nsides(K1) .EQ. 0) THEN
                CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_1)
                M = K1
                HPC = 1
                LHPC = 1
                GOTO 33
              ENDIF
           END DO

          OPEN(11, FILE=FileName)
           WRITE(11,*) NCELL
            DO N = 1, NCELL
             WRITE(11,*)
             WRITE(11,*) N, Nsides(N)
            DO J = 1, Nsides(N)
            WRITE(11,131) J, XC(N,J), YC(N,J), BC(N,J), TB(N,J), KB(N,J)
            END DO
           END DO
 131         FORMAT(1X,I2,3X,F6.2,3X,F6.2,3X,I2,3X,F6.2,3X,E7.1)
          CLOSE(11)

           CALL SWIN2(FileName, FileState, NCELL, Kill)

c On return the FileName will be reset
           CALL SET_SUFFIX@(FileName, 'PLN', LOG)

           IF (Kill .EQ. 1) GOTO 99

         ELSE
           GOTO 99
         ENDIF
      ELSEIF(KEY.EQ.ESC_KEY) THEN
         HPC = NITEM - 1
      ELSE
         CALL BEEP@
         GOTO 9
      ENDIF

        LHPC = 1 + CM_TAB*(HPC-1)
      GOTO 3

25     CALL WREAD_EDITED_LINE@(LINE,18,2,Win_1,-1,IC)
       IF(IC.EQ.-1) THEN
         CALL WCOUP@('                    ',-1,HP_R,VP_R,Win_1)
         GOTO 3
       ENDIF
     READ(LINE,*,ERR=10) Nsides(M)
     IF(Nsides(M) .GE.3 .AND. Nsides(M) .LT. 11) GOTO 6
10    CALL WCOUP@('2'//' < VALUE < '//'11',RCOLR,HP_R,VP_R,Win_1)
```

```
      Nsides(M) = 0
      LINE=' '
      GOTO 25

  6   CALL WCOUP@('                    ',-1,HP_R,VP_R,Win_1)
      WRITE(LINE,'(I2)') Nsides(M)
      CALL WCOUP@(LINE,-1,18,2,Win_1)

*.............................................*

c... To clear previous values
      DO I = 7, L
        CALL WCOUP@(Msg(I),WCOLOUR,0,I,Win_1)
      END DO

c... Writes new number of sides values
      DO I = 1, Nsides(M)
        WRITE(LINE1,'(I2)')I
        CALL WCOUP@(LINE1,WCOLOUR,3,I+6,Win_1)
      END DO
*................. Entering Data ....................*
      VP = 7
      DO I = 1, Nsides(M)
        HP = 10                  ! Start value position

        J = 1
        WRITE(LineV(J),'(F6.2)') XC(M,I)
        J = J+1
        WRITE(LineV(J),'(F6.2)') YC(M,I)
        J = J+1
        WRITE(LineV(J),'(I2)')   BC(M,I)
        J = J+1
        WRITE(LineV(J),'(F6.2)') TB(M,I)
        J = J+1
        WRITE(LineV(J),'(E7.1)') KB(M,I)

      DO J = 1, 5

 21     CALL WREAD_EDITED_LINE@(LineV(J),HP,VP,Win_1,-1,IC)

         IF(IC.EQ.-1) THEN
           CALL WCOUP@('                    ',-1,HP_R,VP_R,Win_1)
           GOTO 3
         ENDIF
       READ(LineV(J),*,ERR=20) VALUE(J)
       IF(VALUE(J).GE.LLV(J) .AND. VALUE(J).LE. ULV(J)) GOTO 31
 20   CALL WCOUP@(LLC(J)//' < VALUE < '//ULC(J),RCOLR,HP_R,VP_R,Win_1)
       LineV(J) = ' '
       GOTO 21

 31    CALL WCOUP@('                    ',-1,HP_R,VP_R,Win_1)
       CALL WCOUP@('      ',-1,HP,VP,Win_1)

       IF(J .EQ. 1) THEN
         WRITE(LineV(J),'(F6.2)') VALUE(J)
         XC(M,I) = VALUE(J)
```

```
        ELSEIF(J .EQ. 2) THEN
          WRITE(LineV(J),'(F6.2)') VALUE(J)
          YC(M,I) = VALUE(J)

        ELSEIF(J .EQ. 3) THEN
          BC(M,I) = INT(VALUE(J))
          WRITE(LineV(J),'(I2)') BC(M,I)

        ELSEIF(J .EQ. 4) THEN
          WRITE(LineV(J),'(F6.2)') VALUE(J)
          TB(M,I) = VALUE(J)

        ELSEIF(J .EQ. 5) THEN
          WRITE(LineV(J),'(E7.1)') VALUE(J)
          KB(M,I) = VALUE(J)
        ENDIF

        CALL WCOUP@(LineV(J),-1,HP,VP,Win_1)
       HP = HP+10
      END DO
       VP = VP+1
     END DO

     HPC = 3     ! After finishing entering values, Control at Next
     LHPC = 1 + CM_TAB*(HPC-1)
     GOTO 13

  99 CALL KILLW@(Win_1)
     RETURN
     END

C     PROGRAM WIN13
     SUBROUTINE SWIN2(FileName,FileState,NCELL,Kill)
     IMPLICIT INTEGER*2 (A-Z)
     PARAMETER(TC=10,TL=10)
     INCLUDE 'COLOURS.INS',NOLIST
     INCLUDE 'KEYS.INS'   ,NOLIST

     COMMON/Winhand/ Win_h, Win_0, Win_1, Win_2, Win_3

     CHARACTER LineV(5)*7, Msg(20)*80, Line*2, Line1*2, Blk*40
     CHARACTER LLC(5)*4,ULC(5)*4,Cell_P(TC)*2,Control(6)*4,F_help(6)*30
     CHARACTER FileName*13

     INTEGER*2 Nlayers(TC),FM(TC,TL)
     REAL DL(TC,TL), DenL(TC,TL), KL(TC,TL), Th(TC,TL)
     REAL LLV(5), ULV(5), VALUE(5)

c   Nlayers number of layers in a cell
c   DL      depth of layer of a cell
c   FM      filling material used in a cell layer
c   DenL    density of a cell layer
c   KL      saturated hydraulic conductivty of a cell layer

     LOGICAL*2 LOG
     CALL SET_SUFFIX@(FileName, 'SEC', LOG)
```

```
      DATA LLV/ 0.0, 0.0,  0.0, 1e-7,0/
      DATA ULV/ 1000.0, 4.0, 999.0, 0.1,1/

      DATA LLC/  '0',      '123',  '0', '1e-7',  '0'/
      DATA ULC/ '1000',    'SWC', '1000', '0.1','1'/

      DATA Control/'Edit','Back','Next','Help','^Q^Q^Q^Q','^P^P^P^P'/
      DATA F_HELP/
     & 'Edits an existing cell','Previous cell','Next cell',
     & 'Help about this window','Returns to the previous window',
     & 'Saves data & Moves to the next window'/
      Blk ='                    '
      HELPCOL = BLUE+INVERSE_CYAN

*.................... Window Definition .................*
      BORDER = 2
      SHADOW = 0
      HP1 = 2
      VP1 = 2
      WHS = 61
      WVS = 21
      WCOLOUR = BLACK+INVERSE_CYAN
      TCOLOUR = WHITE+INVERSE_BLUE+INTENSE
      RCOLR   = YELLOW+INVERSE_CYAN
      CALL WCREATE@(HP1,VP1,WHS,WVS,WCOLOUR,Win_2)
      CALL WBORDER@(Win_2,BORDER)
      CALL WSHADOW@(Win_2,SHADOW)
      CALL WTITLE@(Win_2,' Section Data',TCOLOUR)
      CALL POPW@(Win_2)

      L = 17
      Msg(1)='          Cell # '
      Msg(2)='  No of Layers = '

 Msg(3)=' ┌───────────┬───────────────┬─────────────────┬──────────────
───┬──────────────┬─────────────
    1┐ '
      Msg(4)=' | Layer  |  Depth   | Material  | Density  |    K    |    Θ
    1 | '
      Msg(5)=' |   #    |    m     |  S1W2C3   | Kg/m^3  | cm/sec  | Vol/Vol
    1 | '

 Msg(6)=' ├───────────┼───────────────┼─────────────────┼──────────────
───┼──────────────┼─────────────
    1┤ '
      Msg(7)=' |        |          |           |          |         |
    1 | '

 Msg(L)=' └───────────┴───────────────┴─────────────────┴──────────────
───┴──────────────┴─────────────
    1┘ '
c          12345678901234567890123456789012345678901234567890123456789012345678
      DO Im = 8, L-1
        Msg(Im) = Msg(7)
      END DO
```

```
      DO Im = 1, L
        CALL WCOUP@(Msg(Im),WCOLOUR,0,Im,Win_2)
      END DO

      CALL WCOUP@('  Total Cells  =  ',WCOLOUR,0,0,Win_2)

 * Window control parameters ...........
      Line = ' '
      NITEM = 6   ! Number of Commands Edit Back etc
      HP_R = 2    ! Horizontal Position of Range
      VP_R = L+1  ! Vertical   Position of Range
      HPC = 1     ! Horizontal Position of Command
      VPC = L+2   ! Vertical   Position of Command
      LHPC = 1
      HP_H = 3    ! Horizontal Position of Help
      VP_H = L+3  ! Vertical   Position of Help
      CM_TAB = 10 ! Command Tab
 *.....................................................*

 *   Data intialization ........
 c     NCELL = 10  ! Number of Cells used in a file
      DATA Nlayers/10*0/
      DATA DL/100*10.0/
      DATA FM/100*2/
      DATA DenL/100*450.0/
      DATA KL/100*1E-6/
      DATA Th/100*0.4/
 *...........

      M = 1
      DO N = 1, NCELL
        WRITE(Cell_P(N),'(I2)') N
      END DO

      IF (FileState .EQ. 1) THEN
        OPEN(10, FILE=FileName)
         Read(10,*) NCELL
         DO N = 1, NCELL
         READ(10,*) K, Nlayers(N)
          DO J = 1, Nlayers(N)
            READ(10,*)I, DL(N,J), FM(N,J), DenL(N,J), KL(N,J), Th(N,J)
          END DO
        END DO
        CLOSE(10)
      ENDIF

       WRITE(Line1,'(I2)') NCELL
       CALL WCOUP@(Line1,WHITE+INVERSE_RED+INTENSE,18,0,Win_2)

 33   HP = 1
      VP = 1

      CALL WCOUP@(Cell_P(M),TCOLOUR,18,VP,Win_2)

c..... If file exists then change all values
```

```
      WRITE(Line1,'(I2)') Nlayers(M)
      CALL WCOUP@(Line1,-1,18,2,Win_2)

*.... To clear previous values............
     DO I = 7, L
       CALL WCOUP@(Msg(I),WCOLOUR,0,I,Win_2)
     END DO

*..... Displays new values
     VP = 7
     DO I = 1, Nlayers(M)
       WRITE(Line1,'(I2)')I
       CALL WCOUP@(Line1,WCOLOUR,3,I+6,Win_2)
       HP = 9
      DO J = 1, 5
       IF(J .EQ. 1) THEN
          WRITE(LineV(J),'(F6.2)') DL(M,I)
        ELSEIF(J .EQ. 2) THEN
          WRITE(LineV(J),'(I2)') FM(M,I)
        ELSEIF(J .EQ. 3) THEN
          WRITE(LineV(J),'(F6.2)') DenL(M,I)
        ELSEIF(J .EQ. 4) THEN
          WRITE(LineV(J),'(E7.1)') KL(M,I)
        ELSEIF(J .EQ. 5) THEN
          WRITE(LineV(J),'(F6.2)') Th(M,I)
       ENDIF

       CALL WCOUP@(LineV(J),-1,HP,VP,Win_2)
      HP = HP+10
     END DO
      VP = VP+1
    END DO

*................ Window control section ...........*
 3  KHPC = 1
    DO K = 1, NITEM
      CALL WCOUP@(Control(K),WCOLOUR,KHPC,VPC,Win_2)
      KHPC = KHPC + CM_TAB
    END DO

13  CALL WCOUP@(Control(HPC),TCOLOUR,LHPC,VPC,Win_2)
    CALL WCOUP@(F_help(HPC),HELPCOL,2,VPC+1,Win_2)

 9  CALL GET_KEY@(KEY)

    IF(KEY.EQ.RIGHT_KEY .OR. KEY .EQ. TAB_KEY)THEN
      HPC=HPC+1
      IF (HPC .GT. NITEM) HPC=1
    ELSEIF(KEY.EQ.LEFT_KEY .OR. KEY .EQ. STAB_KEY)THEN
      HPC=HPC-1
      IF (HPC .LT. 1) HPC=NITEM
    ELSEIF(KEY.EQ.ENTER_KEY) THEN
      IF(HPC.EQ.1)THEN
        CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_2)
        CALL WCOUP@(Blk,WCOLOUR,2,VPC+1,Win_2)
```

```
           WRITE(Line,'(I2)')Nlayers(M)
           GOTO 25
         ELSEIF(HPC.EQ.2)THEN
           IF(M.EQ.1) GOTO 9
           M=M-1
           GOTO 33
         ELSEIF(HPC.EQ.3)THEN
           IF(M.EQ.NCELL) GOTO 9
           M=M+1
           GOTO 33
         ELSEIF(HPC.EQ.4)THEN   ! Help window
           CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_2)
           CALL WCOUP@(Blk,WCOLOUR,2,VPC+1,Win_2)
           Wn = 3
           CALL WIN_HELP (Wn)
           GOTO 3

         ELSEIF(HPC.EQ.6)THEN   ! Saves File and advances

           DO K1 = 1, NCELL
             IF(Nlayers(K1) .EQ. 0) THEN
               CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_2)
               M = K1
               HPC = 1
               LHPC = 1
               GOTO 33
             ENDIF
           END DO

          OPEN(11, FILE=FileName)
           WRITE(11,*) NCELL
           DO N = 1, NCELL
            WRITE(11,*)
            WRITE(11,*) N, Nlayers(N)
           DO J = 1, Nlayers(N)
         WRITE(11,131) J, DL(N,J), FM(N,J), DenL(N,J), KL(N,J), Th(N,J)
           END DO
          END DO
  131      FORMAT(1X,I2,3X,F6.2,3X,I2,3X,F6.2,3X,E7.1,3X,F6.2)
         CLOSE(11)

         CALL SWIN3(FileName, FileState, Kill)

c On return from SWIN3, the FileName will be reset

            CALL SET_SUFFIX@(FileName, 'SEC', LOG)
           IF (Kill . EQ. 1) GOTO 99

        ELSE
         GOTO 99
        ENDIF
      ELSEIF(KEY.EQ.ESC_KEY) THEN
        HPC = NITEM - 1
      ELSE
        CALL BEEP@
```

```
        GOTO 9
      ENDIF

       LHPC = 1 + CM_TAB*(HPC-1)
      GOTO 3

 25    CALL WREAD_EDITED_LINE@(Line,18,2,Win_2,-1,IC)
       IF(IC.EQ.-1) THEN
         CALL WCOUP@(Blk,-1,HP_R,VP_R,Win_2)
         GOTO 3
       ENDIF
      READ(Line,*,err=10) Nlayers(M)
      IF(Nlayers(M) .GT.0 .AND. Nlayers(M) .LT. 11) GOTO 6
 10    CALL WCOUP@('0'//' < VALUE < '//'11',RCOLR,HP_R,VP_R,Win_2)
      Nlayers(M) = 0  ! very important
      Line=' '
      GOTO 25

  6    CALL WCOUP@(Blk,-1,HP_R,VP_R,Win_2)
      WRITE(Line,'(I2)') Nlayers(M)
      CALL WCOUP@(Line,-1,18,2,Win_2)

*......................................................*

c... To clear previous values
      DO I = 7, L
        CALL WCOUP@(Msg(I),WCOLOUR,0,I,Win_2)
      END DO

c... Writes new number of sides values
      DO I = 1, Nlayers(M)
        WRITE(Line1,'(I2)')I
        CALL WCOUP@(Line1,WCOLOUR,3,I+6,Win_2)
      END DO


*........................Entering Data..................*
      VP = 7
      DO I = 1, Nlayers(M)
        HP = 10                    ! Start value position

          J = 1
          WRITE(LineV(J),'(F6.2)') DL(M,I)
          J = J+1
          WRITE(LineV(J),'(I2)') FM(M,I)
          J = J+1
          WRITE(LineV(J),'(F6.2)') DenL(M,I)
          J = J+1
          WRITE(LineV(J),'(E7.1)') KL(M,I)
          J = J+1
          WRITE(LineV(J),'(F6.2)') Th(M,I)


      DO J = 1, 5

 21     CALL WREAD_EDITED_LINE@(LineV(J),HP,VP,Win_2,-1,IC)
```

```
        IF(IC.EQ.-1) THEN
          CALL WCOUP@(Blk,-1,HP_R,VP_R,Win_2)
          GOTO 3
        ENDIF
      READ(LineV(J),*,err=20) VALUE(J)
      IF(VALUE(J).GT.LLV(J) .AND. VALUE(J).LT. ULV(J)) GOTO 31
 20   CALL WCOUP@(LLC(J)//' < VALUE < '//ULC(J),RCOLR,HP_R,VP_R,Win_2)
      LineV(J) = ' '
      GOTO 21

 31    CALL WCOUP@(Blk,-1,HP_R,VP_R,Win_2)
      CALL WCOUP@('      ',-1,HP,VP,Win_2)

      IF(J .EQ. 1) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        DL(M,I) = VALUE(J)

      ELSEIF(J .EQ. 2) THEN
        FM(M,I) = INT(VALUE(J))
        WRITE(LineV(J),'(I2)') FM(M,I)

      ELSEIF(J .EQ. 3) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        DenL(M,I) = VALUE(J)

      ELSEIF(J .EQ. 4) THEN
        WRITE(LineV(J),'(E7.1)') VALUE(J)
        KL(M,I) = VALUE(J)

      ELSEIF(J .EQ. 5) THEN
        WRITE(LineV(J),'(F6.2)') VALUE(J)
        Th(M,I) = VALUE(J)

      ENDIF

      CALL WCOUP@(LineV(J),-1,HP,VP,Win_2)
      HP = HP+10
     END DO

      VP = VP+1
    END DO

    HPC = 3     ! After finishing entering values, Control at Next
    LHPC = 1 + CM_TAB*(HPC-1)
    GOTO 13

 99 CALL KILLW@(Win_2)
    RETURN
    END

C    PROGRAM WIN3
    SUBROUTINE SWIN3(FileName,FileState,Kill)
    IMPLICIT INTEGER*2 (A-Z)

    INCLUDE 'COLOURS.INS', NOLIST
```

```
      INCLUDE 'KEYS.INS'   , NOLIST

      COMMON/Winhand/ Win_h, Win_0, Win_1, Win_2, Win_3

      CHARACTER LineV(3)*6,Msg(20)*80,LINE*2,Blank*40
      CHARACTER LLC(3)*4,ULC(3)*4,Control(4)*4,F_help(4)*40
      CHARACTER FileName*13, TempF*13

      REAL Th_S_w, Th_S_f, Th_S_s, Th_W_f, Th_W_s, Th_C_s

      REAL LLV(3), ULV(3), VALUE(3)

      LOGICAL*2 LOG
      CALL SET_SUFFIX@(FileName, 'MOS', LOG)

      DATA LineV/'0','0','0'/
      DATA LLV  /0.0,0.0,0.0/
      DATA ULV  /1.0,1.0,1.0/
      DATA LLC  /'0','0','0'/
      DATA ULC  /'1','1','1'/

      DATA Control/'Edit','^Q^Q^Q^Q','Help','Exit'/
      DATA F_help/
     & 'Edits an existing window','Returns to the previous window',
     & 'Help about this window','Saves File & Exits to the main menu'/

      Blank = '                                        '

*.................... Window Definition ..............*
      BORDER = 2
      SHADOW = 0
      HP = 2
      VP = 2
      WHS = 50
      WVS = 21
      WCOLOUR = BLACK+INVERSE_CYAN
      TCOLOUR = WHITE+INVERSE_BLUE+INTENSE
      V_LIM_C = YELLOW+INVERSE_CYAN
      CALL WCREATE@(HP,VP,WHS,WVS,WCOLOUR,Win_3)
      CALL WBORDER@(Win_3,BORDER)
      CALL WSHADOW@(Win_3,SHADOW)
      CALL WTITLE@(Win_3,' Moisture Capacities',TCOLOUR)
      CALL POPW@(Win_3)

      Msg(1) =' Moisture Capacities of Different Materials '
                                             Msg(2)
=' ┌──────────────────┬────────────────────────────────────────────────
─────────┐ '
      Msg(3) =' |          |           Volume Basis          | '
                    Msg(4)      = ' |         Material
├─────────────────┬──────────────────────────┬──────────────────────────┤ '
      Msg(5) =' |          |   Θw    |    Θf    |   Θs    | '
                                             Msg(6)
=' ├─────────────────┼──────────────────┼──────────────────┼────────────
─────────┤ '
      Msg(7) =' |          |         |          |         | '
```

```
      Msg(8) =' |  Soil   |          |          |          |'
      Msg(9) =' |         |          |          |          |'
      Msg(10)=' |  Waste  |    NA    |          |          |'
      Msg(11)=' |         |          |          |          |'
      Msg(12)=' |  Liner  |    NA    |    NA    |          |'
      Msg(13)=' |         |          |          |          |'

Msg(14)=' └──────────────────────────┴──────────────────────────┴──────────────────────────┴─────
──────────────────┘'
c            12345678901234567890123456789012345678901234567890123456789012345678
c                    *           *           *

      DO Im = 1, 14
        CALL WCOUP@(Msg(Im),WCOLOUR,0,Im,Win_3)
      END DO

      LINE = ' '
      NITEM = 4 ! NUMBER OF COMMANDS Edit Back etc
      VPC   = WVS-2
      HPC = 1
      LHPC= 1
*...................................................*

*..... Data Initialization
      Th_S_w = 0.2
      Th_S_f = 0.3
      Th_S_s = 0.45
      Th_W_f = 0.32
      Th_W_s = 0.55
      Th_C_s = 0.35
      Advance = 0
*..... If File exists
      IF (FileState .EQ. 1) THEN
        Advance = 1
        OPEN(10, FILE=FileName)
          READ(10,*) Th_S_w, Th_S_f, Th_S_s
          READ(10,*) Th_W_f, Th_W_s
          READ(10,*) Th_C_s
        CLOSE(10)
      ENDIF
*........

*....... Display values
      VP = 8
      DO I = 1, 3
        HP = 14                   ! START VALUE POSITION
        IF (I .EQ. 1) THEN
          WRITE(LineV(1), '(F6.2)') Th_S_w
          WRITE(LineV(2), '(F6.2)') Th_S_f
          WRITE(LineV(3), '(F6.2)') Th_S_s
        ELSEIF (I .EQ. 2) THEN
          WRITE(LineV(2), '(F6.2)') Th_W_f
          WRITE(LineV(3), '(F6.2)') Th_W_s
        ELSEIF (I .EQ. 3) THEN
          WRITE(LineV(3), '(F6.2)') Th_C_s
        ENDIF
```

```
     DO J = 1, 3
       IF (I .EQ. 2 .AND. J .EQ. 1) GOTO 22
       IF (I .EQ. 3 .AND. J .EQ. 1) GOTO 22
       IF (I .EQ. 3 .AND. J .EQ. 2) GOTO 22
       CALL WCOUP@(LineV(J),-1,HP,VP,Win_3)
 22     HP = HP + 11
     END DO
      VP = VP + 2
    END DO
*......................

 3  KHPC = 1
    DO K = 1, NITEM
      CALL WCOUP@(Control(K),WCOLOUR,KHPC,VPC,Win_3)
      KHPC = KHPC+10
    END DO

    HP = 1
    VP = 1

13   CALL WCOUP@(Control(HPC),WHITE+INVERSE_BLUE+INTENSE,LHPC,VPC
   &,Win_3)
    CALL WCOUP@(F_help(HPC),BLUE+INVERSE_CYAN,2,VPC+1,Win_3)

 9  CALL GET_KEY@(KEY)

    IF(KEY.EQ.RIGHT_KEY .OR. KEY .EQ. TAB_KEY)THEN
      HPC=HPC+1
      IF (HPC .GT. NITEM) HPC=1
    ELSEIF(KEY.EQ.LEFT_KEY .OR. KEY .EQ. STAB_KEY)THEN
      HPC=HPC-1
      IF (HPC .LT. 1) HPC=NITEM
    ELSEIF(KEY.EQ.ENTER_KEY) THEN
      IF(HPC.EQ.1)THEN
        CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_3)
        CALL WCOUP@(Blank,WCOLOUR,2,VPC+1,Win_3)
        GOTO 25

      ELSEIF(HPC .EQ. 2) THEN
        Kill = 0
        GOTO 99

      ELSEIF(HPC.EQ.3)THEN
        CALL WCOUP@(Control(HPC),WCOLOUR,LHPC,VPC,Win_3)
        CALL WCOUP@(Blank,WCOLOUR,2,VPC+1,Win_3)
        Wn = 4
        CALL WIN_HELP (Wn)
        GOTO 13

     ELSEIF(HPC.EQ.4)THEN ! Saves file and exists to main menu

      OPEN(11, FILE=FileName)
       WRITE(11,*) Th_S_w, Th_S_f, Th_S_s
       WRITE(11,*) Th_W_f, Th_W_s
```

```
        WRITE(11,*) Th_C_s
       CLOSE(11)
        Kill = 1
        GOTO 99
      ENDIF
    ELSEIF(KEY.EQ.ESC_KEY) THEN
       HPC=NITEM
    ELSE
      CALL BEEP@
      GOTO 9
    ENDIF

     LHPC = 1+10*(HPC-1)
    GOTO 3

25    VP = 8

    DO I = 1, 3
      HP = 14                   ! START VALUE POSITION

      IF (I .EQ. 1) THEN
        WRITE(LineV(1), '(F6.2)') Th_S_w
        WRITE(LineV(2), '(F6.2)') Th_S_f
        WRITE(LineV(3), '(F6.2)') Th_S_s
      ELSEIF (I .EQ. 2) THEN
        WRITE(LineV(2), '(F6.2)') Th_W_f
        WRITE(LineV(3), '(F6.2)') Th_W_s
      ELSEIF (I .EQ. 3) THEN
        WRITE(LineV(3), '(F6.2)') Th_C_s
      ENDIF

     DO J = 1, 3
       IF (I .EQ. 2 .AND. J .EQ. 1) GOTO  12
       IF (I .EQ. 3 .AND. J .EQ. 1) GOTO  12
       IF (I .EQ. 3 .AND. J .EQ. 2) GOTO  12

21     CALL WREAD_EDITED_LINE@(LineV(J),HP,VP,Win_3,-1,IC)
        IF(IC.EQ.-1) THEN
          CALL WCOUP@(Blank,-1,2,18,Win_3)
          Advance = 0
          GOTO 3
        ENDIF
      READ(LineV(J),*,ERR=20) VALUE(J)
      IF(VALUE(J).GT.LLV(J) .AND. VALUE(J).LT. ULV(J)) GOTO 31
20    CALL WCOUP@(LLC(J)//' < VALUE < '//ULC(J),V_LIM_C,2,18,Win_3)
      LineV(J)=' '
      GOTO 21

31    CALL WCOUP@(Blank,-1,2,18,Win_3)
      CALL WCOUP@('      ',-1,HP,VP,Win_3)

      WRITE(LineV(J),'(F6.2)') VALUE(J)

      IF (I .EQ. 1) THEN
        IF(J .EQ. 1)  THEN
```

```
          Th_S_w = VALUE(J)
         ELSEIF(J .EQ. 2)  THEN
          Th_S_f = VALUE(J)
         ELSEIF(J .EQ. 3)  THEN
          Th_S_s = VALUE(J)
         ENDIF

       ELSEIF (I .EQ. 2) THEN

         IF(J .EQ. 2) THEN
          Th_W_f = VALUE(J)
         ELSEIF(J .EQ. 3) THEN
          Th_W_s = VALUE(J)
         ENDIF
       ELSE
          Th_C_s = VALUE(J)
       ENDIF

      CALL WCOUP@(LineV(J),-1,HP,VP,Win_3)

 12    HP = HP + 11
      END DO
     VP = VP + 2
    END DO

    HPC  = 4
    LHPC = 1+10*(HPC-1)
c    LHPC = 21
    GOTO 13

 99 CALL KILLW@(Win_3)
    RETURN
    END


        SUBROUTINE WIN_HELP(Wn)

        PARAMETER (NL=1000)
        IMPLICIT INTEGER*2(A-Z)
        INCLUDE 'KEYS.INS',NOLIST
        INCLUDE 'COLOURS.INS',NOLIST
        INTEGER*2 Nrows(5)
        CHARACTER CENTRE@*80, Hline(5, NL)*80, CR*5
        COMMON/hlp/ Nrows, Hline

        CALL RESTORE_CURSOR@
        N0 = 0
C  Open the window display
        N = Nrows(Wn)
        HP = 6
        VP = 3
        HS = 70
        VS = 15
        WCOLOR = BLACK+INVERSE_CYAN
        TCOLOR = BLUE +INVERSE_WHITE
```

```
      CALL WCREATE@(HP,VP,HS,VS,WCOLOR,Win_h)
      CALL WTITLE@(Win_h,' Help Window ',TCOLOR)
      CALL POPW@(Win_h)


      CALL WCOUP@(CENTRE@('Use cursor keys to scroll, Esc when finished
     +',HS), TCOLOR,0,VS-1,Win_h)

      LN = 1
      K  = 1
      IF (N .GT. VS) THEN
       NOLINES = VS-3
      ELSE
       NOLINES = N - 1
      ENDIF

    6 M = 1
      DO J = LN, NOLINES+LN
       IF(Hline(Wn,J)(1:1) .EQ. 'Φ') THEN
         CALL WCOUP@(Hline(Wn,J)(2:),RED+INVERSE_CYAN,0,M,Win_h)
       ELSE
         CALL WCOUP@(Hline(Wn,J),-1,0,M,Win_h)
       ENDIF
       M = M+1
      END DO

    5 CALL SET_CURSOR_POSW@ (Win_h, N0, K)

      WRITE(CR,'(I5)') LN + K - 1
      CALL WCOUP@(CR,WHITE+INVERSE_BLUE+INTENSE,1,VS-1,Win_h)

C  WAIT FOR THE USER TO PRESS A KEY
    9 CALL GET_KEY@(KEY)

      IF(KEY.EQ.ESC_KEY)THEN
        FILE= ' '
        GOTO 17

      ELSEIF(KEY.EQ.DOWN_KEY)THEN
        IF (K .LT. VS-2)THEN
          K = K + 1
          GOTO 5
        ELSEIF (LN+NOLINES .LT. N) THEN
          LN = LN+1
        ENDIF

      ELSEIF(KEY.EQ.PGDOWN_KEY)THEN
        LN=LN+NOLINES
        IF(LN+NOLINES .GE. N) LN=N-NOLINES

      ELSEIF(KEY.EQ.UP_KEY)THEN
        IF (K.GT.1)THEN
         K=K-1
         GOTO 5
        ELSEIF(LN .GT. 1) THEN
```

```
                LN=LN-1
              ENDIF

           ELSEIF (KEY .EQ. PGUP_KEY) THEN
              LN = LN - NOLINES
              IF (LN .LE. 1)   THEN
               LN = 1
               K = 1
              ENDIF
           ELSEIF (KEY .EQ. END_KEY) THEN
              LN = N - NOLINES
              K = VS-2

           ELSEIF (KEY .EQ. HOME_KEY) THEN
              LN = 1
              K = 1
           ELSE
              GOTO 9
           ENDIF
           GOTO 6

  17  CALL HIDE_CURSOR@
           CALL KILLW@(Win_h)
           RETURN
           END

      subroutine SPLAN
      PARAMETER(NTLAYERS=10,NTCELL=10,NTC=10)
C       IMPLICIT INTEGER*2(A-Z)
      include 'colours.ins'
      INTEGER*2 YDEPTH2(NTCELL,NTLAYERS),HANDLE(NTCELL),ERROR_CODE
      INTEGER*2 CELL_NS(NTCELL),NLAYERS(NTLAYERS),K

      REAL XC(NTCELL,NTC),YC(NTCELL,NTC),XMAX,XMIN,XCMAX(NTCELL),
     & XCMIN(NTCELL),YMAX,YMIN,YCMAX(NTCELL),YCMIN(NTCELL)
      INTEGER*2 AREA(NTCELL)

      INTEGER*2 IXC(NTCELL),IYC(NTCELL),N(10),XCMID(10),YCMID(10)
      INTEGER*2 XCAVG(10),YCAVG(10)
      CHARACTER*2 CELL_N(NTCELL)

      COMMON/AREAP/AREA

C       COMMON/SECTION/NLAYERS(NTLAYERS),YDEPTH2(NTCELL,NTLAYERS)
*
      OPEN(3,FILE='PLAN.DAT')
        READ (3,*) NCELL
        DO I = 1, NCELL
          READ(3,*) N(I)
          READ(3,*) (XC(I,J),YC(I,J),J=1,N(I)+1)
        END DO
      CLOSE(3)

c AREA of POLYGONE

      DO I = 1, NCELL
```

```
      SUM=0
      YC(I,N(I)+1)=YC(I,1)
       DO j = 2, N(I)
         SUM=SUM+(XC(I,1)-XC(I,J))*(YC(I,J+1)-YC(I,J-1))
       END DO
      AREA(I) = INT(ABS(SUM)/2.)
     END DO
*
     OPEN(4,FILE='SECTION.DAT')
       READ(4,*)NCELLS
       DO I=1,NCELLS
         READ(4,*)CELL_NS(I)
         READ(4,*)NLAYERS(I)
         READ(4,*)(YDEPTH2(I,J),J=1,NLAYERS(I))
       END DO
     CLOSE(4)
*

     DO I = 1, NCELL
       XMAX = XC(I,1)
       XMIN = XMAX
       YMAX = YC(I,1)
       YMIN = YMAX
         DO J = 1, N(I)
           XMAX = MAX(XMAX,XC(I,J))
           XMIN = MIN(XMIN,XC(I,J))
           YMAX = MAX(YMAX,YC(I,J))
           YMIN = MIN(YMIN,YC(I,J))
         END DO
       XCMAX(I) = XMAX
       XCMIN(I) = XMIN
       YCMAX(I) = YMAX
       YCMIN(I) = YMIN
     END DO

       XMAX1 = XCMAX(1)
       XMIN1 = XCMIN(1)
       YMAX1 = YCMAX(1)
       YMIN1 = YCMIN(1)

     DO I = 1, NCELL

       XMAX1 = MAX(XMAX1,XCMAX(I))
       XMIN1 = MIN(XMIN1,XCMIN(I))
       YMAX1 = MAX(YMAX1,YCMAX(I))
       YMIN1 = MIN(YMIN1,YCMIN(I))

     END DO
       XMAX1= XMAX1 * 1.05
       XMIN1= XMIN1 * 1.05

       YMAX1= YMAX1 * 1.05
       YMIN1= YMIN1 * 1.05

C       XMIN1=0.0
```

```
      IF(XMAX1 .GT. YMAX1) THEN
          SCALE = (470.0-20.0)/(XMAX1-XMIN1)
      ELSE
          SCALE = (470.0-20.0)/(YMAX1-YMIN1)
      ENDIF

C      YSCALE = XSCALE
c     SCALE = XSCALE
C      SCALE = 2.5    ! FUNCTION OF A XMAX AND XMIN

      DO I = 1, NCELL
        DO J = 1, N(I)+1
          XC(I,J) = XC(I,J) * SCALE
          YC(I,J) = 470.0 - YC(I,J) * SCALE
        END DO
      END DO

      DO I = 1, NCELL
       XMAX = XC(I,1)
       XMIN = XMAX
       YMAX = YC(I,1)
       YMIN = YMAX
        DO J = 2, N(I)
          XMAX = MAX(XMAX,XC(I,J))
          XMIN = MIN(XMIN,XC(I,J))
          YMAX = MAX(YMAX,YC(I,J))
          YMIN = MIN(YMIN,YC(I,J))
        END DO
       XCMAX(I) = XMAX
       XCMIN(I) = XMIN
       YCMAX(I) = YMAX
       YCMIN(I) = YMIN

       XCMID(I) = (XCMAX(I)+XCMIN(I))/2.0
       YCMID(I) = (YCMAX(I)+YCMIN(I))/2.0
       WRITE(CELL_N(I),'(I2)')I
      END DO

      DO I = 1, NCELL
       XAVG = XC(I,1)
       YAVG = YC(I,1)
        DO J = 2, N(I)
          XAVG = XAVG+XC(I,J)
          YAVG = YAVG+YC(I,J)
        END DO
       XCAVG(I) = XAVG/N(I)
       YCAVG(I) = YAVG/N(I)
      END DO

      CALL VGA@
      CALL SET_TEXT_ATTRIBUTE@(1,1.0,0.0,0.0) !DEFAULT VALUES

      CALL rectangle@ (0,0,639,479,RED)
      CALL rectangle@ (1,1,638,478,12)
```

```
  5  CALL CLEAR_SCREEN_AREA@(2,2,637,477,0)

      call rectangle@ (20,20,470,470,BLUE)

      CALL DRAW_TEXT@('Press a Cell # or Esc to Exit',26,26,green)

     DO I=1,NCELL
       DO J=1,N(I)+1
         IXC(J)=XC(I,J)
         IYC(J)=YC(I,J)
       END DO
      CALL POLYLINE@(IXC,IYC,N(I)+1,I+1)
      CALL DRAW_TEXT@(CELL_N(I),XCAVG(I),YCAVG(I),15)
      CALL CREATE_POLYGON@(IXC,IYC,N(I),HANDLE(I),ERROR_CODE)
     END DO

  3  CALL GET_KEY@(K)

     IF(K.GE.49 .AND. K.LE.54) THEN
       I=K-48
       CALL FILL_POLYGON@(HANDLE(I),3,ERROR_CODE)
       CALL DRAW_TEXT@(CELL_N(I),XCAVG(I),YCAVG(I),0)
       CALL SECTION(I,NLAYERS(I),YDEPTH2,CELL_N)

     ELSEIF(K.EQ.27) THEN
       GOTO 13

     ELSE
       CALL CLEAR_SCREEN_AREA@(480,470,600,60,0)
       GOTO 3
     ENDIF

     CALL GET_KEY@(K)
     GOTO 5

 13  CALL TEXT_MODE@
     return
     END

**************
     SUBROUTINE SECTION(II,NLAYERS,YDEPTH2,CELL_N)
     PARAMETER(NTLAYERS=10)
     INTEGER*2 YDEPTH2(10,10),YDEPTH(NTLAYERS),ERROR_CODE,ISCALE
C      COMMON/SECTION/NLAYERS(NTLAYERS),YDEPTH2(NTCELL,NTLAYERS)

     INTEGER*2 AREA(10)
     COMMON/AREAP/AREA

     CHARACTER*2 CELL_N(10), STR*4

     ISUMD = 0
     DO I=1,NLAYERS
       YDEPTH(I)=YDEPTH2(II,I)
       ISUMD = ISUMD + YDEPTH(I)
     END DO
```

```
      ISCALE = 3
      IBASE = 460

      YDEPTH(1)=IBASE-YDEPTH(1)*ISCALE
      DO I=2,NLAYERS
        YDEPTH(I)=YDEPTH(I-1)-YDEPTH(I)*ISCALE
      END DO

      IX1 = 480
      IX2 = 600

      CALL CLEAR_SCREEN_AREA@(IX1,IBASE,IX2,60,0)
      CALL DRAW_LINE@(IX1,IBASE,IX2,IBASE,15)
      CALL DRAW_LINE@(IX1,IBASE,IX1,YDEPTH(NLAYERS),15)
      CALL DRAW_LINE@(IX2,IBASE,IX2,YDEPTH(NLAYERS),15)

      DO I=1,NLAYERS
        CALL DRAW_LINE@(IX1,YDEPTH(I),IX2,YDEPTH(I),4)
      END DO


      CALL DRAW_TEXT@('Cell No     = ',460,IBASE-420,15)

      CALL DRAW_TEXT@(CELL_N(II), 570,IBASE-420,15)

      CALL DRAW_TEXT@('Area (m^2) = ',460,IBASE-400,15)

        WRITE(STR,'(I4)')AREA(II)
      CALL DRAW_TEXT@(STR,        570,IBASE-400,15)

      CALL DRAW_TEXT@('Depth (m)  = ',460,IBASE-380,15)

        WRITE(STR,'(I3)')ISUMD
      CALL DRAW_TEXT@(STR,        570,IBASE-380,15)


      CALL DRAW_TEXT@('Layers      = ', 460,IBASE-360,15)
        WRITE(STR,'(I2)')NLAYERS
      CALL DRAW_TEXT@(STR,        570,IBASE-360,15)
      RETURN
      END

C       PROGRAM SIMULATION
      SUBROUTINE SIMULATION
      IMPLICIT INTEGER*2 (A-Z)
      PARAMETER(NMSGL=13)
      INCLUDE 'COLOURS.INS'
      INCLUDE 'KEYS.INS'

      CHARACTER MSG(NMSGL)*25,DATEC(2)*10,OK*1,TDAYSC*6
      CHARACTER CONTROL(4)*4,F_HELP(4)*30,BLKH*30,YESNO*3
      INTEGER*2 MSGL(3), MSGE(8), NDAYS(2)

      DATA CONTROL/'Edit','Run','Help','Exit'/
      DATA F_HELP/'Edits an existing window','Starts simulation',
     &'Help about window','Exits to the main menu'/
```

```
      BLKH='                    '
      YESNO='NO'

      DATA MSG/
     & 'Simulation Input Files :',   ! 1
     & ' Simulation File       :',   ! 2
     & ' Cimatic Data Fie      :',   ! 3
     & ' Landfill Data File    :',   ! 4
     & ' Topographic Data File :',   ! 5
     & ' Section Data File     :',   ! 6
     & '   ****************    ',    ! 7 *
     & 'Simulation period :',        ! 8
     & '        Starting  date:',    ! 9
     & '        Finishing date:',    ! 10
     & '        Number of days:',    ! 11
     & '   ****************    ',    ! 12 *
     & 'Simulation Output Files:'/   ! 13

      DATA MSGL/ 1, 8, 13/
      DATA MSGE/2, 3, 4, 5, 6, 9, 10 , 13/
      MSGC = RED+INVERSE_WHITE
      RCOLR= WHITE+INVERSE_RED+INTENSE
      BORDER6 = 2
      SHADOW6 = 0
      WTEXTC = BLACK+INVERSE_WHITE
      HP6 = 5
      VP6 = 2
      VS6 = 21
      HS6 = 45
      CALL WCREATE@(HP6,VP6,HS6,VS6,BLACK+INVERSE_WHITE,HAN)
      CALL WBORDER@(HAN,BORDER6)
      CALL WSHADOW@(HAN,SHADOW6)
      CALL WTITLE@(HAN,' SIMULATION',WHITE+INVERSE_BLUE)

      DO I = 1, NMSGL
       CALL WCOUP@(MSG(I),WTEXTC,0,I+1,HAN)
      END DO

      DO I=1,3
       CALL WCOUP@(MSG(MSGL(I)),MSGC,0,MSGL(I)+1,HAN)
      END DO

c      CALL WCOUP@('Files F1 Key',WHITE+INVERSE_BLUE,0,8,HAN)

      CALL POPW@(HAN)

      NITEM = 4 ! NUMBER OF COMMANDS Edit Back etc
      VPC = VS6 - 2
      HPC = 1
      LHPC= 1
      DATEC(1) = 'dd-mm-year'


 3    KHPC = 1
      DO K = 1, NITEM
       CALL WCOUP@(CONTROL(K),WCOLOUR,KHPC,VPC,HAN)
```

```
      KHPC = KHPC+10
     END DO

           1          3          C              A              L              L
WCOUP@(CONTROL(HPC),WHITE+INVERSE_BLUE+INTENSE,LHPC,VPC,HAN)
     CALL WCOUP@(F_HELP(HPC),BLUE+INVERSE_CYAN,2,VPC+1,HAN)

  9  CALL GET_KEY@(KEY)

     IF(KEY.EQ.RIGHT_KEY .OR. KEY .EQ. TAB_KEY)THEN
       HPC = HPC+1
       IF (HPC .GT. NITEM) HPC = 1

     ELSEIF(KEY.EQ.LEFT_KEY .OR. KEY .EQ. STAB_KEY)THEN
       HPC = HPC-1
       IF (HPC .LT. 1) HPC = NITEM

     ELSEIF(KEY.EQ.ENTER_KEY) THEN
       IF(HPC.EQ.1)THEN
         CALL WCOUP@(CONTROL(HPC),WCOLOUR,LHPC,VPC,HAN)
         CALL WCOUP@(BLKH,WCOLOUR,2,VPC+1,HAN)
         S=1
         GOTO 25
       ELSEIF(HPC.EQ.2)THEN
         CALL WCOUP@(CONTROL(HPC),-1,LHPC,VPC,HAN)
         CALL WCOUP@(BLKH,WCOLOUR,2,VPC+1,HAN)
         CALL STARTER(YESNO,TDAYS)
         GOTO 13

       ELSEIF(HPC.EQ.3)THEN
         CALL WCOUP@(CONTROL(HPC),-1,LHPC,VPC,HAN)
         CALL WCOUP@(BLKH,WCOLOUR,2,VPC+1,HAN)
          Wn = 5
          CALL WIN_HELP(Wn)
         GOTO 13

       ELSE
         GOTO 99
       ENDIF

     ELSEIF(KEY.EQ.ESC_KEY) THEN
        HPC = NITEM
     ELSE
       CALL BEEP@
       GOTO 9
     ENDIF

      LHPC = 1+10*(HPC-1)
     GOTO 3

*.........................*
 25  DO J = S, 2
 26    CALL WREAD_EDITED_LINE@(DATEC(J),26,J+9,HAN,-1,IC)
      IF(IC.EQ.-1) THEN
        CALL WCOUP@(BLKH,-1,1,18,HAN)
```

```
          GOTO 13
        ENDIF

        CALL CHECKDATE(DATEC(J),OK,NDAYS(J))  !Call Checkdata Subroutine

        IF (OK .EQ. 'N') THEN
          CALL WCOUP@('Date is incorrect',RCOLR,1,18,HAN)
          GOTO 26
        ENDIF

          CALL WCOUP@(BLKH,-1,1,18,HAN)
          CALL WCOUP@(DATEC(J),-1,26,J+9,HAN)
          IF(J .EQ. 1) DATEC(2)=DATEC(1)
      END DO

      TDAYS = NDAYS(2)-NDAYS(1)
       IF(TDAYS .LT. 0) THEN
         CALL WCOUP@('Date is incorrect',RCOLR,1,18,HAN)
         S=2
         GOTO 25
       ENDIF
      S=1
      WRITE(TDAYSC, '(I6)')TDAYS
      CALL WCOUP@(TDAYSC,TCOLOUR_H,26,12,HAN)
      YESNO='YES'
      GOTO 13
*..................................*

 99  CALL KILLW@(HAN)
      RETURN
      END


      SUBROUTINE CHECKDATE(LINED,OK,NDAYS)
      INTEGER*2 MONTHDAYS(12),YEAR,MONTH,DAY
      CHARACTER LINED*10,OK*1,CD*2,CM*2,CY*4
      DATA MONTHDAYS/31,28,31,30,31,30,31,31,30,31,30,31/

      READ(LINED(1: 2),*,ERR=10) DAY
      READ(LINED(4: 5),*,ERR=10) MONTH
      READ(LINED(7:10),*,ERR=10) YEAR

      IF (MOD(YEAR,4) .EQ. 0) MONTHDAYS(2)=29

      IF(YEAR .GE. 1980 .AND. YEAR .LE. 2030) THEN
       IF(MONTH .GT. 0 .AND. MONTH .LT. 13) THEN
        IF( DAY .GT. 0 .AND. DAY .LE. MONTHDAYS(MONTH)) THEN
          OK='Y'
          CALL NODAYS(DAY,MONTH,YEAR,NDAYS)
          WRITE(CD,'(I2)')DAY
          WRITE(CM,'(I2)')MONTH
          WRITE(CY,'(I4)')YEAR
          LINED=CD//'-'//CM//'-'//CY
          GOTO 25
        ENDIF
```

```
        ENDIF
      ENDIF

   10 OK='N'
      NDAYS=0
   25 RETURN
      END

      SUBROUTINE NODAYS(ID,IM,IYR,NDAYS)
      INTEGER*2 IYR,IM,ID, NDAYS
      INTEGER*4 M1,I1,IDAY,LEAPS,BYR
      BYR=1990
      M1=MOD(IM+9,12)+1
      I1=(13*M1-1)/5 -2
      IDAY=ID+28*(M1-1)+I1
      NYR=IYR-BYR-M1/11
      LEAPS=NYR/4-NYR/100+NYR/400
      NDAYS=IDAY+365*NYR+LEAPS

      RETURN
      END

      SUBROUTINE STARTER(YESNO,TDAYS)
      IMPLICIT INTEGER*2 (A-Z)
      INCLUDE 'COLOURS.INS'
      INCLUDE 'KEYS.INS'
      CHARACTER YESNO*3,INC*4, FileName*13

*.................... Starter Window .....................*
      HP_S = 10
      VP_S = 10
      HS_S = 30
      VS_S = 6
      BORDER_S = 0
      SHADOW_S = 3
      WCOLOUR_S = WHITE+INVERSE_BLUE+INTENSE
      TCOLOUR_S = WHITE+INVERSE_RED+INTENSE

      CALL WCREATE@(HP_S,VP_S,HS_S,VS_S,WCOLOUR_S,HAN_S)
      CALL WBORDER@(HAN_S,BORDER_S)
      CALL WSHADOW@(HAN_S,SHADOW_S)
      CALL WTITLE@(HAN_S,' PROCESSING WINDOW',TCOLOUR_S)
*******************************************************
      FileName = 'TEST'
      CALL POPW@(HAN_S)
      IF(YESNO .EQ. 'NO') THEN
        CALL WCOUP@(YESNO,-1,2,2,HAN_S)
      ELSE
        CALL WCOUP@(' PLEASE WAIT ',WCOLOUR_S+BLINKING,2,4,HAN_S)
c        CALL RESERVOIR(HAN_S,TDAYS)
         CALL SURFACE(FileName,TDAYS, HAN_S)
C        DO I = 1, TDAYS
C          WRITE(INC,'(I4)')I
C          CALL WCOUP@(INC,-1,2,2,HAN_S)
C          CALL SLEEP@(0.01)
C        END DO
```

```
      ENDIF

      CALL WCOUP@(' Press Esc Key ',-1,2,4,HAN_S)

  1   CALL GET_KEY@(KEY)
      IF(KEY .NE. ESC_KEY) GOTO 1
      CALL KILLW@(HAN_S)
      RETURN
      END


C       PROGRAM GRAPHMAIN
          SUBROUTINE GRAPHM
          IMPLICIT INTEGER*2(A-Z)
          INCLUDE 'COLOURS.INS'
          INCLUDE 'KEYS.INS'
          PARAMETER(NGRAPHS=2,NPOINTS=400)
          CHARACTER*20 LEGENDS(3)
          REAL*4 X(NPOINTS),Y(NPOINTS,3)
          DATA LEGENDS/'RAINFALL','RUNOFF','LEACHATE'/

C  PREPARE THE DATA
          OPEN(9,file='GRAPH.DAT')
          DO  I=1,NPOINTS
            X(I)=FLOAT(I)*100
            READ(9,*) Y(I,1),Y(I,2)
          END DO
          CLOSE(9)

C  SET THE SCREEN IN THE GRAPHIC MODE

          CALL VGA@
          CALL RECTANGLE@(0,0,639,479,CYAN)
C  DO THE GRAPHS
          CALL GRAPH(X,Y,NPOINTS,NGRAPHS,LEGENDS)

C  WAIT FOR THE USER TO PRESS A KEY AND RETURN TO TEXT MODE
  1   CALL GET_KEY@(KEY)
          IF(KEY .NE. ESC_KEY) GOTO 1

          CALL TEXT_MODE@
          CALL HIDE_CURSOR@
          END

          SUBROUTINE GRAPH(X,Y,NPOINTS,NGRAPHS,LEGENDS)
C       IMPLICIT INTEGER*2(A-Z)
          INCLUDE 'COLOURS.INS'
          CHARACTER*(*) LEGENDS(NGRAPHS)
          CHARACTER*40 TITLES
          CHARACTER*40 XAXIS,YAXIS
          REAL X(NPOINTS),Y(NPOINTS,NGRAPHS),XMIN,XMAX,YMIN,YMAX
          REAL*4 SIZEX,ITALICX,ROTATIONX,SIZEY,ITALICY,ROTATIONY
          REAL*4 SIZEL,ITALICL,ROTATIONL,SIZET,ITALICT,ROTATIONT
          REAL*4 SIZEV,ITALICV,ROTATIONV
          INTEGER*2 COLOUR(6),XOL,XOR,YOT,YOB
```

```
      INTEGER*2 FONTX,FONTY,FONTL,FONTT,FONTV

      DATA COLOUR/RED,YELLOW,GREEN,CYAN,BROWN,WHITE/

      DATA FONTT,SIZET,ROTATIONT,ITALICT/0, 1.3, 0.0, 0.0/
      DATA FONTL,SIZEL,ROTATIONL,ITALICL/0, 1.1, 0.0, 0.0/
      DATA FONTX,SIZEX,ROTATIONX,ITALICX/0, 1.0, 0.0, 0.0/
      DATA FONTL,SIZEY,ROTATIONY,ITALICY/0, 1.0, 90.0, 0.0/
      DATA FONTV,SIZEV,ROTATIONV,ITALICV/0, 0.5, 0.0, 0.0/

      TITLES='Figure: Time History of Rainfall'
      XAXIS='MONTH'
      YAXIS='INTENSITY '

C DETERMINE THE DATA RANGE
      XMAX=X(1)
      YMAX=Y(1,1)
      XMIN=XMAX
      YMIN=YMAX
      DO 1 I=1,NPOINTS
       XMAX=MAX(XMAX,X(I))
       XMIN=MIN(XMIN,X(I))
       DO 1 J=1,NGRAPHS
         YMAX=MAX(YMAX,Y(I,J))
         YMIN=MIN(YMIN,Y(I,J))
  1 CONTINUE

      XMAX=1.05*XMAX
      YMAX=1.05*YMAX

      XOL=20
      XOR=20
      YOT=20
      YOB=20
      NXPOINTS=620
      NYPOINTS=460

      XMIN=0
      IX0=XOL
      XSCALE=(NXPOINTS-XOL)/(XMAX-XMIN)

      YMIN=0
      IY0=NYPOINTS
      YSCALE=(NYPOINTS-YOT)/(YMAX-YMIN)

C DRAW THE AXES
      CALL DRAW_LINE@(IX0,YOT,IX0,NYPOINTS,WHITE) !Y-AXIS
      CALL  DRAW_LINE@(NXPOINTS,YOT,NXPOINTS,NYPOINTS,WHITE)  !Y-AXIS
RIGHT
      CALL DRAW_LINE@(XOL,IY0,NXPOINTS,IY0,WHITE) !X-AXIS
      CALL DRAW_LINE@(XOL,YOT,NXPOINTS,YOT,WHITE) !X-AXIS TOP

C AND TICKS WITH DIMENSIONS
      IEPS=10
      DO I=1,9
       IYT=19+I*44
```

```
         IXT=19+I*60
         CALL DRAW_LINE@(IX0+IEPS,IYT,IX0,IYT,WHITE) ! Y-AXIS
         CALL DRAW_LINE@(IXT,IY0-IEPS,IXT,IY0,WHITE) ! X-AXIS
        END DO

C  DRAW THE TITLES, LEGENTS, AXIS
        CALL SET_TEXT_ATTRIBUTE@(FONTT,SIZET,ROTATIONT,ITALICT)
        CALL DRAW_TEXT@(TITLES,30,20,YELLOW)

        IY=NYPOINTS*1/3
        IX=500
        CALL SET_TEXT_ATTRIBUTE@(FONTL,SIZEL,ROTATIONL,ITALICL)
        DO J=1,NGRAPHS
         CALL DRAW_TEXT@(LEGENDS(J),IX,IY,COLOUR(J))
         IY=IY+20
        END DO

        CALL SET_TEXT_ATTRIBUTE@(FONTX,SIZEX,ROTATIONX,ITALICX)
        CALL DRAW_TEXT@(XAXIS,300,465,WHITE)

        CALL SET_TEXT_ATTRIBUTE@(FONTY,SIZEY,ROTATIONY,ITALICY)
        CALL DRAW_TEXT@(YAXIS,20,240,WHITE)

C  DRAW THE GRAPHS
        DO I=2,NPOINTS
         IX1=(X(I-1)+XMIN)*XSCALE+19
         IX2=(X(I)+XMIN)*XSCALE+19
          DO  J=1,NGRAPHS
              IY1=(Y(I-1,J)-YMIN)*YSCALE+0.5
              IY1=NYPOINTS-IY1
              IY2=(Y(I,J)-YMIN)*YSCALE+0.5
              IY2=NYPOINTS-IY2
              CALL DRAW_LINE@(IX1,IY1,IX2,IY2,COLOUR(J))
          END DO
        END DO
        END

c      PROGRAM SURFACE
      SUBROUTINE SURFACE (FileName, Ndays, HAN_S)

* Purpose:
*     This program takes daily precipitation and evpotranspiration data
*      as input and distribtes into landfill surface.

* Constants:
      INTEGER*2 TNC, TNL, TNS, HAN_S
      PARAMETER (Nyears=10, ID = Nyears*365)
      PARAMETER (TNC=10, TNL=10, TNS = 20, MoL = 100)
      CHARACTER INC*4
*  FileName.NUM
      INTEGER*2 TC, Nlayers(TNC)
      REAL CN, Slope, Cpf, DC(TNC), Area(TNC), Dlength(TNC)

*  FileName.LDF
c      INTEGER*2
      REAL  HD(TNC), LL(TNC), Rcir(TNC)
```

```
* FileName.PLN
     INTEGER*2  Nsides(TNC), BC(TNC,TNS)
     REAL XC(TNC,TNS+1), YC(TNC,TNS+1), TB(TNC,TNS), KB(TNC,TNS)
     REAL Lside(TNC,TNS)

     COMMON/RES/TC, XC, YC, BC, Area, TB, KB, Nsides, Lside

* FileName.SEC
     INTEGER*2  Ltype(TNC,TNL)

     REAL DL(TNC,TNL), DenL(TNC,TNL), KL(TNC,TNL), Th(TNC,TNL)

     REAL Mli(TNC,MoL), Mlf(TNC,MoL), Mls(TNC,MoL),Mlk(TNC,MoL),
    &     Mlden(TNC,MoL), Mld(TNC,MoL)

     INTEGER*2 Mlt(TNC,MoL), Nml(TNC)

*  FileName.MOS
     REAL Th_S_w, Th_S_f, Th_S_s, Th_W_f, Th_W_s, Th_C_s

* Local
     INTEGER*2 MonthDays(12)

     REAL Lambda

     CHARACTER FileName*13, Fs

* Common block statements

     COMMON/BLK1/ ThW(8), ThF(8), ThS(8), ThI(TNC,8)
     COMMON/BLK3/ ClayDpth, Cshc, Cpf
     COMMON/BLK7/ Slope, Dlength

* Arguments
     DIMENSION P(ID), E(ID), Q(TNC,ID), R(TNC,ID), SatDep(TNC,ID)
     DIMENSION Qper(TNC,ID), Qdrn(TNC,ID), Ec(TNC,ID)
     DIMENSION PM(12), EM(12), QM(12),RM(12), QperM(12), QdrnM(12)
     DIMENSION O(ID,8), Sthick(8), ET(8), WF(7)

     REAL LeaLev(TNC, ID), ThetaA(TNC,ID)

* Common block statements

     COMMON/BLKW1/Mlt, Nml, Mli, Mlf, Mls, Mlk, Mld, Mlden,
    1 Rcir, ThetaA

     COMMON/SUR/LeaLev


c parameters

c Initialise variables:
     DATA WF/0.111, 0.397, 0.254, 0.127, 0.063, 0.032, 0.016/
     DATA MonthDays/31,28,31,30,31,30,31,31,30,31,30,31/
     FileName = 'TEST'
     Fs ='N'
```

```
      dlay = 30.0
c      NDAYS = 3

* Open file for soil cover and liner properties
      OPEN (9, FILE = 'MODEL-IN.DAT')
       READ (9,*) Tdepth, Rdepth, Slope
       READ (9,*) TheW, TheF, TheS, TheI, SHC, CN
       READ (9,*) ClayDpth, Cshc, Cpf
      CLOSE (9)

* Open file for landill capping properties
      OPEN(6, FILE=FileName//'.NUM')
       READ(6,*) CN
       READ(6,*) Slope
       READ(6,*) Cpf
       READ(6,*) TC
       DO NC = 1, TC
        READ(6,*) K, DC(NC),  Area(NC),  Nlayers(NC), Dlength(NC)
       END DO
      CLOSE(6)
*++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++
      OPEN (10, FILE = FileName//'.LDF')
         Read(10,*)
c        Read(10,'(A40)') SiteName
        Read(10,*) TC
        DO I = 1, TC
         Read(10,*) n, DC(I), HD(I), LL(I), Rcir(I)
        END DO
       CLOSE(10)

*++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++
       OPEN (10, FILE=FileName//'.MOS')
        READ(10,*) Th_S_w, Th_S_f, Th_S_s
        READ(10,*) Th_W_f, Th_W_s
        READ(10,*) Th_C_s
       CLOSE(10)

*++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++
c  Read a data file  .SEC

      Open (4, File=FileName//'.SEC')
       READ (4,*) TC
       DO NC = 1, TC
        READ(4,*) N, Nlayers(NC)
        DO J = 1, Nlayers(NC)
         READ(4,*) K, DL(NC,J), Ltype(NC,J), DenL(NC,J), KL(NC,J),
     1             Th(NC,J)
        END DO
       END DO
      CLOSE(4)
*+++++++++++++++++++++++++++
* Units adjustments
      DO NC = 1, TC
```

```
      DO J = 1, Nlayers(nc)
        DL (NC, J) = DL(NC, J) * 100.0        ! To convert into cm
        KL (NC, J) = KL(NC, J) * 24.0 *3600.0 ! To convert into cm/day
      END DO
     END DO
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++

* Set-up modelling layers in a cell
     DO NC = 1, TC

       k  = 0
       ki = 1

       DO 71 J = 1, Nlayers(nc)

       IF (Ltype(NC,J) .EQ. 2) THEN
         Nlay = DL(NC,J) / dlay
c          IF (Nlay .EQ. 0) Nlay = 1
         k = k + Nlay

         DO L = ki, k
           Mld(NC,L) = dlay
           IF (L .EQ. k) Mld(NC,L) = dlay + AMOD(DL(NC,J), dlay)
           Mlt(NC,L) = Ltype(NC,J)
           Mli(NC,L) = Th(NC,J)
           Mlf(NC,L) = Th_W_f
           Mls(NC,L) = Th_W_s
           Mlk(NC,L) = KL(NC,J)
           Mlden(NC,L) = DenL(NC,J)
         END DO

       ELSEIF (Ltype(NC,J) .EQ. 1) THEN
         k = k + 1
           Mld(NC,k) = DL(NC,J)
           Mlt(NC,L) = Ltype(NC,J)
           Mli(NC,L) = Th (NC,J)
           Mlf(NC,L) = Th_S_f
           Mls(NC,L) = Th_S_s
           Mlk(NC,L) = KL(NC,J)
           Mlden(NC,L) = DenL(NC,J)

         ki = k + 1
       ENDIF
 71    CONTINUE

       Nml(NC) = k
     END DO

*   Units adjustment
     Tdepth = Tdepth * 100.0       ! To convert into cm
     Rdepth = Rdepth * 100.0       ! To convert into cm
     Slope = Slope / 100.0        ! To convert into cm
     DO NC = 1, TC
       Dlength(NC) = Dlength(NC) * 100.0    ! To convert into cm
     END DO
```

```
      SHC  = SHC  * 24.0 * 3600.0   ! To convert into cm/day
      Cshc = Cshc * 24.0 * 3600.0   ! To convert into cm/day
      ClayDpth = ClayDpth * 100.0   ! To convert into cm

*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
* Open file to read landfill plan data

      OPEN(10, FILE=FileName//'.PLN')
       READ(10,*) TC
        DO N = 1, TC
         READ(10,*) I, Nsides(N)
          DO J = 1, Nsides(N)
           READ(10,*) K, XC(N,J), YC(N,J), BC(N,J), TB(N,J), KB(N,J)
          END DO
        END DO
      CLOSE(10)

* Units adjustments

      DO NC = 1, TC
        DO J = 1, Nsides(NC)
          XC(NC,J) = XC(NC,J) * 100.0
          YC(NC,J) = YC(NC,J) * 100.0
          TB(NC,J) = TB(NC,J) * 100.0
          KB(NC,J) = KB(NC,J) * 24.0 * 3600.0
        END DO
      END DO

*  Calculates sides length of cells
      DO NC = 1, TC
        DO J = 1, Nsides(NC)
            Jp = J + 1
          IF(J. EQ. Nsides(NC)) Jp = 1
          Lside(NC,J) = SQRT((XC(NC,J)-XC(NC,Jp))**2 +
     1                       (YC(NC,J)-YC(NC,Jp))**2)
        END DO
      END DO

* Area calculations
      DO NC = 1, TC
        CALL AREAPOLY (Nsides(NC), NC, XC, YC, AREA(NC))
c        PRINT*, NC, AREA(NC)
      END DO
*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

*  Open precipitation and evapotranspiration data file
      OPEN (8, FILE = FileName//'.PET')
c        READ(8,*) NDAYS
       READ(8,*) (P(i), E(i), i = 1, NDAYS)
      CLOSE(8)

* IF number of simulation days are greater than precipitation records
*   than re-generate the data by repeating it
```

```
* Units adjustment
      DO i = 1, NDAYS
        P(i) = P(i) / 10.0      ! To convert into cm
        E(i) = E(i) / 10.0      ! To convert into cm
      END DO


* SUMI is the initial moisture storage of soil cover
      SUMI = TheI * Tdepth

* Calculates Brooks and Corey equation parameters
      RS = 0.014 + 0.253 * TheW
      Lambda = ALOG((TheF - RS)/(TheW - RS))/ALOG(45.0)
      EXP = 3.0 + 2.0/Lambda


C Assigns thickness to the top seven segments
      Nslay = 7
      Sthick(1) = Rdepth/36.0
      Sthick(2) = 5.0 * Rdepth/36.0
      DO j = 3, Nslay
       Sthick(j) = Rdepth/6.0
      END DO

      IF (Tdepth .GT. Rdepth) THEN
        Sthick(8) = Tdepth - Rdepth
        Nslay = 8
      ENDIF

      DO j = 1, Nslay
       ThW(j) = TheW
       ThF(j) = TheF
       ThS(j) = TheS
       DO NC = 1, TC
        ThI(NC,j) = TheI
       END DO
      END DO

      CN = 0.3750701*CN + 2.756779E-03*CN**2 - 1.638951E-05*CN**3 +
     1     5.142644E-07*CN**4

      SMX = 2.54*(1000.0/CN - 10.0)


*.*.*.*.*.*.*.*. Start of Daily Loop .*.*.*.*.*.*.*.*.*.*
      DO 10 ND = 1, NDAYS

       WRITE(INC,'(I4)')ND
       CALL WCOUP@(INC,-1,2,2,HAN_S)

       DO 70 NC = 1, TC

       DO j = 1, 7
        ET(j) = E(ND) * WF(j)
       END DO
        ET(8) = 0.0
```

```
      CALL RUNOFF (NC, P(ND), RUN, AB, SMX)

*  Q is the amount of infiltration

c      Q(NC,ND) = P(ND) - RUN  - AB

      Q(NC,ND) = P(ND) - RUN

      IF (Q(NC,ND) .LT. 0.0) Q(NC,ND) = 0.0
      PIN = Q(NC,ND)

* Loop to consider water balance for top seven segments and extra segment

     DO 30 j = 1, Nslay

*  Calculates drainage 'O' out of segment j
      IF (ThI(NC,j) .GT. ThF(j) .AND. j .NE. Nslay) THEN
        A = (ThI(NC,j) - ThF(j)) * Sthick(j)
        UHC = SHC * ((ThI(NC,j) - ThF(j)) / (ThS(j) - ThF(j)))**EXP
        IF (UHC .GT. A ) UHC = A
      ELSE
        UHC = 0.0
      ENDIF

      O(ND,j) = UHC

*  Distributes the input and output into segment j

     IF (j .EQ. 1) THEN
        ThI(NC,j) = ThI(NC,j) + (PIN - ET(j) - O(ND,j)) / Sthick(j)
     ELSE
      ThI(NC,j) = ThI(NC,j) + (O(ND,j-1) - ET(j) - O(ND,j))/Sthick(j)
     ENDIF

      IF (ThI(NC,j) .LT. ThW(j)) THEN
        ET (j) = ET(j) - (ThW(j)-ThI(NC,j))*Sthick(j)
        ThI(NC,j) = ThW(j)
      ENDIF
   30 CONTINUE

      Ec(NC,ND) = 0.0
      DO j = 1, 7
       Ec(NC,ND) = Ec(NC,ND) + ET(j)
      END DO
       IF (Ec(NC,ND) .LT. 0) Ec(NC,ND) = 0.0

*  Checks for oversaturation and add extra water to the top layers

     DO 40 j = Nslay, 1, -1

       Excess = 0.0
       IF(ThI(NC,j) .GT. ThS(j)) THEN
         Excess = ThI(NC,j) - ThS(j)
         ThI(NC,j) = ThS(j)
       ENDIF
```

```
        IF (j .NE. 1) THEN
           ThI(NC,j-1) = ThI(NC,j-1) + Excess * Sthick(j)/Sthick(j-1)
        ELSE
           RUN = RUN + Excess * Sthick(j)
        ENDIF

   40 CONTINUE

        R(NC,ND) = RUN
        Q(NC,ND) = P(ND) - R(NC,ND)
        if(Q(NC,ND) .lt. 0.0)  Q(NC,ND) = 0.0

c       IF(R(NC,ND) .GT. 0.0) THEN
c         Qc(ND) = P(ND) - R(NC,ND) - E(ND)
c       ELSE
c         Qc(ND) = 0.0
c       ENDIF

*  Calculates depth of saturation starting from bottom segment
        SUM = 0.0
        DO j = Nslay, 1, -1
         IF(ThI(NC,j) .GT. ThF(j)) THEN
           SUM = SUM + Sthick(j) * (ThI(NC,j) - ThF(j))/(ThS(j)-ThF(j))
         ENDIF
           IF(ThI(NC,j) .LT. ThS(j)) GOTO 15
        END DO
   15   SatDep(NC,ND) = SUM


C       write(*,44)ND,ThI(1),ThI(2),ThI(3),ThI(4),ThI(5),
C     1  ThI(6),ThI(7),ThI(8)
C  44  format(1x,I3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X,F5.3,3X
C     1 ,F5.3,3X,F5.3)

*  Calculates percolation and lateral drainage rate

        IF (SatDep(NC,ND) .GT. 0.0) THEN

          CALL LATFLO (NC,SatDep(NC,ND), SHC, DRN, PRC, QOUT)

*    Updates the moisture capacities of layers
          SDEPTH = SatDep(NC,ND)
          DO j = Nslay, 1, -1
            IF (SDEPTH .LT. Sthick(j)) THEN
              ThI(NC,j) = ThI(NC,j) - QOUT/Sthick(j)
              GOTO 25
            ELSE
              SDEPTH = SDEPTH - Sthick(j)
            ENDIF
          END DO
        ELSE
          PRC = 0.0
          DRN = 0.0
        ENDIF
 25     Qper(NC,ND) = PRC
```

```
         Qdrn(NC,ND) = DRN

*  Call subroutine to distribute percolation water into waste layers

        CALL UNSATURATED (NC, ND, EXP, Qper)

   70  CONTINUE  ! Repeats cell

*  Call subroutine to distribute leachate within landfill cells

        CALL RESERVOIR (ND)

*  Updates Moisture Capacities

*  Call subroutine to determine the leachate seepage from landfill bottom

        CALL COLLECTOR (ND)

   10  CONTINUE  ! Repeats day
*............. Daily Loop End .............*

         SUMF = 0.0
         DO j = 1, Nslay
           SUMF = SUMF + Thl(NC,j) * Sthick(j)
         END DO

*............... Printing Results ....................*

       OPEN (31, FILE=FileName//'.SUR', STATUS='unknown')

       IF (Fs .EQ. 'Y') THEN
          PRINT*, 'Total Number of Cells =', TC
          PRINT*
       ENDIF

       WRITE(31,*) 'Total Number of Cells =', TC
       WRITE(31,*)

       DO 65 NC = 1, TC

c    DO 60 ND = 1, NDAYS

        IF (Fs .EQ. 'Y') THEN   ! Results to screen
          PRINT*,'Cell # ',NC
          WRITE(*,61)
       PRINT*,   ' Day   RAIN    EVP     RUN     INF     PER
      &DRN'
       PRINT*,   '  #      mm      mm      mm      mm      mm
      &mm'
          WRITE(*,62)
        ENDIF

       WRITE(31,*) 'Cell # ',NC
       WRITE(31,*)
       WRITE(31,61)
       WRITE(31,*)' Day   RAIN    EVP     RUN     INF     PER
```

```
     &DRN'
      WRITE(31,*)' #      mm       mm       mm       mm       mm
     &mm'
      WRITE(31,62)

   61 FORMAT(1X, 62('-'))
   62 FORMAT(1X, 62('-')/)

 * Initilization
       SUMIO  = 0.0
       SUMIOC = 0.0
       ToP = 0.0
       ToE = 0.0
       ToR = 0.0
       ToPER = 0.0
       ToD = 0.0
       ToQ = 0.0

       DO ND = 1, NDAYS

        IF (Fs .EQ. 'Y') THEN
          WRITE( *,11) ND, P(ND)*10., Ec(NC,ND)*10., R(NC,ND)*10.,
     1     Q(NC,ND)*10., Qper(NC,ND)*10.0, Qdrn(NC,ND)*10.0
        ENDIF

         WRITE(31,11) ND, P(ND)*10., Ec(NC,ND)*10., R(NC,ND)*10.,
     1   Q(NC,ND)*10., Qper(NC,ND)*10.0, Qdrn(NC,ND)*10.0

   11 FORMAT(1X,I4,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3)

c      Llevel(ND),DRNOUT(ND)

         SUMIO = SUMIO+P(ND)-Ec(NC,ND)-R(NC,ND)-Qper(NC,ND)-Qdrn(NC,ND)
c         SUMIOC = SUMIOC+P(ND)-E(ND)-R(NC,ND)-Qper(NC,ND)-Qdrn(NC,ND)
         ToP = ToP + P(ND)
         ToE = ToE + Ec(NC,ND)
         ToR = ToR + R(NC,ND)
         ToQ = ToQ + Q(NC,ND)
         ToPER = ToPER + Qper(NC,ND)
         ToD = ToD + Qdrn(NC,ND)

       END DO


       IF (Fs .EQ. 'Y') THEN
         WRITE (*, 62)
         PRINT*,'@'
         PRINT*
       ENDIF

        WRITE (31,62)
        WRITE(31,*)'@'
        WRITE(31,*)

 * Initilization
      DO I = 1, 12
```

```
      PM(I) = 0.0
      EM(I) = 0.0
      RM(I) = 0.0
      QM(I) = 0.0
      QperM(I) = 0.0
      QdrnM(I) = 0.0
 END DO

 IF (Fs .EQ. 'Y') THEN
 WRITE(*,61)
 PRINT*,' Month    RAIN     EVP     RUN      INF      PER     DRN'
 PRINT*,'  #        mm       mm      mm       mm       mm      mm'
 WRITE(*,62)
 ENDIF

 WRITE(31,61)
 WRITE(31,*)' Month    RAIN     EVP     RUN      INF      PER
1 DRN'
 WRITE(31,*)'  #        mm       mm      mm       mm       mm
1 mm'
 WRITE(31,62)


 I  = 1
 IM = 1
 IC = 0

 DO ND = 1, NDAYS
  IC = IC + 1

  IF (IC .LE. MonthDays(I)) THEN
      PM(I) = PM(I) + P(ND)
      EM(I) = EM(I) + Ec(NC,ND)
      RM(I) = RM(I) + R(NC,ND)
      QM(I) = QM(I) + Q(NC,ND)
      QperM(I) = QperM(I) + Qper(NC,ND)
      QdrnM(I) = QdrnM(I) + Qdrn(NC,ND)

   IF(IC .EQ. MonthDays(I)) THEN
     IC = 0
     I = I + 1
     IM = IM + 1
     IF( IM .gt. 12) IM = 1
   ENDIF
  END IF

 END DO

  IMT = I - 1

 DO I = 1, IMT

 IF (Fs .EQ. 'Y') THEN
   WRITE( *,23)I, PM(I)*10.,EM(I)*10.,RM(I)*10., QM(I)*10.,
1  QperM(I)*10.,  QdrnM(I)*10.
 ENDIF
```

```
        WRITE(31,23)I, PM(I)*10.,EM(I)*10.,RM(I)*10., QM(I)*10.,
     1  QperM(I)*10.,  QdrnM(I)*10.

       END DO
   23  FORMAT(3X,I2,6X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2,3X,F6.2)

       IF (Fs .EQ. 'Y') THEN
        WRITE( *,61)
        PRINT*, '@'
        PRINT*
        PRINT*,'  Summary Output for Cell #',NC
        PRINT*,'  ------------------------'
        PRINT*
       ENDIF

        WRITE(31,61)
        WRITE(31,*)'@'
        WRITE(31,*)

        WRITE(31,*)'  Summary Output for Cell #',NC
        WRITE(31,*)'  ------------------------'
        WRITE(31,*)

        WRITE(31,*)' Total precipitation              (m)  =',
     1  ToP/100.0

        WRITE(31,*)' Total evapotranspiration          (m)  =',
     1  ToE/100.0

        WRITE(31,*)' Total volume of runoff           (m^3) =',
     1  ToR*Area(NC)/100.0

        WRITE(31,*)' Total volume of infiltration     (m^3) =',
     1  ToQ*Area(NC)/100.0

        WRITE(31,*)' Total volume of percolation       (m^3) =',
     1  ToPER*Area(NC)/100.0

        WRITE(31,*)' Total volume of lateral drainage  (m^3) =',
     1  ToD*Area(NC)/100.0

        WRITE(31,*)'@@'
   65  CONTINUE
       CLOSE (31)

c Prepares graphic data files

       OPEN (21, FILE=FileName//'.GDS', STATUS='Unknown')
        WRITE(21,*) NDAYS

       DO 42 ND = 1, NDAYS
          Sum1 = 0.0
          Sum2 = 0.0
          Sum3 = 0.0
          Sum4 = 0.0
```

```
          Sum5 = 0.0
          Sum6 = 0.0

        DO 41 NC = 1, TC
             Sum1 = P(ND)
             Sum2 = Sum2 + Ec(NC,ND)
             Sum3 = Sum3 + R(NC,ND)
             Sum4 = Sum4 + Q(NC,ND)
             Sum5 = Sum5 + Qper(NC,ND)
             Sum6 = Sum6 + Qdrn(NC,ND)

   41   CONTINUE

        WRITE(21,11) ND, Sum1*10.0,   Sum2*10.0/TC, Sum3*10.0/TC,
     1              Sum4*10.0/TC, Sum5*10.0/TC, Sum6*10.0/TC

c  11  FORMAT(1X,I4,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3,3X,F6.3)

   42  CONTINUE
       CLOSE (21)

       OPEN(25, FILE = FileName//'.GDL')
        WRITE(25,*)' Total Number of Cells =', TC
        WRITE(25,*)
        WRITE(25,61)
        WRITE(25,*)'                    Leachate Levels in metres'
        WRITE(25,*)'  DAY',(NC, Nc = 1, TC)
        WRITE(25,62)
         DO ND = 1, Ndays
           Write(25,*)(LeaLev(NC, ID), NC = 1, TC)
         END DO
       CLOSE (25)
       return
       END

       SUBROUTINE UNSATURATED (NC, ND, Sexp, PRC)

* Purpose:
*     Distributes the amount of percolation water from landfill cover
*     into landfill cell and marks leachate levels in a landfill cells

* Called by:
*     SURFACE

* Input:
*     NC    - Number of cell under consideration  [I]
*     ND    - Number of simulation day            [I]
*     Sexp  - soil layer exponent used in Irmay's model [R]
*     PRC   - Percolation from soil cover into first modelling layer [2A]
*     Rcir

* Output:
*     LeaLev  - Leachate levels in a landfill cells [2A]
*     Nml     - Number of modelling layers
*     Mlt     - Modelling layer type Soil(1), Waste(2), Clay(3)
*     Mli     - Initial moisture capacity of modelling layer [2A]
```

```
*     Mlf     - Modelling layer field capacity [2A]
*     Mls     - Modelling layer saturation capcity [2A]
*     Mlk     - Modelling layer saturated conductivty [2A]
*     Mld     - Modelling layer depth [2A]
*     Mlden   - Modelling layer density [2A]
*     ThetaA  - Average moisture content of a landfill cell [A]

* Constants:
      INTEGER*2 TNC
      PARAMETER (NYEARS=10, ID = NYEARS*365)
      PARAMETER (TNC=10, MoL = 100)

* Variables:
      INTEGER*2 Mlt(TNC,MoL), Nml(TNC)
      REAL Mli(TNC,MoL), Mlf(TNC,MoL), Mls(TNC,MoL), Mlk(TNC,MoL),
     1   Mlden(TNC,MoL), Mld(TNC,MoL)
      REAL PRC(TNC, ID), Rcir(TNC), Qdrain(TNC, ID)
      REAL LeaLev(TNC, ID), ThetaA(TNC,ID)

      COMMON/BLKW1/Mlt, Nml, Mli, Mlf, Mls, Mlk, Mld, Mlden,
     1 Rcir, ThetaA
      COMMON/SUR/LeaLev

*  ThetaA   Aveage moisture content of a landfill cell [2A]
*  Rcir     Leachate recirculation from landfill bottom onto
*           the top of first modelling layer [2A]

* Local variables:
      REAL Inp(MoL), Oup(MoL), F

*  Inp      Inputs to the modelling layer [A]
*  Oup      Outputs from  modelling layer [A]
*  F(X)     User defined function


c  Defines statement function Irmay's model

      F (X) = (-10.77 + 0.03 * X )

        Inp(1) = PRC(NC,nd) + Rcir(NC)

      DO 14 L = 1, Nml(NC)-1
c        IF(L .NE. Nml(NC) .AND. Mli(NC,L) .GT. Mlf(NC,L)) THEN

        IF(Mli(NC,L) .GT. Mlf(NC,L)) THEN
          Qmax = (Mli(NC,L) - Mlf(NC,L)) * Mld(NC,L)
          IF( Mlt(NC,L) .EQ. '1') THEN      ! waste modelling layer
            Oup(L) = Mlk(NC,L) * ((Mli(NC,L)-Mlf(NC,L)) /
     1      (Mls(NC,L) - Mlf(NC,L)))** F(Mlden(NC,L))

          ELSE                          ! intermediate soil layer
            Oup(L) = Mlk(NC,L) * ((Mli(NC,L)-Mlf(NC,L)) /
     1      (Mls(NC,L) - Mlf(NC,L)))**Sexp

          ENDIF
```

```
            IF(Oup(L) .GT. Qmax) Oup(L) = Qmax

          ELSE
             Oup(L) = 0.0
          ENDIF

c             IF(LD .EQ. 0 .AND. L. EQ. Nml(NC)) THEN
c               Oup(L) = 0.0          ! bottom drainage zero
c             ENDIF

              IF (L .eq. Nml(NC)-1 .and. Oup(L) .GE. Rcir(NC)) THEN
                 Recharge = Rcir(NC)
              ELSE
                 Recharge = 0.0
              ENDIF

              IF(L. EQ. Nml(NC)-1) THEN
                Oup(L) = Recharge
              ENDIF

            Inp(L+1) = Oup(L)
            Qdrain(NC,nd) = Oup(L)
  14   CONTINUE


*  Distributes input and output into layers
       DO L = 1, Nml(NC)-1

          Mli(NC,L) = Mli(NC,L) + (Inp(L) - Oup(L)) / Mld(NC,L)

       END DO
*--------------------------------*
          DO 16 L = Nml(NC)-1, 1, -1

          IF (Mli(NC,L) .GT. Mls(NC,L)) THEN
            EXTRA = Mli(NC,L) - Mls(NC,L)
            Mli(NC,L) = Mls(NC,L)
          IF(L .NE. 1) Mli(NC,L-1) = Mli(NC,L-1) + EXTRA * Mld(NC,L)
     1      / Mld(NC,L-1)
          ENDIF
  16   CONTINUE
*--------------------------------*

*  Computes depth of leachate in a cell
       sum = 0.0
       DO L = Nml(NC)-1, 1, -1
          IF(Mli(NC,L) .GT. Mlf(NC,L)) THEN
            sum = sum + Mld(NC,L) * (Mli(NC,L)-Mlf(NC,L))/
     1        (Mls(NC,L)-Mlf(NC,L))
          ENDIF
          IF(Mli(NC,L) .LT. Mls(NC,L)) GOTO 53
       END DO
 53  LeaLev(NC,nd) = sum

*  Calculates average moisture content
```

```
sum = 0
DO J = 1, Nml(NC)-1
  sum = sum + Mli(NC,J)
END DO

ThetaA(NC,ND) = sum / real (Nml(NC)-1)

RETURN
END
```

```
      SUBROUTINE RESERVOIR (ND)

* Purpose:
*     This subroutine distributes leachate within landfill cells
*      and updates leachate levels

* Called By:
*     SURFACE Module

* Input:
*     ND      - number of simulation day
*     Nsides  - number of sides of landfill cell
*     TC      - total number of cells in landfill
*     BC      - boundary condition of a side of landfill cell
*     KB      - saturated hydraulic conductivity of barrier between two cells
*     TB      - thickness of barrier between two adjacent cells
*     Lside   - length of side of landfill cell
*     Area    - plan area of landfill cell
*     NC      - Number of cell under consideration  [I]
*     ND      - Number of simulation day            [I]
*     Rcir

* Output:
*     LeaLev  - Leachate levels in a landfill cells [2A]
*     Nml     - Number of modelling layers
*     Mlt     - Modelling layer type Soil(1), Waste(2), Clay(3)
*     Mli     - Initial moisture capacity of modelling layer [2A]
*     Mlf     - Modelling layer field capacity [2A]
*     Mls     - Modelling layer saturation capcity [2A]
*     Mlk     - Modelling layer saturated conductivty [2A]
*     Mld     - Modelling layer depth [2A]
*     Mlden   - Modelling layer density [2A]
*     ThetaA  - Average moisture content of a landfill cell [2A]

* Constants:
*     TNC    - total number of cells
*     TNS    - total number of sides
*     Nyears  number of years
*     ID     - integer day

      INTEGER*2 TNC, TNS, TC
      PARAMETER (TNC = 10,TNS = 20,MoL = 100, Nyears=10, ID= Nyears*365)

* Arguments:
      INTEGER*2 Mlt(TNC,MoL), Nml(TNC)
      REAL Mli(TNC,MoL), Mlf(TNC,MoL), Mls(TNC,MoL), Mlk(TNC,MoL),
     1   Mlden(TNC,MoL), Mld(TNC,MoL)
      REAL Rcir(TNC), LeaLev(TNC, ID), ThetaA(TNC,ID)

      COMMON/BLKW1/Mlt, Nml, Mli, Mlf, Mls, Mlk, Mld, Mlden,
     1 Rcir, ThetaA

      COMMON/SUR/LeaLev

* ThetaA   Aveage moisture content of a landfill cell [2A]
* Rcir     Leachate recirculation from landfill bottom onto
```

```
*         the top of first modelling layer [2A]

* Local Variables:
*    Qs    - seepage flow rate from cell 'i' into adjecent cell 'j'
*    DH1   - decrease in leachate level of cell i
*    DH2   - increase in leachate level of cell j
*    Sdepth1  -  depth of saturation in cell i
*    Sdepth2  -  depth of saturation in cell j

* Arguments:
     INTEGER*2  Nsides(TNC), BC(TNC,TNS)
     REAL XC(TNC,TNS+1), YC(TNC,TNS+1), TB(TNC,TNS), KB(TNC,TNS)
     REAL Lside(TNC,TNS), Area(TNC)

* Common Statements:
     COMMON/RES/TC, XC, YC, BC, Area, TB, KB, Nsides, Lside

*
      DO NC = 1, TC

     DO 31 J = 1, Nsides(NC)

       IF (BC(NC,J) .NE. 0) THEN
        JA = BC(NC,J)
       Qs = KB(NC,J) * (LeaLev(NC,ND)**2 - LeaLev(JA,ND)**2)
   1        * Lside(NC,J) / (2.0 * TB(NC,J))

      IF (Qs .LE. 0.0) GOTO 31

*  Qs seepage flow rate [cm^3/day]

         DH1 = Qs/Area(NC)
         DH2 = Qs/Area(JA)
         IF (ND .NE. 1) THEN
          LeaLev (NC,ND) = LeaLev (NC, ND-1) - DH1
          LeaLev (JA,ND) = LeaLev (JA, ND-1) + DH2

*   Updates the moisture capacities of layers of cell i and j
        Sdepth1 = LeaLev (NC,ND)
        Sdepth2 = LeaLev (JA,ND)

        DO L = Nml(NC)-1, 1, -1
         IF (Sdepth1 .LT. Mld(NC,L)) THEN
           Mli(NC,L) = Mli(NC,L) - DH1/Mld(NC,L)
           GOTO 25
          ELSE
           Sdepth1 = Sdepth1 - Mld(NC,J)
          ENDIF
        END DO

 25      DO L = Nml(JA)-1, 1, -1
         IF (Sdepth2 .LT. Mld(NC,L)) THEN
           Mli(JA,L) = Mli(JA,L) - DH1/Mld(NC,L)
           GOTO 26
          ELSE
           Sdepth2 = Sdepth2 - Mld(NC,J)
```

```
        ENDIF
       END DO
 26     CONTINUE

      ENDIF
     ENDIF

 31  CONTINUE

*  Calculates average moisture content

    sum = 0
    DO J = 1, Nml(NC)-1
     sum = sum + Mli(NC,J)
    END DO

    ThetaA(NC,ND) = sum / real (Nml(NC)-1)

    END DO
    END
```

```
      SUBROUTINE COLLECTOR(ND)
* Purpose:
*     This subroutine determines leachate discharged from landfill cells
*      through bottom and updates leachate levels

* Called By:
*     SURFACE Module

* Input:
*     ND       - number of simulation day
*     Nsides  - number of sides of landfill cell
*     TC       - total number of cells in landfill
*     BC       - boundary condition of a side of landfill cell
*     KB       - saturated hydraulic conductivity of barrier between two cells
*     TB       - thickness of barrier between two adjacent cells
*     Lside   - length of side of landfill cell
*     Area    - plan area of landfill cell
*     NC       - Number of cell under consideration  [I]
*     ND       - Number of simulation day            [I]
*     Rcir

* Output:
*     LeaLev  - Leachate levels in a landfill cells [2A]
*     Nml      - Number of modelling layers
*     Mlt     - Modelling layer type Soil(1), Waste(2), Clay(3)
*     Mli     - Initial moisture capacity of modelling layer [2A]
*     Mlf     - Modelling layer field capacity [2A]
*     Mls     - Modelling layer saturation capcity [2A]
*     Mlk      - Modelling layer saturated conductivty [2A]
*     Mld      - Modelling layer depth [2A]
*     Mlden   - Modelling layer density [2A]
*     ThetaA  - Average moisture content of a landfill cell [2A]

* Constants:
*     TNC   - total number of cells
*     TNS   - total number of sides
*     Nyears  number of years
*     ID    - integer day

      INTEGER*2 TNC, TNS, TC
      PARAMETER (TNC = 10,TNS = 20,MoL = 100, Nyears=10, ID= Nyears*365)

* Arguments:
      INTEGER*2 Mlt(TNC,MoL), Nml(TNC)
      REAL Mli(TNC,MoL), Mlf(TNC,MoL), Mls(TNC,MoL), Mlk(TNC,MoL),
     1   Mlden(TNC,MoL), Mld(TNC,MoL)
      REAL Rcir(TNC), LeaLev(TNC, ID), ThetaA(TNC,ID)

      COMMON/BLKW1/Mlt, Nml, Mli, Mlf, Mls, Mlk, Mld, Mlden,
     1 Rcir, ThetaA

      COMMON/SUR/LeaLev

*  ThetaA   Aveage moisture content of a landfill cell [2A]
*  Rcir     Leachate recirculation from landfill bottom onto
*           the top of first modelling layer [2A]
```

```
* Arguments:
    INTEGER*2  Nsides(TNC), BC(TNC,TNS)
    REAL XC(TNC,TNS+1), YC(TNC,TNS+1), TB(TNC,TNS), KB(TNC,TNS)
    REAL Lside(TNC,TNS), Area(TNC)

* Common Statements:
    COMMON/RES/TC, XC, YC, BC, Area, TB, KB, Nsides, Lside

*
     DO NC = 1, TC
       IF (LeaLev(NC,ND) .GT. 0.0) THEN
        Qs = Mlk(NC, Nml(NC)) *(LeaLev(NC,ND)+Mld(NC, Nml(NC)))
   1          / Mld(NC, Nml(NC))

        IF (ND .NE. 1) THEN

         LeaLev (NC,ND) = LeaLev (NC, ND-1) - Qs

*   Updates the moisture capacities of layers of cell i and j
        Sdepth1 = LeaLev (NC,ND)

        DO L = Nml(NC)-1, 1, -1
         IF (Sdepth1 .LT. Mld(NC,L)) THEN
           Mli(NC,L) = Mli(NC,L) - Qs/Mld(NC,L)
           GOTO 25
          ELSE
           Sdepth1 = Sdepth1 - Mld(NC,J)
          ENDIF
        END DO
 25      CONTINUE

       ENDIF
      ENDIF

* Calculates average moisture content

    sum = 0
    DO J = 1, Nml(NC)
     sum = sum + Mli(NC,J)
    END DO

    ThetaA(NC,ND) = sum / real (Nml(NC))

    END DO
    END
```

```
      SUBROUTINE RUNOFF (NC, RAIN, RUN, AB, SMX)

* Purpose:
*      Calculates effective rainfall using SCS model

* Called by:
*     SURFACE Module

* Input:
*     Rain  - daily amount of precipitation
*     SMX   - present soil cover moisture

* Output:
*     RUN   - daily runoff
*     AB    - initial abstraction

* Constants:
      INTEGER TNC
      PARAMETER (TNC = 10)

* Common variables
      COMMON/BLK1/ ThW(8),ThF(8),ThS(8),ThI(TNC,8)

* Arguments:
      DIMENSION WF(7)
      DATA WF/0.111, 0.397, 0.254, 0.127, 0.063, 0.032, 0.016/


      IF (RAIN .LE. 0.0) GOTO 999

C  Compute depth-weighted effective soil water content in vol/vol
      SUM = 0.0
      DO j = 1, 7

*add
c          SW = ThS(j)

         SWAMCI = (ThF (j) + ThW (j))/2.0

         if (ThI(NC,j) .gt. SWAMCI) then
           Sj = SMX * (1 - ((ThI(NC,j) - SWAMCI)/(ThS(j) - SWAMCI)))
         else
           Sj = SMX
         endif

         SUM = SUM + WF(j) * Sj
*add
c     SUM = SUM + WF(j) * (ThI(j)-ThW(j)) / (ThS(j)-ThW(j))

      END DO

C Computes storage retention parameter

      S = SUM

c     S = SMX*(1.0 - SUM)
```

```
C Computes initial abstraction

      IF (S .LT. 0.0) S = 0.0
      AB = 0.2 * S
      IF (RAIN .LE. AB) GOTO 999

C Computes runoff

      RUN = ((RAIN - AB)**2)/(RAIN + S - AB)

c      PRINT *, RUN

      RETURN
 999  CONTINUE
      RUN = 0.0
      RETURN
      END

      SUBROUTINE LATFLO (NC, SD, ELKS, DRN, PRC, Qout)
* Purpose:
*     This subroutine computes the lateral drainage over clay liner into
*     site drain and percolation from clay cap.

* Called by:
*     SURFACE Module

* Input:
*     NC    - number of cell under consieration
*     SD    - saturated depth over clay liner
*     ELKS  - effective laterla saturated hydraulic conductivity

* Output:
*     DRN   - drainage over a clay liner into side drain
*     PRC   - percolation from clay liner
*     Qout  - daily amount of water lossed from soil cover

* Local variavles:
*     EPS   - tolerance criteria
*     PI    - value of π

      PARAMETER (NTC = 10)
      DIMENSION Dlength(NTC)

* Common Variables
*     ClayDpth - Depth of clay
*     Cshc     - clay saturated hydraulic conductivty
*     Cpf      - clay percent failure
*     Slope    - slope of a landfill cell
*     Dlength  - drainage length of a landfil cell [A]

* Arguments:
      COMMON/BLK3/ ClayDpth, Cshc, Cpf
      COMMON/BLK7/ Slope, Dlength

*     Defines Statement Function
```

```
      F (X) = (A*(B**((X/C)**D)))

*      Assign values for Tolerance and Pi

      DATA EPS/0.003/
      DATA PI/3.141592654/

      IF (SD  .GT. 0.0) GOTO 1000

*     No drainage and percolation if the head is zero.
      DRN = 0.0
      PRC = 0.0
      RETURN

*     Compute Lateral Drainage Rate by Regula Falsi Method
*     Define Variables in Dimensionless form

 1000 CONTINUE
      ITER  = 1
      ALPHA = ATAN (Slope)
      YSTAR = SD/Dlength(NC)
      QSTAR = 2.0 * YSTAR * SIN(ALPHA) * COS(ALPHA)

      IF (ALPHA .LE. 0.) THEN
        QSTAR = ((4.D0/PI)*YSTAR)**2
        DRN   = QSTAR * ELKS
        GOTO 1030
      ENDIF

      A = PI/4.0/COS (ALPHA)
      B = 2.0 * SQRT(0.4)/PI
      C = 0.4 * (SIN (ALPHA))**2
      D = 0.5/ LOG (B)

      IF (YSTAR .LT. C)THEN
        DRN = QSTAR * ELKS
        GOTO 1030
      ENDIF

 1010 QSTARN = (YSTAR*YSTAR) / F(QSTAR)
      TOLER  = 2.0 * ABS(QSTARN-QSTAR)/(QSTARN+QSTAR)
      IF (EPS .LT. TOLER .AND. ITER .LT. 30) THEN
        ITER  = ITER + 1
        QSTAR = (QSTAR + QSTARN) /2.0
        GOTO 1010
      ENDIF

      DRN = (QSTAR + QSTARN) * ELKS/2.0

 1030 CONTINUE
* Computes the Percolation Rate.
      PRC = Cshc * (SD + ClayDpth) / ClayDpth
      PRC = PRC * (1.0 + Cpf/100.0)
      Qout = DRN + PRC
      RETURN
      END
```

```
      SUBROUTINE AREAPOLY (N, NC, X, Y, SUM)

* Purpose:
*     Calculates area of polygone from its XY coordinates

* Called By:
*     SURFACE Module, PLAN Module
*

* Input:
*     N     - number of nodes of a polygone
*     NC    - number of a landfill cell under consideration
*     X     - x coordinate of landfil cell nodes
*     Y     - y coordinate of landfil cell nodes

* Output:
*     SUM   - area of a landfill cell

* Constants:
      INTEGER TNC, TNS
      PARAMETER(TNC = 10, TNS = 10)

* Arguments:
      DIMENSION X(TNC,TNS+1), Y(TNC,TNS+1)

      SUM = 0.0
      Y(NC, N+1) = Y(NC,1)
      DO I = 2, N
         SUM = SUM + (X(NC,1) - X(NC,I)) * (Y(NC,I+1) - Y(NC,I-1))
      END DO
      SUM = ABS(SUM) / 2.0
      RETURN
      END
```