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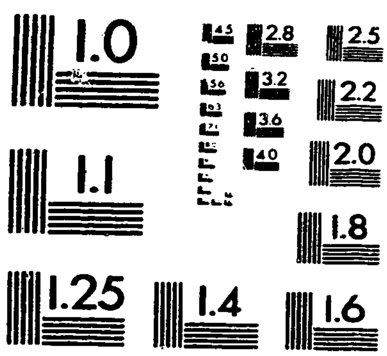

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University of Alberta

Moisture Movement Through Municipal Solid Waste

by

Mark Anthony Uguccioni

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Master of Science

in

Environmental Engineering

Department of Civil Engineering

Edmonton, Alberta

Fall 1995

ISBN 0-612-06548-0

University of Alberta

Library Release Form

Name of Author: Mark Anthony Uguccioni

Title of Thesis: Moisture Movement Through Municipal Solid Waste

Degree: Master of Science

Year this Degree Granted: 1995

208 Tanguay Avenue
Sudbury, Ontario
P3C 5G6

Date: ______________

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Moisture Movement Through Municipal Solid Waste** submitted by **Mark Anthony Uguccioni** in partial fulfillment of the requirements for the degree of **Master of Science in Environmental Engineering**.

Dr. C. A. Zeiss - Supervisor

Dr. T. Y. Gan

Dr. C. A. Mendoza

Date: July 6, 1998

To my Family and Friends...

Who make me who I am.

ABSTRACT

An experiment was performed to determine if channeling through municipal solid waste (MSW) occurs on a pilot scale, and to determine if infiltration intensity, waste compaction, and density affect moisture movement through MSW. Also, the HELP model (Schroeder et. al., 1994) and a two-domain fractured - porous media model, PREFLO (Workman and Skaggs, 1990), were used to simulate the experimental leachate discharge.

The results show that channeling is a significant flow mechanism, and that infiltration intensity and waste density significantly affect moisture movement. The HELP model was shown to be more capable of predicting moisture movement than PREFLO when input parameters were adjusted to account for channeling. However breakthrough time is predicted better by PREFLO.

The effects of channeling should be considered when modeling leachate discharge from landfills, and a two-domain model should be developed to model moisture movement. Also, more research into MSW properties such as moisture content - capillary pressure characteristic is needed.

ACKNOWELDGEMENT

I would like to thank the members of my advisory committee, Dr. Carl Mendoza, and Dr. Thian Yew Gan for their valuable suggestions for refining my work. I would especially like to thank my supervisor, Chris Zeiss, for challenging me to make something out of nothing, thereby giving me the confidence to do anything.

I also wish to thank Dr. Steve Workman, formally of the USDA-ARS, Soil Drainage Research Unit, for his guidance and advice during my modification of his PREFLO model, and Dr. Paul Schroeder of the U.S. Army Engineer Waterways Experiment Station, for his guidance on the HELP model, and for his time in reviewing this document.

My thanks also go out to Mr. Peter Zyrmiak, Ms. Patricia Sawka, Mr. Wayne Arbour and the staff at Waste Management Incorporated's West Edmonton Landfill and Recycle Facility. I could not have completed this project without their assistance.

Mr. Garry Solonynko and Mr. Nick Chernuka of the Civil Engineering Department of the University of Alberta also deserve many thanks for giving me technical and moral support throughout my graduate student career.

Finally, I wish to thank my special friend, Vicky, for supporting me and making my life happier in the past two years, as well as my family and friends who gave me the support to finish this project.

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1 INTRODUCTION

1.1 PROBLEM STATEMENT AND RESEARCH OBJECTIVES

Moisture movement through solid waste has a significant effect on the quantity of leachate generated from municipal solid waste (MSW) landfills (Korfiatis et. al., 1984). Moisture movement is affected by various environmental and operational factors such as infiltration intensity and compaction (Rovers and Farquhar, 1973; Jasper, et. al., 1985). The mechanisms and patterns of moisture movement through MSW, and the factors affecting it, are, therefore, important in accurately predicting leachate quantity. Models commonly used to predict leachate quantity, such as HELP (Hydrologic Evaluation of Landfill Performance, Schroeder et. al., 1994), represent moisture movement through MSW as one-dimensional Darcian flow through homogeneous porous media. However, previous studies have shown that due to the heterogeneity of waste, water flow through conduits between adjacent waste particles, or channeling, is also a significant flow mechanism (Zeiss and Major, 1993). Moisture movement may be more accurately represented by a model which accounts for both Darcian flow and channeling. More accurate prediction of moisture movement through municipal solid waste leads to greater accuracy in the prediction of leachate quantity.

The goals of this research, then, are to determine if channeling is significant on a larger scale then was previously used to study moisture movement, to determine which environmental and operating conditions affect moisture movement through MSW, and to determine if accounting for channeling to predict moisture movement yields better results than not considering channeling. The problem stated above may be resolved by satisfying various research objectives. These objectives are:

1. Collect models used to describe moisture flow through municipal solid waste as well as other models describing flow through porous, fractured, and fractured - porous media which could be applied to solid waste based on a literature review.
2. Perform literature review to determine environmental and operational factors which affect the mechanisms of moisture movement through municipal solid waste.
3. Rank the models according to their applicability of modeling moisture movement through MSW based on how each accounts for waste and flow characteristics, environmental and landfill operating conditions such as infiltration intensity and waste compaction, and the type of information the model provides. Applicability is determined through the use of a checklist developed from previous experimental results and a literature review.
4. Perform an experiment to determine if channeling occurs on a larger scale system than has been previously tested, and, test the effects of the environmental and operational conditions identified in the literature on moisture movement through solid waste (see objective 2).

5. Calibrate both the HELP model and the highest ranking model collected from the literature using previous and supplementary experimental results and literature values.
6. Test both models using pilot-scale experimental results and determine which model more accurately predicts moisture movement through MSW (with respect to leachate discharge).
7. Analyze and discuss further areas of research and model modifications to enable more accurate prediction of moisture flow through municipal solid waste.

1.2 SIGNIFICANCE

Previous moisture movement studies focusing on channeling were performed on bench-scale cells. These cells may have biased the results towards channeling due to wall effects (Major, 1993). Therefore, it is important to determine the presence of channeling on a pilot-scale because this would show that wall effects are not the main cause of channeling. Should channeling occur on a pilot-scale system, it is likely to occur on larger scale systems, such as MSW landfills, which experience similar environmental and operating conditions.

Also, channeling implies that the moisture content of the waste varies over a landfill. If channeling occurs, then, it would affect methane generation and biodegradation in the landfill because moisture significantly affects both of these processes (Klink and Ham, 1982; Hartz and Ham, 1983). Controls to optimize the effects of infiltration intensity, compaction, and waste density on leachate generation could be implemented in landfill operations should these factors significantly affect moisture movement. For example, if compaction is found to increase the storage capacity of MSW, the compactive effort applied to the waste before landfilling may be increased to raise the storage capacity and limit leachate generation. Furthermore, legislation (such as the United States' Subtitle D of the Resource Conservation and Recovery Act - RCRA; U.S. EPA, 1991) limits maximum leachate head on a liner to 30 cm, it is therefore necessary to evaluate the HELP model which is commonly used to design and monitor landfills to determine if it accurately predicts moisture flow through the landfill, thus, accurately predicting leachate head on a liner. Also, in the design of leachate collection systems it is necessary to know the peak and average leachate volumes, as well as the time of peak flow and the duration of the leachate event (Korfiatis and Demetracopoulos, 1986; Demetracopoulos, 1988; McEnroe, 1988, Peyton and Schroeder, 1990; Tchobanoglous, et. al., 1993). It is therefore necessary to evaluate how, and how well existing models predict these quantities.

1.3 SCOPE AND LIMITATIONS

The term moisture, used in this study, refers to water in a liquid state. Both precipitation and leachate are referred to as moisture. The gas phase of water is not included in this definition.

In addition to leachate quantity, moisture affects leachate quality and methane generation rates. However, the scope of this study is limited to the effects of moisture movement on leachate quantity only. Also, the municipal solid waste used for the experimental portion of the study was collected from residential areas of Edmonton, in mid-October, and early November, 1994. The characteristics of the waste, listed in the results section, should be noted before the results of this study are applied to other waste streams (e.g., commercial waste, or municipal waste generated in the summer) to ensure these results are applicable. Finally, the experiment was performed to examine unsaturated moisture movement in pilot-scale cells. The scale of the experiment should be considered before applying the information stated in this thesis to full scale landfills.

1.4 OVERVIEW OF THESIS

The thesis is structured so existing theory on moisture movement can be discussed, followed by the experimental and statistical methods used to investigate moisture movement through municipal solid waste. The experimental results and analysis are then presented, followed by a summary and a list of conclusions and areas of further study. Each chapter first considers the process of channeling, followed by the effects of environmental and operational factors on moisture movement, and finishes with the modeling of moisture movement through waste.

The next chapter, Chapter 2, presents a review of previous studies of moisture movement through solid waste. Also, various methods of representing moisture flow through solid waste are discussed. These include the water balance method, as well as flow through porous media, flow through fractured media and flow through fractured - porous media. Environmental and operating conditions which affect moisture movement are discussed, as is the nature and characteristics of solid waste. Models representing the various methods of representing moisture movement are also listed. Finally, the theory is synthesized into hypothesis which are tested using experimental results.

Chapter 3 presents the experimental methods and the evaluation of the models collected from the literature review. The statistical methods used to analyze these results are also presented in this chapter.

Chapter 4 presents and discusses the experimental results with respect to channeling, environmental and operating conditions, and modeling of moisture movement through the waste. Raw data in the form of figures and tables, followed by summary tables and the discussion of the analysis is presented for each hypothesis.

Chapter 5 summarizes the study, and presents conclusions based on the analysis of chapter 4. Also, the significance and implications of the study and areas for further research are discussed in this chapter.

2 LITERATURE REVIEW AND THEORY DEVELOPMENT

This chapter presents a review of previous studies of moisture movement through municipal solid waste (MSW). Various methods used by experimenters to represent this movement are also discussed. Environmental and landfill operating conditions affecting moisture movement are presented. Models developed to represent moisture flow through subsurface media, which may be applicable to municipal solid waste are also listed. Finally, the theory is synthesized into hypotheses which are tested using experimental results.

2.1 MOISTURE MOVEMENT THROUGH MUNICIPAL SOLID WASTE

Moisture movement through municipal solid waste has been investigated in a number of studies. Many of these focused mainly on the chemistry of landfills (Qasim and Burchinal, 1970; Fungaroli and Steiner, 1971; Rovers and Farquhar, 1973; Raveh and Avnimelech, 1979; Robinson and Lucas, 1985; Cancelli et. al., 1988; Huber et. al, 1994). However, moisture movement has been the main focus of some researchers (Gee, 1981; Straub and Lynch, 1982; Korfiatis, 1984; Demetracopoulos, et. al., 1986; Noble and Arnold, 1991; Ahmed et. al., 1992, Connell et. al., 1993; Zeiss and Major, 1993; Khanbilvardi et. al., 1995; Chen and Canter, in-press; Zeiss and Uguccioni, 1995). Most investigators have assumed and observed that moisture flow through unsaturated MSW is well represented as a uniform wetting front or "plug flow"(Qasim and Burchinal, 1970; Fungaroli and Steiner, 1971; Rovers and Farquhar, 1973; Raveh and Avnimelech, 1979; Straub and Lynch, 1982; Korfiatis, 1984; Noble and Arnold, 1991; Ahmed et. al., 1992; Khanbilvardi et. al., 1995). The waste above the horizontal front is at a higher moisture content than the waste below, and the moisture content of all waste above the front is equal (see Figure 2.1).

The assumption of a horizontal, uniform, moisture front implies that the medium, waste in this case, is homogeneous (the value of properties of the medium, such as saturated hydraulic conductivity, and hydraulic gradient are independent of position; Freeze and Cherry, 1979), and the medium consists of a porous matrix through which water flows (De Wiest, 1965). The water flows through the pore space between the particles which make up the matrix. Because of their size (less than 10 μm in diameter for fine grained soils; Luxmoore, 1981) these pores are called micropores (Vermeul et. al., 1993). Flow is driven through the pores by a hydraulic gradient which is made up of a capillary pressure and elevation head (see section 2.1.2, figure 2.3). Because pores are oriented in all directions water flows horizontally and vertically through the waste, so the capillary pressure acts to distribute water over the entire cross-section of a medium. Also, as moisture is added, the pores fill with water, and the moisture content of the waste increases. The researchers mentioned above have observed water moving downward through the waste because water was added to the top of the waste column. Therefore, the capillary pressure, and the elevation, at the top of the column were greater than in the porous matrix below. Since water flows from higher to lower pressure the flow was directed towards the bottom of the column. Homogeneous porous media contain a range of pore diameters with smaller pores exerting greater capillary forces, therefore, water may move though the pores at different rates, on a microscopic scale (e.g., micrometres to millimetres, Freeze and Cherry, 1979). However, MSW research, specifically this study, is based on the flow of water on a macroscopic scale (on the order of centimetres to metres) where the differences in flow rates of different size micropores are indistinguishable (Freeze and Cherry, 1979). Therefore, an average velocity can be used to represent the velocity of flow through all pores, thus the flow of water through a homogeneous porous media, is represented as a horizontal, uniform moisture front. This type of moisture movement has been mathematically expressed by using a one-dimensional Darcian-type equation, which will be discussed further in section 2.1.2.

Some researchers, while assuming a uniform moisture front, have noticed that water often flows through channels separating waste particles in addition to flowing through the porous matrix of the waste (Fungaroli and Steiner, 1971; Rovers and Farquhar, 1973; Raveh and Avnimelech, 1979; Korfiatis et. al., 1984; Oweis and Khera, 1990; Noble and Arnold, 1991; Roberson et. al., 1991). The flow of water through these channels, or macropores, is called channeling, and, like matrix flow, also depends on pore diameter. For micropores, capillary pressure, along with elevation, is an important driving force for flow, however, capillary pressure is not as important as elevation in driving the flow through macropores because of their larger pore diameter (Chen and Wagenet, 1992). Therefore, the amount of flow conveyed through macropores is diameter dependent, with larger macropores conveying more water than smaller macropores (section 2.1.4).

Flow through macropores may be laminar of turbulent (Chen and Wagenet, 1992), however, matrix flow is laminar (Price, 1985). Laminar flow through macropores can be represented by the Hagan-Poiseuille equation, while turbulent channeled flow can be modeled using, for example, Manning's equation (see section 2.1.4). As mentioned, matrix flow is represented by Darcy's Law. It should be noted that Darcy's Law is a special case of the Hagen-Poiseuille pipe flow equation, that gives a macroscopic average flow rate through a porous media which acts like a number of individual pipes (this averaging is accounted for with the hydraulic conductivity term which is a function of the packing, size and shape factor of the pores of a medium; De Wiest, 1965).

Also, unlike matrix flow, channeled flow does not spread over the entire cross-section of a porous matrix, instead, water flows only through the channels, although some absorption of water by the matrix through the channel walls may occur. Therefore, a uniform moisture front is not an accurate representation of channeled flow because flow is faster through the macropores than the matrix and the front is not horizontal. Rather this type of flow is better represented as small areas around the macropores at greater moisture contents than areas further from the pores (assuming a porous matrix exists, otherwise, water will flow only through the macropores and the moisture content of the material around these channels will remain the same). The size which distinguishes channels from micropores is media specific

(Beven and Germann, 1982). Table 2.1 lists the sizes and capillary pressures which researchers have used to distinguish micropores from macropores for soil.

Table 2.1: Defined Range of Macropore Sizes for Soil
After Chen and Wagenet, 1992

REFERENCE	CAPILLARY PRESSURE (KPa)	EQUIVALENT DIAMETER (μm)
Nelson and Baver (1940)	> -3.0	-
Marshall (1959)	> -10.0	> 30
Brewer (1964)	-	75 - 5000
McDonald (1967)	> -6.0	-
Dullien (1979)	> 0.5 - 1	-
Bouma and Wosten (1979)	-	>30
Bullock and Thomasson (1979)	> -5.0	> 60
Luxmoore (1981)	> -3.0	> 1000
Beven and Germann (1981)	> -0.1	> 3000
Radulovich et. al., (1989)	> -5.0	> 200

The table shows that macropores are not uniquely defined, and, as mentioned the characteristic size is media specific. Research to determine macropore size for MSW has not yet been conducted. However, in this study, any flow through pores which is gravity or elevation driven (not influenced by capillary forces) is considered channeled flow (unlike some researchers listed in the table who assume flow through macropores is also affected by capillary pressure). It is difficult to determine which driving force acts on an individual pore, due to the size of the pores; however, the difference between matrix and channeled flow can be distinguished by the effect each type of flow has on moisture movement. Macropore flow usually occurs for soil when infiltration intensity is greater than the saturated hydraulic conductivity of a porous matrix (Beven and Germann, 1982). However, it also occurs at infiltration rates less than the saturated hydraulic conductivity of MSW (Zeiss and Uguccioni, 1995). Water will flow faster through the macropores than the micropores because the diameter of the macropores is larger and provides less resistance to flow, also, water is not held up in the macropore by capillary forces (assuming capillary forces are negligible). As a result, leachate generation rates are significantly affected by channeling as it causes leachate to be discharged sooner than would be expected if only matrix flow was occurring (Schroeder et. al., 1994). Table 2.2 summarizes the differences between matrix and channeled flow.

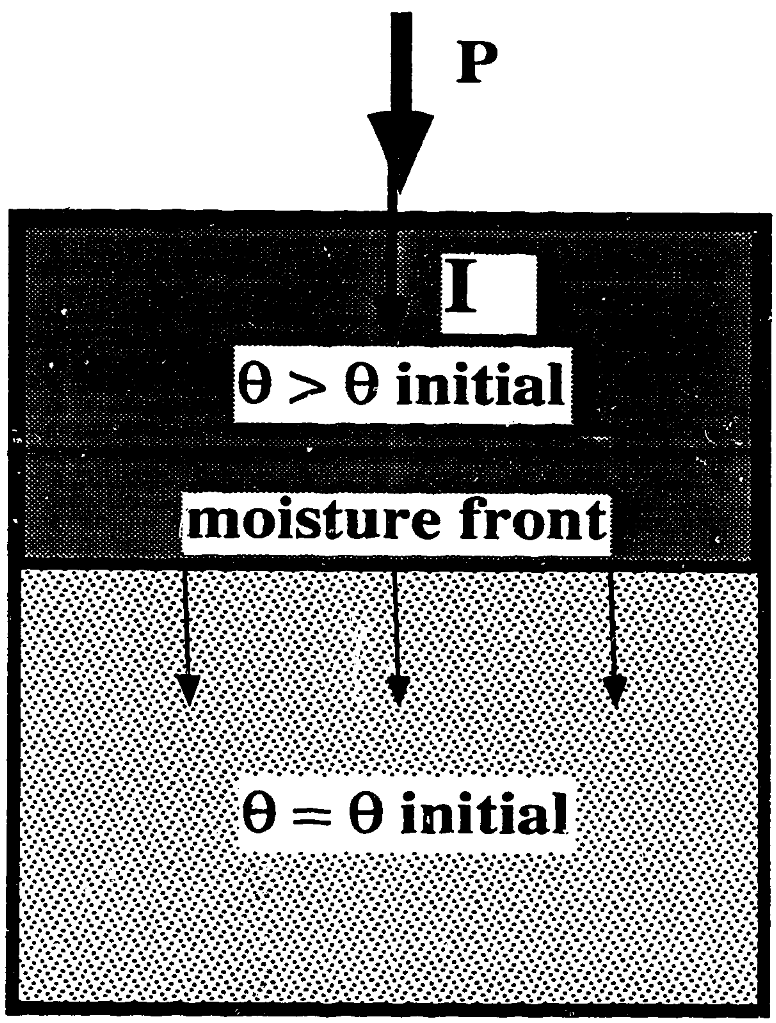
Table 2.2: Differences Between Matrix and Channeled Flow

PROPERTY	MATRIX FLOW	CHANNELED FLOW
Driving Force for Flow Under Unsaturated Conditions	Elevation (positive pressure head) and Capillary Pressure (negative pressure head)	Elevation (positive pressure head)
Pore Size	< 10 μm	> 30 μm*
Type of Flow	Laminar	Laminar or Turbulent
Representation of Flow	uniform, horizontal, moisture front; moisture content above the front is greater than the moisture content below the front (assuming a homogeneous matrix)	moisture front is non-uniform, non-horizontal; moisture content of fractures and waste around fractures greater than moisture content of entire volume
Equations used to Represent Flow	Darcy's Equation (section 2.1.2)	Hagen-Poiseuille Equation or Manning Equation (section 2.1.4)
Impact of Flow on Moisture Movement Through MSW	1) moisture spreads out over the cross-section of the medium 2) leachate discharge rate governed by hydraulic gradient and hydraulic conductivity of medium (which accounts for the size differences between individual pores) 3)moisture stored in micropores of porous matrix	1) moisture confined to channels and area around channels 2) leachate discharge rate governed by hydraulic gradient and size of channel 3) negligible storage in channels

Note: * 30 μm represents smallest macropore size defined in the literature, in this study macropores or channels are defined as pores which drain at 0 KPa of pressure

Two moisture movement studies specifically intended to study the effects of channeling concluded that channeling is a significant flow mechanism during imbibition, so a one-dimensional Darcian representation of moisture movement that ignores channeling may be inappropriate to describe flow through MSW (Zeiss and Major, 1993; Zeiss and Uguccioni, 1995). It should be noted, however, that a number of experiments in which channeling was observed were performed on a relatively small scale (Raveh and Avnimelech, 1979; Korfiatis et. al., 1984; Noble and Arnold, 1991). The experimental cells used by Zeiss and Major, for example, were 1.8 m high with a cross-sectional area of 0.26 m^2 and a diameter of 0.55m. The cell diameter was approximately six times the average particle size diameter for MSW (Hasselriis, 1984). This small difference between cell and particle diameter encourages channeling because flow between the particles and the cell walls becomes significant (Wall, 1993). Though channeling has been observed in larger scale systems (Fungaroli and Steiner, 1971; Rovers and Farquhar, 1973) its effects on moisture movement have not been studied. If channeling is significant in larger scale systems, it is more likely to be significant to moisture movement over an entire landfill. Both channeling and matrix flow occur in MSW (Zeiss and Major, 1993), and the various methods used to represent moisture movement through solid waste are described in the following section. The first method discussed, the water balance method does not explicitly consider the mechanisms by which moisture is transported through MSW. The other three methods discussed (one-dimensional Darcian flow, flow through fractured media, and flow through fractured - porous media) explicitly consider the moisture movement mechanisms.

Figure 2.1: Uniform Wetting Front

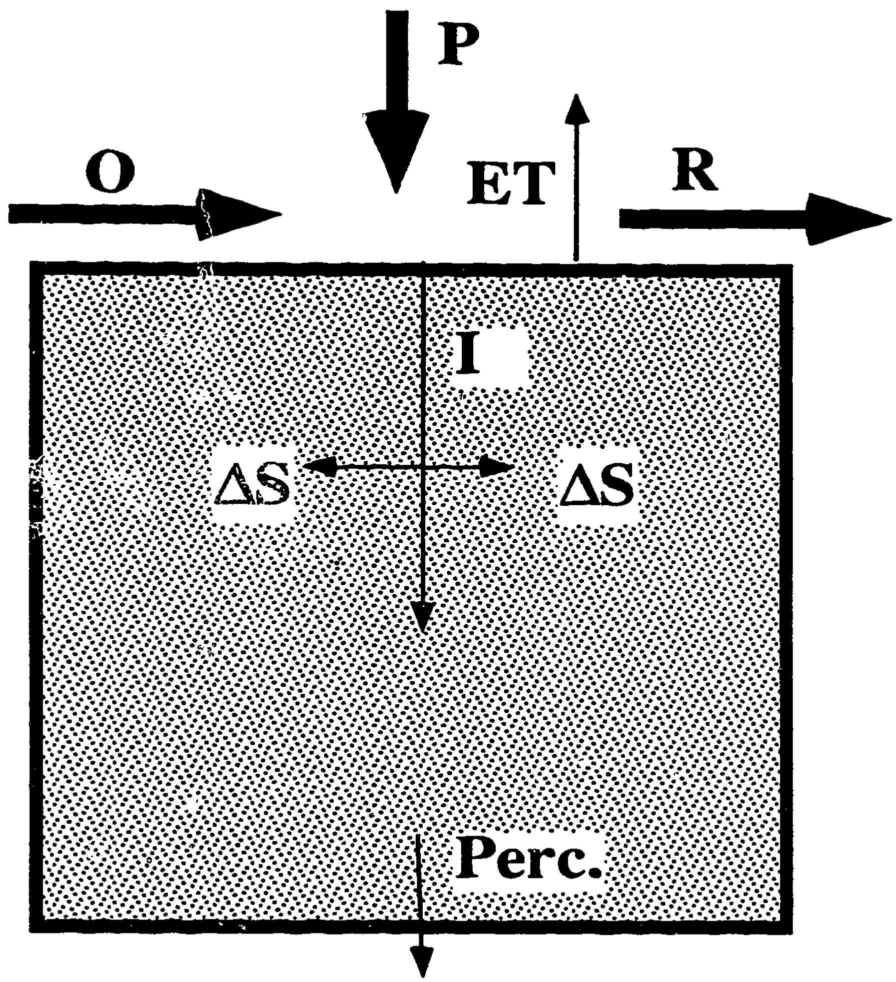


2.1.1 Water Balance

Moisture, that comes in contact with municipal solid waste is called leachate (Dass et. al., 1977; Stegmann, 1983; Baccini et. al., 1987; Farquhar, 1989; Radnoff et. al., 1992). The movement of moisture through the waste controls the rate of leachate flow. The water balance method may be used to provide an indirect estimate of leachate percolation through solid waste (Baetz and Byer, 1989). A water balance is performed by setting water inputs into the waste equal to the sum of all water outputs and the change in water storage of the waste (see Figure 2.2). The result provides the magnitude and direction of the component in question (Gee, 1981). For example, the amount of leachate percolating through a solid waste column can be indirectly calculated if all other water inputs, outputs, and storage of the column are known. The amount of leachate is set equal to the sum of precipitation and surface run-on, from which is subtracted the sum of evapotranspiration, runoff, and storage capacity of the waste, referring to Figure 2.2; Perc. = $P + O - R - ET - \Delta S$, or Perc. = $I - \Delta S$. A positive result indicates that leachate is generated from the column.

A water balance can be an efficient method to determine the amount of leachate generated from solid waste (Jasper et. al., 1985). The accuracy of the method depends on how well the components of the water balance are estimated. For instance, if the amount of runoff is estimated instead of directly measured, the error in leachate generation will be equal to the error between actual and estimated runoff, provided all other inputs and outputs are exactly known (Gee, 1981). The balance provides less accurate results if many of the inputs and outputs are estimated. This is particularly true of performing the method over small time steps, such as minute intervals, where the change of some parameters such as storage may be difficult to measure directly. The averaging of parameters over long periods, such as months or years, may produce more accurate long term water balance results (Blight et. al., 1992). Since hydrologic components are simply added or subtracted, the actual mechanisms of leachate movement through the waste are not considered in the water balance method (Gee, 1981). Therefore, leachate is assumed to flow through the waste as a uniform horizontal moisture front (see Figure 2.1), and is only generated when the sum of all inputs is greater than all outputs and storage (e.g., $I > \Delta S$). The water balance is not an extremely accurate tool for predicting leachate discharge because these assumptions lead to an underestimation of breakthrough time and total volume of leachate generated (Zeiss and Major, 1993; Zeiss and Uguccioni, 1995). However, other methods of representing moisture movement through MSW exist which explicitly consider the mechanisms of flow through the media. One of these methods, one-dimensional Darcian flow, is described in the following section.

Figure 2.2: Water Balance



P: precipitation
O: run-on
ET: evapotranspiration
R: runoff
ΔS: change in storage
I: infiltration
Perc.: percolation through the waste

2.1.2 Flow Through Porous Media

As mentioned is section 2.1, moisture movement is commonly represented as flow through a homogeneous porous media. In this representation moisture flows as a horizontal front through the waste, uniformly wetting the media as it passes through. The equation used to describe this movement, called Darcy's Law (Bear, 1972; Freeze and Cherry, 1979), expresses the flow rate of water through a media as a function of both the permeability of the media, and the driving force of the fluid. It can be used to describe both saturated and unsaturated flow conditions. Darcy's law, for saturated flow, is written as:

$$Q = -K_s * A * (dh / dl) \qquad (1)$$

where: Q = the volumetric flow rate (L^3/T)

K_s = the saturated hydraulic conductivity; a function of the media as well as the fluid (L/T)

A = the cross-sectional area through which fluid flows (L^2)

dh/dl = the hydraulic gradient, or driving force caused by a change in pressure or elevation of the fluid over a length of media (L/L)

As mentioned Darcy's Law can only be used if the flow is laminar because it assumes a linear relationship between head loss and velocity (the exponent of dh/dl in equation 1 is one, if the flow was turbulent this value would be less than one). Therefore, laminar flow through a porous media is called Darcian flow (Bouwer, 1978). The Reynolds number is used to determine if the flow is laminar or turbulent. For pore flow it is represented as:

$$Re = (\rho * q * d)/\mu \qquad (2)$$

where: ρ = the density of the fluid flowing through the pore (M/L^3)

q = the specific discharge; flow rate per unit area, or flux (L/T)

d = the diameter of the pore (L)

μ = the absolute viscosity of the fluid ($M/L/T$)

Flow is considered laminar in a porous matrix if the Reynolds number is below 10 (Bear, 1972). If the Reynolds number is above this value Darcy's Law can not be used to represent the flow, and the flow cannot be considered Darcian (Bouwer, 1978). In this study all matrix flow is assumed laminar, and, therefore, Darcian.

Darcy's law was originally developed for flow in saturated zones, which consists of two phases; solid and liquid (water). It can be modified for unsaturated conditions where air (or gas) is present. The presence of air in the pore spaces of the media changes the driving forces for flow (Fetter, 1993). Water flow through porous media, under both saturated and unsaturated conditions, is dependent on the hydraulic head of the fluid. The hydraulic head (h) is the sum of the elevation head of the fluid (z) and the pressure head (ψ) (see Figure 2.3). Under unsaturated conditions the pressure head is often referred to as the suction head (Fetter, 1993). As mentioned in section 2.1, in the unsaturated flow regime the pressure head is negative (suction head is positive), indicating that water is held under capillary tension in the pores of the porous media (Jury et. al., 1991). Also, unlike the saturated zone where the hydraulic conductivity, K_s, and the moisture content of the media, θ_s, are constants, these properties are functions of the pressure head in the unsaturated zone. The unsaturated hydraulic conductivity, and the unsaturated moisture content are always less than K_s and θ_s, except when the pressure head (or tension head) is zero (Freeze and Cherry, 1979). To represent water movement through unsaturated media as Darcian flow, these characteristics of the unsaturated zone must be taken into account. The Buckingham Flux Law, in which the unsaturated hydraulic conductivity is expressed as a function of the suction head of the media, is used to describe Darcian flow through the unsaturated zone (Fetter, 1993). In vector form it may be expressed as:

$$\mathbf{q} = -\mathbf{K}(\psi)\nabla(\mathbf{h}) \qquad (3)$$

where: $K(\psi)$ = the unsaturated hydraulic conductivity as a function of the suction head of the media (L/T)

$\nabla(h)$ = the hydraulic gradient (L/L)

This equation may be combined with the continuity equation to express the change in moisture content with time as a function of the unsaturated hydraulic conductivity and the hydraulic gradient. This equation is known as the Richard's equation (Fetter, 1993), and is written in vector form as:

$$\partial\theta/\partial t = \nabla\ (-\mathbf{K}(\psi)\nabla(\mathbf{h})) \qquad (4)$$

where: θ = the volumetric moisture content of the media at a given capillary pressure ψ (L^3/L^3)

t = time (T)

As this equation is derived from the Buckingham Flux Law, the change in moisture content is represented as a uniform, horizontal front through the media (Van der Ploeg and Benecke, 1974; Korfiatis, 1984; Milly, 1985, and Ross, 1990).

The moisture content - capillary pressure relationship, and the relationship between unsaturated hydraulic conductivity and capillary pressure of the media are needed to use equations 2 and 3. While field methods exist to obtain this data (Marshall and Holmes, 1979; Reynolds and Elrick, 1986; Ankeny et. al., 1989; Daniel, 1989; Elrick et. al., 1989; Shan and Stephens, 1993; Tseng and Jury, 1993), often these relationships are not known for MSW. Many models exist to represent these relationships in soils, however. Commonly, the moisture content - capillary pressure relationship is modeled using the Brooks - Corey equation (Brooks and Corey, 1966), though other expressions do exist (Farrell and Larson, 1972; Arya and Paris, 1981; Tyler and Wheatcraft, 1990). The Brooks - Corey equation is written as:

$$(\theta - \theta_r)/(n - \theta_r) = (\psi_b / \psi)^{\lambda} \qquad (5)$$

where: θ_r = the residual soil moisture content (L^3/L^3)

n = the porosity of the media, also equal to θ_s (L^3/L^3)

ψ_b = the bubbling pressure, or air entry pressure of the media ($ML^{-3}T^{-2}$)

ψ = the capillary pressure ($ML^{-3}T^{-2}$)

λ = the pore size distribution index of the media (-)

A common expression relating the unsaturated and saturated hydraulic conductivities of a media is the Campbell equation (Campbell, 1974). Again, many other relationships between these two parameters have been developed for soils (Mualem, 1976; Clapp and Hornberger, 1978; Mualem, 1978; van Genuchten, 1980; Russo, 1988). The Campbell equation is written as:

$$K = K_s * (\theta / \theta_s)^{3 + 2/\lambda} \qquad (6)$$

where: K = the unsaturated hydraulic conductivity at a given moisture content θ (L/T)

θ_s - the moisture content at saturation, also equal to n (L^3/L^3)

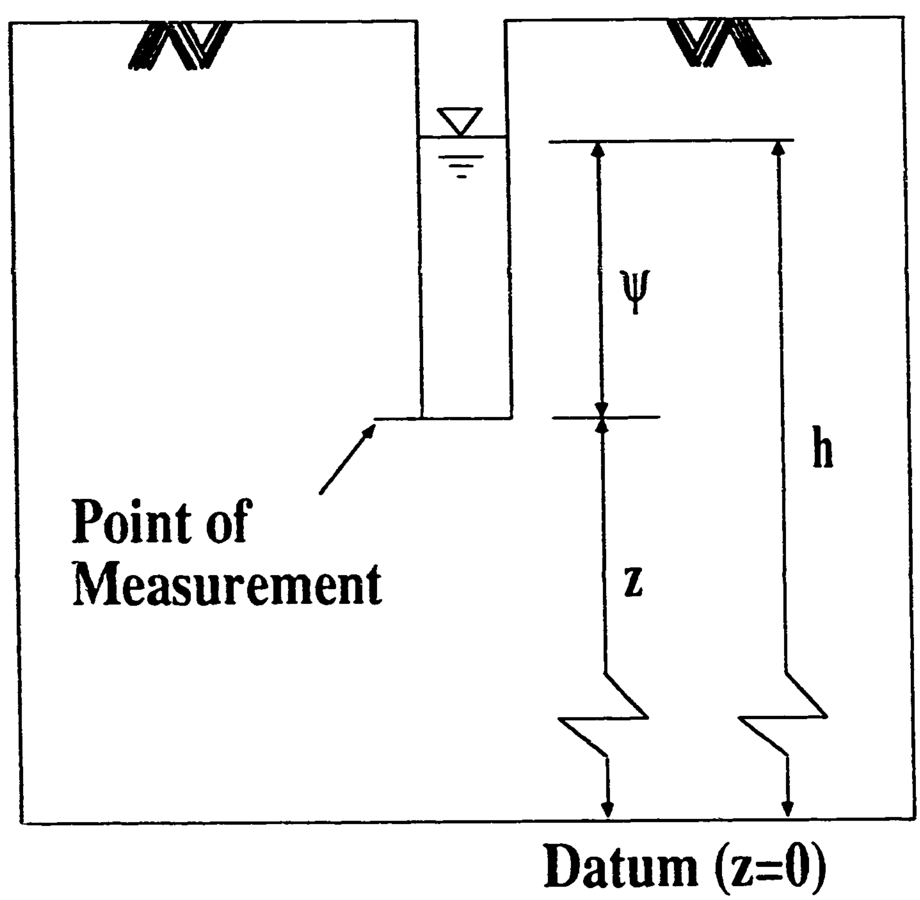
By combining equations 5 and 6, an expression for the unsaturated flow rate can be developed, derived from the Darcy and Buckingham Flux Laws. This equation, used in the HELP model to describe moisture movement through solid waste (Schroeder et. al., 1988; Schroeder et. al., 1994), is written as:

$$q = -K_s \cdot ((\theta - \theta_r)/(n - \theta_r))^{3+2/\lambda} * dh/dl \qquad (7)$$

where all parameters have been defined in previous equations.

Both Darcy's Law and the Buckingham Flux Law (and all of the above forms) were originally developed for homogeneous, isotropic porous media. However, they have also been used to describe flow through heterogeneous, anisotropic media (Freeze and Cherry, 1979). Flow through both heterogeneous soil (Yeh, 1989; Selker et. al., 1992; El-Kadi, 1993), and fractured rock (Long et. al., 1982; Phillips, 1991) may be modeled using Darcy's law if the value of the saturated hydraulic conductivity is corrected for the heterogeneities of the media, such as the presence of large pores, or very slightly permeable material. When applying either model to heterogeneous media, or media with channels or macropores, a large enough representative elementary volume (REV) must be used in order to account for the variability in the matrix and the macropores (Beven and Germann, 1982; Huyakorn and Pinder, 1986; Mantoglou, 1992). Also, these models are invalid for media with large fractures or channels if flow through these macropores is turbulent, since Darcy's Law is only valid for laminar flow (Chen et. al., 1993). Therefore, the composition of MSW, as well as the characteristic size of channels in the waste should be determined to ensure that a one-dimensional Darcian flow model is valid for representing flow through MSW. Due to the limitations of this model, it may be necessary to model moisture movement another way. Fractured media models are discussed in the next section.

Figure 2.3: Hydraulic Head Determination



After Freeze and Cherry, 1979

2.1.3 Flow Through Fractured Media

Municipal solid waste is composed of a large amount of impermeable material such as plastic (approximately 10% of municipal solid waste, excluding recycled material is plastic; Tchobanoglous et. al., 1993). Water cannot flow through plastic but must flow around the plastic waste particles. Therefore, moisture movement through the waste as flow through a porous medium may not accurately represent the flow mechanism, instead flow may be better represented as flow through fractured rock (see Figure 2.4). This type of flow model assumes water only flows through channels or fractures in the rock, and no flow through the rock matrix occurs (Evans and Huang, 1983; Fogg, 1986, Tsang and Tsang, 1987; Tsang et. al., 1988; Desbarats, 1990; Nordqvist et. al, 1992). The fractures are idealized as parallel flow plates of constant aperture (Evans and Huang, 1983), or a range of apertures (Neuzil and Tracy, 1981).

Laminar flow in the fractures is also assumed, which is expressed mathematically as (Evans and Huang, 1983):

$$Q = (\gamma/12\mu)LJ\int_{0}^{\infty} b^3 f(b)\,db \qquad (8)$$

where:

Q = volume flux of water (L^3/T)

γ = specific weight of water (M/L^2T^2)

μ = dynamic viscosity of water (M/LT)

L = segment length normal to flow, or width (L)

J = potential hydraulic gradient (L/L)

b = aperture (L)

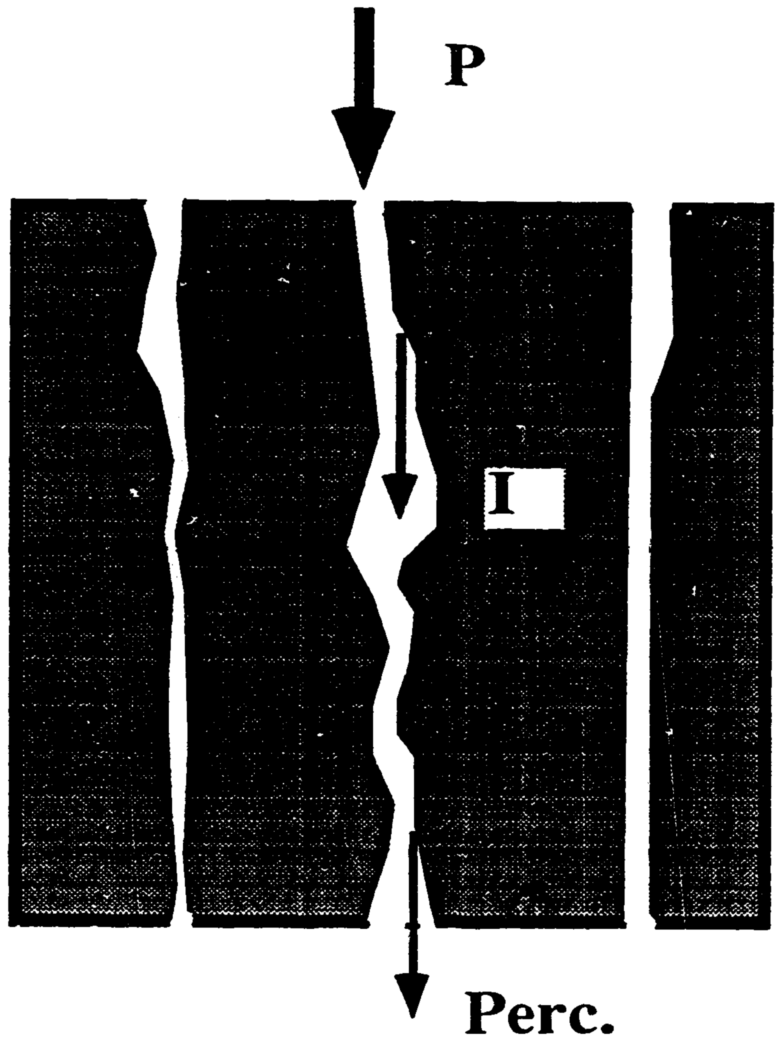
f(b) = aperture distribution usually represented by a lognormal distribution

This equation may also be used to describe unsaturated flow through a fracture by substituting a maximum saturated aperture size for infinity, in the evaluation of the integral. This implies that under unsaturated conditions fractures greater than the maximum saturated aperture will not contribute to liquid flow because they do not contain liquid.

The accuracy of these models depends on the how well aperture size is estimated or measured (Evans and Huang, 1983). However, this data has not been previously determined for MSW. The variability in the composition of MSW may make it difficult to determine a representative aperture size, or select a distribution of aperture sizes which will accurately represent the waste (section 2.1). The shape of the channel is also important in determining flow rate; the shape is usually assumed to be a rectangular crack (parallel plates) or cylinder. Again, the characteristic shape of channels in MSW has not been determined. Also, flow through the channels may be laminar or turbulent (Gerhart and Gross, 1985; Potter and Wiggert, 1991). However, because a characteristic size of channel for MSW has not been determined, the type of flow through the channel is not known. In the above equation (equation 7) flow is assumed to be laminar. Though experimental methods exist for determining the channel diameter and shape for fractured, and fractured - porous media (Long et al., 1982; Vermeul et. al., 1993), they have not been applied to MSW. Therefore, the determination of channel diameter and shape for solid waste may be difficult if the experimental methods used by other experimenters (e.g., filling fractures with paraffin wax to facilitate the determination of the characteristic diameter; Vermeul et. al., 1993) are not applicable.

Also, as mentioned, matrix flow has been observed through MSW, yet fractured rock models assume flow occurs only through fractures. Therefore, though these models may provide a good estimation of parameters which characterize leachate generation, such as breakthrough time, they do not realistically model the actual flow of water because no matrix flow occurs. For example, breakthrough time may be predicted accurately by a fractured rock model because water is quickly conveyed through the fractures of the system. However, the total volume of leachate discharged may be overestimated because the only storage capacity which exists in the system is the cumulative pore volume, whereas the storage capacity of waste is made up of the channels and the micropores (Zeiss and Uguccioni, 1995). In order to account for this additional storage capacity, matrix flow should be considered. The next section describes the fractured - porous representation of moisture movement. This method accounts for both channeled and matrix flow.

Figure 2.4: Flow Through Fractured Media



P: precipitation
I: infiltration into channel
Perc.: percolation through channel

2.1.4 Flow Through Fractured - Porous Media

In addition to porous and fractured media representations, moisture movement through MSW may be modeled as flow through fractured - porous media. As the title implies, this is a combination of both porous and fractured media and flow characteristics. Fractured - porous media models have been developed for both soil (Germann and Beven, 1981; van Genuchten and Dalton, 1986; Bronswijk, 1988; Jarvis et. al, 1991; Rowe and Booker, 1991; Booltink et. al., 1993; Chen et. al., 1993) and rock (Duguid and Lee, 1977; Wang and Narasimhan, 1985; Dykhuizen, 1992; Rubin and Dveyrin, 1993). These models characterize the flow through the media as being either one or two-domain (Beven and Germann, 1982). One-domain flow models are similar to porous media models, with hydraulic parameters adjusted to account for fractures. The saturated hydraulic conductivity is increased to reflect the greater velocity of flow through the fractures, yet moisture movement is represented by the Darcy equation (El-Kadi, 1993). These models represent flow as a uniform moisture front and share the same limitations as porous media models such as the assumption of laminar flow.

Two-domain models route flow through both the fractures or channels and the porous matrix (see Figure 2.5). Channeled flow is often modeled using the same equation developed for fractured media (equation 8), or if turbulent flow occurs Manning's equation can be used (Chen and Wagenet, 1992). This equation is expressed as:

$$U = 1/n * (R^{2/3} * S_p^{1/2}) \qquad (9)$$

where: U = average flow velocity in the channel (L/T)

n = coefficient of roughness (-)

R = hydraulic radius of the channel (L)

S_p = slope of the energy grade line or gradient(L/L)

Also, the flow through the matrix is modeled using, for example, the Buckingham Flux Law (equation 3):

$$q = -K(\psi)\nabla(h) \qquad (3)$$

where: q = the flow rate per unit area, or flux (L/T)

$K(\psi)$ = the unsaturated hydraulic conductivity as a function of the suction head of the media (L/T)

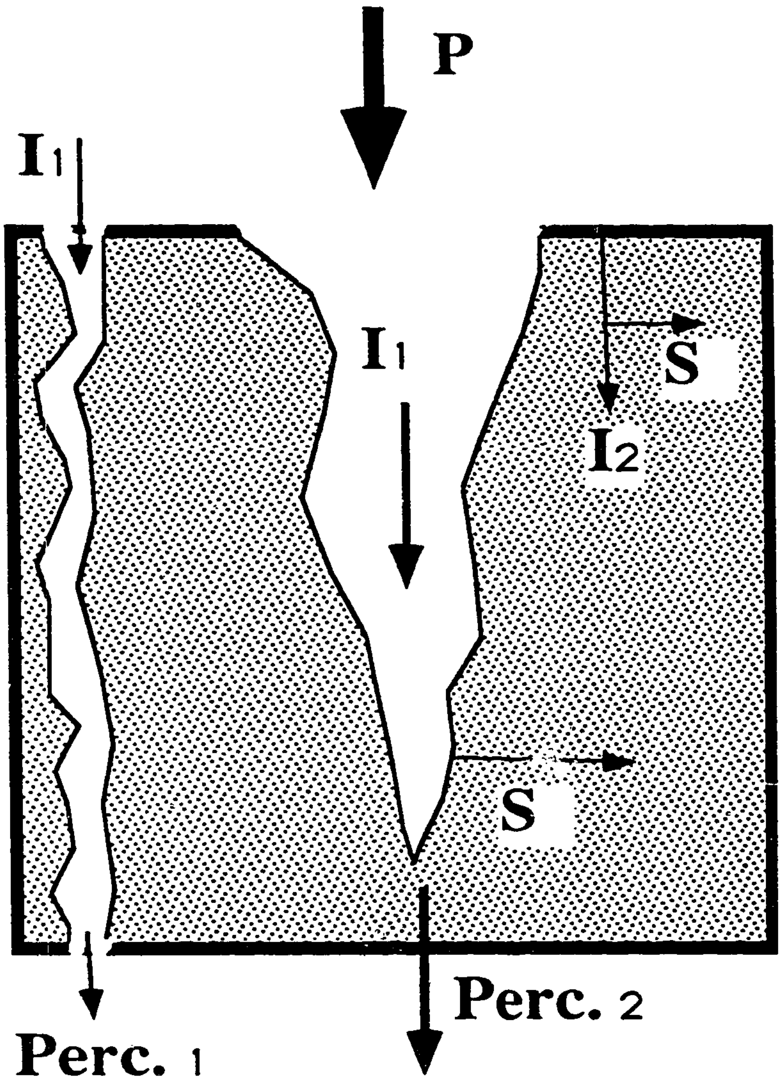
h = the hydraulic gradient (L/L)

Because moisture flows through the two domains at different rates, a uniform moisture front does not occur. Flow may quickly be conveyed through channels while a slower moving wetting front passes through the matrix (Beven and Germann, 1981). Note that the amount of flow through channels is dependent on the loading rate of water applied to the media because at low infiltration intensity and unsaturated conditions, more of the water falling on the surface flows through the matrix than through the channels. This is due to the relatively high tension head associated with the unsaturated zone (Banerjee and Watson, 1984; Woods, 1992). Water is pulled through the matrix by capillary forces, and any flow through the channel is likely to adhere to the walls and be absorbed into the matrix. At high loading rates greater or equal to the saturated hydraulic conductivity of the matrix, the matrix will saturate and ponding will occur (Beven and Germann, 1982). Water will take the path of least resistance to reach the water table and will flow through the channels (assuming that they reach to the surface of the media). Since saturated conditions exist, the flow in the channels cannot be absorbed by the matrix. Flow through the channels is much greater than the matrix flow since it is not limited by the saturated hydraulic conductivity (Booth and Price, 1989). Only the cross-sectional area of channels limit the flow rate through them, since channel flow velocity is always much greater than the saturated hydraulic conductivity of the matrix (Beven and Germann, 1982).

The fractured - porous media approach allows for flow through both fractures and the porous matrix to be considered. Therefore, it may be more representative of flow through MSW than the previous methods discussed. However, it is not without limitations. As mentioned, the characteristic macropore diameter is media specific, and has not been uniquely defined (see Table 2.1). Therefore, it is difficult to define which pore size separates a channel from a micropore which is part of the matrix. Another challenge in applying this type of model is to accurately represent the flow distribution. As water flows through both the channels and the matrix, it may seep into or out of either domain at any time. Additional water in either will affect hydraulic properties such as moisture content and may change the flow rate through that domain. Also, the conservation of mass must apply to both domains; however, mass may be transferred between both the channels and matrix. This has proven difficult to represent (Chen et. al., 1993).

Before attempting to model moisture movement through MSW, flow and other physical characteristics of waste must be determined. These characteristics are discussed in the following section.

Figure 2.5: Flow Through Fractured - Porous Media



P: precipitation
I_1: infiltration into channels
I_2: infiltration into matrix
S: storage
Perc. 1: percolation through channels
Perc. 2: percolation through matrix

2.2 FACTORS INFLUENCING MOISTURE MOVEMENT

2.2.1 Municipal Solid Waste Composition and Properties

Generally, solid waste is defined as all solid or semi-solid materials that the possessor no longer considers to be of sufficient value to retain (Tchobanoglous et. al., 1993). Municipal solid waste generated by the residential, commercial, institutional and municipal sectors, is a subset of the total solid waste stream. Typically, MSW consists of food wastes, yard wastes, plastic, paper, metal, textiles, lumber and white goods (Britton, 1972; Klee, 1993; Tchobanoglous et. al., 1993). The composition varies by location and by season (Klee and Carruth, 1970; Brunner and Ernst, 1986).

The variable composition of the waste leads to variability of physical properties such as initial moisture content and particle size, and hydraulic characteristics such as field capacity, porosity, and saturated hydraulic conductivity (Carpenter, et. al., 1990). Table 2.3 lists the literature values found for these physical and hydraulic properties. Since these parameters are not uniquely defined in the literature they are defined here.

Table 2.3: Typical Values of Physical and Hydraulic Properties of MSW Found in the Literature

PROPERTY	VALUE	REFERENCE
MOISTURE CONTENT	2 to 6	Bagchi (1990)
(% by volume)	10 to 20	Oweis et. al. (1990)
	9 to 24	Tchobanoglous et. al. (1993)
PARTICLE SIZE (cm)	8.9 to 17.8	Hasselriis (1984)
Rosin-Rammler X_o	3.9 to 33.7	Zeiss and Major (1993)
FIELD CAPACITY	12 to 13.7	Bagchi (1990)
(% by volume)	20 to 35	Oweis et. al. (1990)
	30 to 36	Tchobanoglous et. al. (1993)
POROSITY	40 to 50	(Oweis et. al., 1990)
(% by volume)	47 to 58	(Zeiss and Major, 1993)
SATURATED HYDRAULIC	1.76E-3	Ahmed et. al. (1991)
CONDUCTIVITY (cm/s)	1.6E-3 to 3.8E-3	Blight et. al. (1992)
	5.9E-3 to 2.5E-1	Ettala (1987)
	3.2E-3 to 5.1E-3	Korfiatis (1984)
	1E-3	Oweis et. al. (1990)

Initial moisture content is defined as the amount of water initially stored in a media before any input or output of water occurs. It is determined by drying a known mass of media to a constant mass by evaporating the water from the media. The moisture content can be represented on a wet or dry basis, and expressed as a mass or volume ratio. All initial moisture contents listed here are expressed as a wet volume ratio.

In the literature, particle size is defined using a variety of measures, including the Rosin-Rammler particle size (Hasselriis, 1984). Particle sizes listed here will refer to the Rosin-Rammler characteristic particle size (X_o). This quantity is expressed in cm.

Field capacity is usually defined as the moisture content at which free drainage of an initially saturated media ceases (Schroeder et. al., 1988). It is a point on the drainage curve, and is also defined as the moisture content of a porous media to which a pressure of 0.33 bars has been applied (Freeze and Cherry, 1979; Schroeder et. al., 1994).

Porosity is defined as the moisture content at which all pores of the media are filled with water, or saturated (Schroeder et. al., 1994). This quantity is also referred to as the saturation moisture content (Korfiatis et. al., 1984).

Saturated hydraulic conductivity is a measure of the ability of a porous media to transmit water (Fetter, 1993). This parameter will be expressed in cm/s.

In addition to the physical and hydraulic properties listed in Table 2.3, other parameters have been introduced by various researchers which may also be used to characterize waste. Zeiss and Major (1993), and Zeiss and Uguccioni (1995), have described parameters which they used to illustrate the difference between matrix and matrix-channeled flow. These parameters include practical field capacity, effective storage, breakthrough time, time to reach effective storage, initial unsaturated hydraulic conductivity, and ultimate unsaturated hydraulic conductivity. These parameters, derivatives of those shown in Table 2.3, are defined below.

Practical field capacity, a parameter analogous to field capacity expresses the moisture content at which leachate is first discharged after water application to initially unsaturated waste. This parameter, unlike field capacity, corresponds to the point of first drainage on the imbibition curve of the waste (Zeiss and Major, 1993).

Effective storage is defined as the moisture content at which water output from the waste equals the water input (e.g., the volume of leachate discharging from the waste is equal to the volume of water applied as infiltration). In other words effective storage is the moisture content of waste at steady state. Effective storage is usually less than the porosity of the waste, and is greater than the practical field capacity (Zeiss and Uguccioni, 1995). As with the other moisture contents defined here, effective storage is expressed as a wet volume ratio.

Breakthrough time is the time taken to reach practical field capacity. It is determined here (and in studies by Zeiss and Major, 1993, and Zeiss and Uguccioni, 1995) by measuring the time from first application of moisture to first percolation of leachate out of the waste. Breakthrough time is also used to determine the initial unsaturated hydraulic conductivity of the waste (which is defined below). It is expressed in this study in minutes.

Time to effective storage is the time for the waste to reach steady state from the first application of moisture. It is larger than breakthrough time because practical field capacity is reached before effective storage occurs. Time to effective storage usually occurs days after moisture loading commences (Zeiss and Uguccioni, 1995), therefore, it is expressed here in days.

Initial unsaturated hydraulic conductivity is the apparent hydraulic conductivity of the waste at practical field capacity. It is calculated with the following equation (Zeiss and Major, 1993)

$$K_{us} \text{ initial} = (h * n)/(t_{bt}) \qquad (10)$$

where:
K_{us} initial = initial unsaturated hydraulic conductivity (L/T)
h = height of waste column (L)
n = porosity of waste (L^3/L^3)
t_{bt} = breakthrough time (T)

Initial unsaturated hydraulic conductivity is greater than the unsaturated hydraulic conductivity that would be calculated using, for example, the Campbell equation (equation 6) with the practical field capacity moisture content. The initial unsaturated hydraulic conductivity (expressed in cm/s) indicates the effect of channeling on flow rates through the waste.

Ultimate unsaturated hydraulic conductivity is the apparent hydraulic conductivity of the waste at effective storage. This parameter is calculated as (Zeiss and Major, 1993):

$$K_{us} \text{ ultimate} = Q / A \qquad (11)$$

where:
K_{us} ultimate = ultimate unsaturated hydraulic conductivity (L/T)
Q = flow rate of leachate percolating from the waste at steady state (effective storage) (L^3/T)
A = cross sectional area of the waste through which water flows (L^2)

Ultimate unsaturated hydraulic conductivity can be less than the initial unsaturated hydraulic conductivity, particularly if breakthrough time is small. Also, at steady state leachate is percolating through the waste matrix and the channels. The velocity of flow through the matrix is smaller than the channel flow velocity. Therefore, the average velocity of the total flow through the waste is smaller at effective storage than at practical field capacity where more flow is conveyed through the channels resulting in a larger flow velocity. Based on the Campbell equation, for example, actual unsaturated hydraulic conductivities increase with increasing moisture content, so it should be noted again that initial and ultimate K_{us} are apparent hydraulic conductivities which are used to show the effects of channeling on moisture movement through MSW. Ultimate unsaturated hydraulic conductivity is also expressed in cm/s.

Unlike the parameters listed in Table 2.3 the parameters defined above are used specifically to indicate the effects of channeling on matrix flow. (Zeiss and Major, 1993; Zeiss and Uguccioni, 1995)

The waste characteristics listed in Table 2.3 are typical of the range of values expected for MSW. These characteristics of the waste influence leachate flow since they reflect the initial volume of water stored in the waste, the maximum amount of water the waste can hold, and how easily water can flow through MSW. It should be noted that these characteristics and those variables defined above (e.g., practical field capacity), are influenced by environmental factors and landfilling operation. For example, saturated hydraulic conductivity is influenced by compaction of MSW (Ettala, 1987). Increased compaction can decrease the saturated hydraulic conductivity of the waste, therefore, landfills with poor compaction and low waste densities will have saturated hydraulic conductivities nearer to 2.5E-1 cm/s (the largest value given by Ettala, in Table 2.3). Also, initial unsaturated hydraulic conductivity is influenced by moisture loading intensity with higher intensities resulting in shorter breakthrough times (Zeiss and Uguccioni, 1995). Compaction, and moisture loading intensities, as well as other external factors influence moisture movement, in addition to influencing waste characteristics. Their affects on moisture movement are discussed in the following section.

2.2.2 Environmental and Landfill Operating Conditions

A number of environmental and operating conditions influence moisture movement in municipal solid waste landfills (Wall and Zeiss, 1995). Weather and climate are examples of environmental conditions. More specifically, environmental conditions can be divided into precipitation intensity and frequency, temperature, and biodegradation of the refuse in the landfill. Precipitation contributes to the amount of water absorbed by the waste (see Figure 2.2). Therefore, the more precipitation falling on a landfill and infiltrating the waste, either due to increased intensity or frequency, the more leachate generated (Chian et. al., 1985). Precipitation intensity also influences the amount of channeling which may occur (section 2.1), therefore, it may be a more important factor than precipitation frequency. Because the precipitation falling on a landfill must infiltrate the waste in order to affect leachate generation, infiltration intensity is the actual parameters of interest in determining the effects of precipitation on moisture movement. Temperature affects the amount of evapotranspiration that will occur. Higher temperatures lead to greater evapotranspiration. An increase in evapotranspiration decreases the amount of leachate percolating out of a landfill (Jasper et. al., 1985). Biodegradation also affects the leachate generation in a landfill. Water is used by microorganisms to metabolize the waste, thereby increasing the storage capacity of the waste (Mao and Pohland, 1973). The water is converted to end-products such as methane and carbon dioxide and biomass, and is prevented from actively flowing through the waste. Therefore, an actively biodegrading landfill may generate less leachate than a dormant one because water is immobilized during anaerobic biodegradation. In terms of moisture flow through municipal solid waste infiltration intensity has the most influence on leachate generation (Chian et. al., 1985).

Operational conditions also affect leachate generation. These include types of waste accepted by the facility, waste processing such as shredding, and compaction of the waste (Wall, 1993). The waste accepted by the facility influences the amount of leachate generated because certain types of waste, such as food wastes, have high moisture contents. Therefore, the addition of these wastes, as well as liquid wastes decrease storage capacity (Figure 2.2). Shredding affects the particle sizes of the waste (Hasselriis, 1984; Tchobanoglous et. al., 1993), and causes the opening of plastic bags exposing the waste inside. These actions may decrease the amount of leachate generated as more pore volume (micropores of the porous matrix of the waste inside the plastic bags) is available for storage (Zeiss and Major, 1993). Finally, compaction affects the amount of leachate generated because it acts to open plastic bags, exposing more pore volume to flow, and increase the density of the waste, decreasing the hydraulic conductivity of the waste (section 2.2.1). Compaction should be considered the most important operational condition listed here because it performs the above functions. Also, compaction of the waste by heavy equipment flattens and orients waste particles in a horizontal direction (Zeiss and Major, 1993). This affects the size range, length and orientation of the channels formed in the waste, with more horizontal channels of smaller diameter resulting from greater compaction. Therefore, leachate cannot move as quickly through the waste because the channels are smaller (more water may then infiltrate into the porous matrix because channeled flow is reduced). Compaction may be expressed as bulk density; however, it must be recalled that an increase in density is only one effect of compaction on MSW. In this study, compaction refers to the act of compacting the waste with heavy equipment, which opens plastic bags and flattens waste particles.

The environmental and operational conditions discussed above influence moisture movement through MSW because they affect the magnitude of the components of the water balance (e.g., compaction acts to increase the storage of the waste). The conditions which have the most influence on moisture movement are infiltration intensity and compaction. As noted, compaction also affects waste properties, such as saturated hydraulic conductivity. Waste characteristics, such as the physical and hydraulic properties of waste listed in Table 2.3, also affect moisture movement by influencing water balance components such as storage, and influencing the mechanisms of moisture movement (e.g., saturated hydraulic conductivity affects the flow rate of leachate through the matrix). Figure 2.6 summarizes the factors discussed in this section and their affect on moisture movement. The following section discusses the models considered for simulating moisture movement through MSW.

Figure 2.6: Cause-Effect Diagram of Factors Influencing Moisture Movement

ENVIRONMENTAL CONDITIONS

INCREASE Infiltration Intensity ⇒	INCREASE Volume of Water Infiltrating Waste ⇒	INCREASE Amount of Leachate Generated
INCREASE Temperature ⇒	INCREASE Evapotranspiration ⇒	DECREASE Amount of Leachate Generated
INCREASE Biodegradation ⇒	INCREASE Storage Capacity of Waste (immobilize water in biomass) ⇒	DECREASE Amount of Leachate Generated

OPERATIONAL CONDITIONS

INCREASE Amount of Liquid Waste Accepted By The Facility ⇒	DECREASE Storage Capacity of Waste (increase moisture content of waste) ⇒	INCREASE Amount of Leachate Generated
INCREASE Shredding ⇒	INCREASE Storage Capacity of Waste (expose more pore volume to flow) ⇒	DECREASE Amount of Leachate Generated
INCREASE Compaction ⇒	INCREASE Storage Capacity of Waste (expose more pore volume, decrease channel size) ⇒	DECREASE Amount of Leachate Generated
INCREASE Waste Density ⇒	DECREASE Diameter and length of channels ⇒	DECREASE Amount of Leachate Generated

2.3 EVALUATED MODELS

The purpose of selecting moisture movement models is to determine their applicability for use with MSW. Therefore, representative models found in the literature review are examined. The HELP model version 3.03 (Schroeder et. al., 1994) was used for simulations and results were compared with a model chosen from the literature. The HELP model is used as the basis of comparison because it is considered the most commonly used of all moisture movement models for MSW, and has been developed as a management and design tool for landfills (Peyton and Schroeder, 1988).

The models examined include one water balance model, four porous media models, two fractured media models, and eleven fractured - porous media models. The water balance model reviewed is the model reported by Gee, 1981. Porous media models include the model proposed by Straub and Lynch, 1982, the model of Korfiatis et. al., 1984 (LANDFIL), Noble and Arnold's 1991 model (FULFIL), and the model of Connell and Bell, 1993. Fractured media models evaluated are the model of Evans and Huang, 1983, and the model of Nordqvist et. al., 1992. Finally, the fractured-porous media models include the model of Edwards et. al. 1979, Hoogmoed and Bouma's 1980 model, the model of Beven and Germann, 1981, Davidson's 1985 model, the model of Germann and Beven, 1985, Peters and Klavetter's model from 1988, Miller and Mishra's model, presented in 1988, PREFLO (Workman and Skaggs, 1990), and LASOMS (Chen and Wagenet, 1992). Also, two other fractured-porous media models are evaluated, the model of Gerke and van Genuchten, 1993, and MACRO by Jarvis, 1994. The evaluation of these models is presented in chapter 3.

The chosen model is used to predict experimental moisture movement in terms of leachate discharge (percolation through waste). The model results are compared to the results simulated by HELP to determine which model best predicts measured moisture movement. Direct comparison of leachate discharge between models is difficult because discharge is a continuous process. Discrete variables characterizing leachate discharge are examined to facilitate comparison. These parameters are: breakthrough time, time to effective storage, peak leachate discharge, time to peak, total leachate volume discharged, and duration of the leachate event. These parameters allow the leachate percolation to be characterized by discrete parameters which provide information on the event, similar to hydrograph analysis (Ponce, 1989), as well as providing important information for the design of landfill systems (e.g., peak volume is an important design parameter for leachate collection systems, Ettala, 1986). Breakthrough time, defined previously, is the lag time between moisture loading and first discharge (the time to reach practical field capacity) and indicates the responsiveness of the system. Time to effective storage gives an indication of how quickly the system can discharge an equal amount of infiltration. These parameters are also chosen to compare model results as they are used in the analysis of environmental and operational conditions on moisture movement through MSW (see chapter 3: Methods).

The other parameters, peak leachate discharge, time to peak, total leachate volume discharged, and duration of the event are defined below.

Peak leachate discharge is the peak volume of leachate percolating through the waste. This parameter gives information on the maximum amount of leachate the system can discharge (Ettala, 1986). In some cases peak leachate volume equals the percolation volume at steady state. However, these parameters are not always equal since the loading rate of some cells varied over time. If the loading rate is decreased before effective storage is reached, the peak discharge out of the system may be larger than the volume discharged at effective storage. As noted, peak leachate discharge is a volume and expressed in litres.

Time to peak is the time between practical field capacity and the maximum discrete discharge, and is a measure of the response time of the system. This parameter is used in addition to time to effective storage because the peak volume discharged by the low intensity cells was not equal to the volume discharged at steady state. Again, this is due to the variable loading rate of the low infiltration intensity cells (because the loading rate decreased in low infiltration intensity cells before effective storage was reached, the discrete leachate volume discharged by these cells before steady state was greater than the volume discharged when steady state was reached). Time to peak also gives information about the shape of the leachate discharge curve. Knowing the duration of the event and the time to peak, the general shape of the curve can be determined (again, this parameter describes the response of the system). Like time to reach effective storage, time to peak is expressed in days.

Total leachate discharged is the total amount of leachate which percolates through the waste. This parameter is measured by summing up the daily percolation from the time of first discharge until discrete leachate volumes are less than 50 ml (this is 2% of the lowest daily volume of moisture applied to the experimental cells). The total leachate discharge gives an indication of the storage volume of the waste, and is also one of the parameters most used by solid waste professionals in the design and management of landfills (Zeiss and Major, 1993). This parameter is expressed in litres.

Lastly, duration of the leachate event is also used to characterize leachate discharge. This parameter is measured as the time from first discharge to the time that daily percolation reaches 50 ml (or the time for total leachate discharge). Duration of the event indicates the responsiveness of the system to both wetting and drying cycles since it covers periods of moisture loading as well as the period when loading ceases. This parameter is an increment of time and is expressed in days.

These six parameters, then, are used to characterize leachate discharge and facilitate the comparison of model results. Along with this modeling comparison other experimental results are analyzed according to the objectives presented in Chapter 1. The experimental results are used to test hypotheses developed from the objectives. These hypotheses are discussed in the following section.

2.4 SUMMARY AND HYPOTHESES

Moisture flow through municipal solid waste (MSW) has been previously investigated by a number of researchers. While most have assumed moisture flow to move uniformly through waste, a number have also noted channeling of flow through the waste. This channeling is defined as the flow of moisture through large channels separating waste particles. The effects of channeling have been studied in detail only on a small scale (e.g., the cell diameter was only 6 times the average particle diameter). However, channeling may be significant over entire landfills if it is proven to be an important flow mechanism in larger scale systems.

Leachate percolation through MSW can be indirectly estimated using a water balance. However, this method of predicting moisture movement is limited because it does not consider the actual mechanisms of flow. Modeling moisture movement by assuming one-dimensional Darcian flow through the waste matrix, as HELP does, is one way of explicitly including the mechanisms of moisture movement. However, because the effects of channeling are neglected this model may not predict moisture movement as well as models which include the effects of channeling, with respect to the six parameters discussed in the previous section used to characterize moisture movement. Fractured media flow models include the effects of channeling, however, they represent the media as being impermeable, so matrix flow is not considered. Parameters such as breakthrough time should be well predicted by these models because water is quickly conveyed through the channels, however, total leachate volume may be overestimated because no matrix storage occurs. Lastly, moisture movement may also be represented by fractured - porous media models. These models, specifically two-domain models, consider both matrix and channeled flow. However, the exchange between channels and matrix is difficult to simulate and may limit the use of this type of model. As with fractured media models, fractured - porous models have not yet been used to predict moisture movement through MSW.

Modeling may be further complicated by the heterogeneous nature of the media. The composition of municipal solid waste is extremely variable. This variability leads to a wide range in the values of physical and hydrologic properties found in the literature. These waste characteristics, along with others defined by researchers to better represent channeled flow, are influenced by environmental and operational conditions expected at MSW landfills. The two conditions which have the greatest effect on waste characteristics are infiltration intensity and compaction.

Models are evaluated to determine their ability to predict moisture movement through MSW, which is influenced by various environmental and operating conditions, as well as channeling. These models represent water balance, porous media, fractured media, and fractured - porous media methods of determining moisture movement. The results of the model chosen to predict experimental results are compared with the HELP model. The models are compared in terms of their ability to predict experimental leachate discharge. Since leachate discharge is continuous it is characterized by discrete parameters which are used to facilitate model comparison.

The literature review enables six hypotheses to be developed regarding channeling, factors affecting moisture movement, and modeling of flow through municipal solid waste. The experimentation used in this study will be directed by these hypotheses. The six hypotheses are:

Hypothesis 1:

Channeling of moisture through MSW occurs in pilot scale experimental cells.

Null Hypothesis 1: Channeling of moisture through MSW does not occur in pilot scale experimental cells

Hypothesis 2:

Increased infiltration intensity decreases the 1) practical field capacity, 2) effective storage, 3) breakthrough time, and 4) time to reach effective storage. Also, increased infiltration intensity increases 5) initial unsaturated hydraulic conductivity, and 6) ultimate unsaturated hydraulic conductivity.

Null Hypothesis 2: Increased infiltration intensity does not decrease practical field capacity, effective storage, breakthrough time and time to reach effective storage. Also, increased infiltration intensity does not increase initial or ultimate unsaturated hydraulic conductivity

Hypothesis 3:

Increased compaction increases the 1) practical field capacity, 2) effective storage, 3) breakthrough time, and 4) time to reach effective storage. Also, increased compaction decreases 5) initial unsaturated hydraulic conductivity, and 6) ultimate unsaturated hydraulic conductivity.

Null Hypothesis 3: Increased compaction does not increase practical field capacity, effective storage, breakthrough time and time to reach effective storage. Also, increased compaction does not decrease initial or ultimate unsaturated hydraulic conductivity

Hypothesis 4:

Increased density increases the 1) practical field capacity, 2) effective storage, 3) breakthrough time, and 4) time to reach effective storage. Also, increased density decreases 5) initial unsaturated hydraulic conductivity, and 6) ultimate unsaturated hydraulic conductivity.

Null Hypothesis 4: Increased density does not increase practical field capacity, effective storage, breakthrough time and time to reach effective storage. Also, increased density does not decrease initial or ultimate unsaturated hydraulic conductivity

Hypothesis 5:

Implicitly accounting for channeling when modeling moisture movement through MSW as one-domain homogeneous Darcian flow allows for better prediction of moisture movement than if channeling is not considered. Moisture movement, represented by leachate discharge, is characterized by breakthrough time, time to effective storage, peak volume, time to peak, total leachate discharged, and duration of the leachate event. The HELP model is used for these simulations.

Null Hypothesis 5: Implicitly accounting for channeling as one-domain homogeneous Darcian flow does not enable better prediction of breakthrough time, time to effective storage, peak volume, time to peak, total leachate discharged, and duration of the leachate event, than ignoring channeling.

Hypothesis 6:

Accounting for channeling as a two-domain process allows for better prediction of moisture movement than by implicitly considering it by adjusting flow parameters in the one-domain, homogeneous, Darcian flow model. Moisture movement is characterized by breakthrough time, time to effective storage, peak volume, time to peak, total leachate discharged, and duration of the leachate event. Both the HELP model and a two-domain model chosen in evaluation are used for comparison.

Null Hypothesis 6: Accounting for channeling as a two-domain process does not allow better prediction of breakthrough time, time to effective storage, peak volume, time to peak, total leachate discharged, and duration of the leachate event, than considering it by adjusting flow parameters in the one-dimensional, homogeneous, Darcian flow model.

3 METHOD

The experimental and statistical methods used to generate and evaluate data to test the six hypotheses are described in this chapter. The experimental design, setup and analysis of the moisture movement experiment are explained, as is the evaluation of the models chosen in the literature, and the choice of the two-domain model (PREFLO). The setup and use of the models (HELP and PREFLO) to predict moisture movement is discussed, as is the method used to compare model results. Finally the setup of supplementary experiments used to generate calibration data for the models is described.

3.1 MOISTURE MOVEMENT EXPERIMENT

The moisture movement experiment is performed to satisfy the research objectives (Chapter 1). The data generated by this experiment serves a threefold purpose. First, the data is analyzed to determine if channeling occurs in pilot-scale cells (hypothesis 1). Second, statistical analysis is performed to determine the effects of infiltration intensity, compaction and density on moisture movement through MSW (hypotheses 2, 3, and 4). Third, the data from the experiment is used to determine the ability of the HELP and PREFLO models to predict moisture movement (hypotheses 5 and 6). The experimental design is presented in the following section.

3.1.1 Experimental Design

Two 2^2 factorial designs are used in this study. The factors used are infiltration intensity, waste compaction and waste bulk density. Since density is varied through compaction these factors can be examined separately in the same cell. Therefore, this design allows the effects of three factors on moisture movement to be studied. The interaction between the factors may be investigated as well. Each factor is initially set at two levels, high and low. The high level of infiltration intensity is set to 30 mm/hr., while the low level is set to 7 mm/hr. These values are chosen because they correspond to precipitation intensities experienced in the Edmonton area (30 mm/hr. corresponds to the 10 - 15 yr. 1 hr. storm event, while 7 mm/hr. is less than the two year 1 hr. storm event; Hogg and Carr, 1985). Experimental cells compacted with a hydraulic ram are set to the high level of compaction, while cells which are not compacted with the ram are set to the low level of compaction. The amount of compaction directly affects the density of the MSW. The wet bulk density (total mass of waste before water addition divided by the total volume) of uncompacted cells averaged approximately 300 kg/m^3. This value was set as the low level for density, and corresponds with the low range of densities expected at landfills where minimal compaction is experienced (Oweis and Khera, 1990). The high level of density is set to 600 kg/m^3. This value corresponds with good landfill compaction (Tchobanoglous et. al., 1993), and is often achieved at large, modern landfills (Zyrmiak, 1994). Unfortunately, the density of the high compaction experimental cells averaged approximately 500 kg/m^3. This necessitated the use of a botched factorial analysis to determine the effects of these parameters on moisture movement (Box et. al., 1978). Table 3.1 summarizes the experimental settings of the eight cells used in the factorial experiments.

Table 3.1 Settings of Experimental Cells

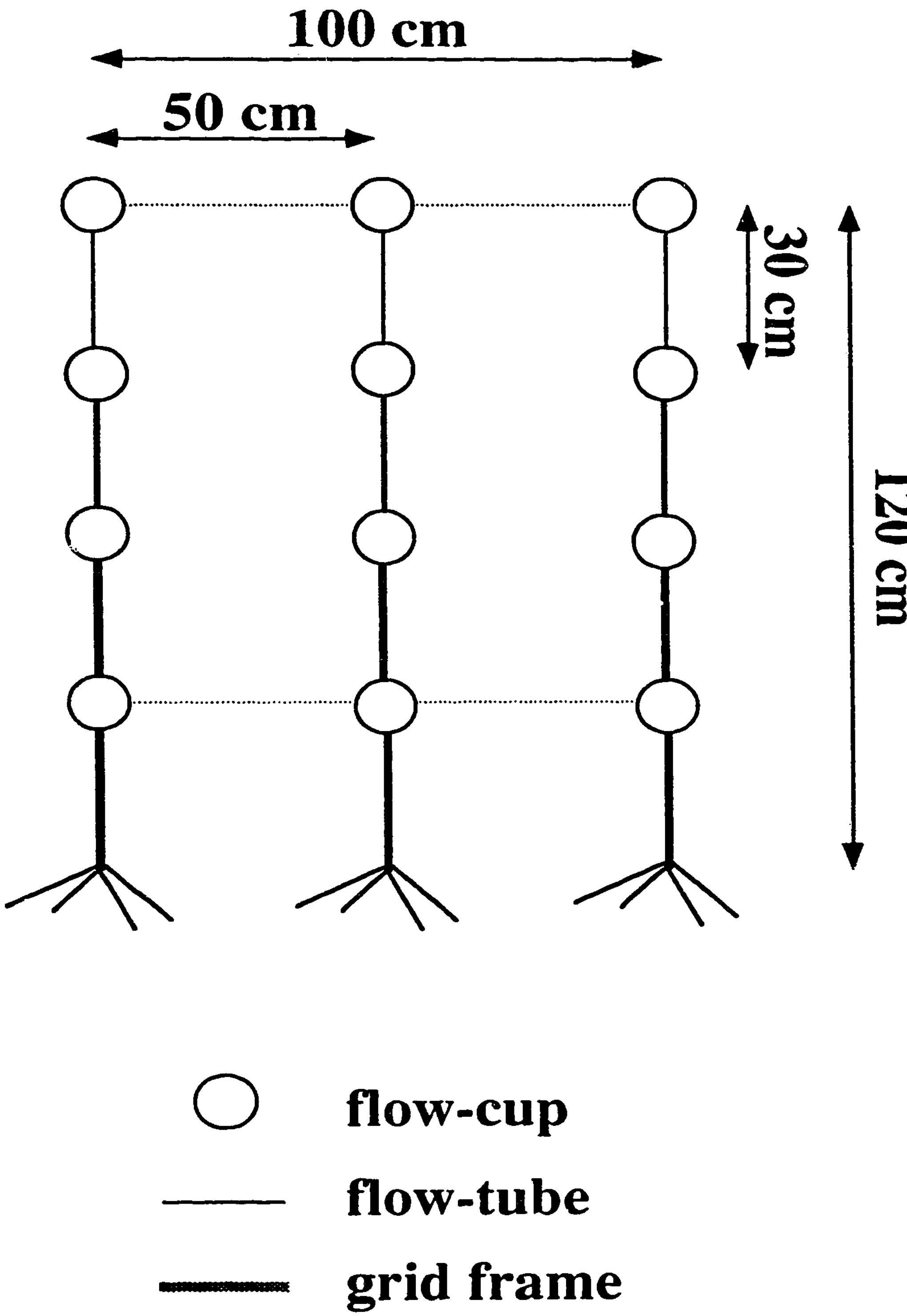
Cell #	Infiltration Intensity	Compaction / Density
1	Low	Low
3	Low	Low
2	Low	High
4	Low	High
5	High	Low
7	High	Low
6	High	High
8	High	High

The pilot scale rectangular steel cells averaged 1.8 m long by 1.6 m wide by 1.5 m high (see Figure 3.1). They have an equivalent diameter greater than 10 times the average Rosin-Rammler particle size listed in Table 2.3 (the actual ratio is 12:1), therefore wall effects are minimized (Wall, 1993). Drainage holes were drilled in the cells to allow drainage of leachate and the placement of the instrumentation. The complete set-up of each cell is described in section 3.1.2. The instrumentation used to collect the data for the analysis is described below.

Channeling is investigated using data from tensiometers and flow-cup grids. Tensiometers ("Jet Fill" series 2725, SoilMoisture Equipment Corp.) measure the suction head in the waste, as well as indirectly measuring moisture content. If a tensiometer reads zero suction head, the medium surrounding the instrument is saturated. The flow-cup grid (Figure 3.2) measures the flow of leachate from specific portions of the cross-sectional area of the waste cell. It also provides an indirect measure of the change in moisture movement patterns over time. The flow-cup grid consists of twelve 10 cm diameter metal cans. A 1.5 m long, 0.65 cm diameter tube is connected to the side of each can, flush with the bottom. The complete can and tube assembly is referred to as a flow-cup. Leachate draining into a cup is conveyed out of the cell through the tube. The volume collected from each cup, along with the capillary pressure readings from the tensiometers are used to determine the presence of channeling (statistical analysis methods are presented in section 3.1.3). Flow-cup data along with the total volume of leachate collected in the experiment are used to determine the effects of infiltration intensity, compaction and density on moisture movement variables and this data is also used to compare the predictive abilities of the HELP and PREFLO models. The experimental setup from which this data was gathered is presented in the next section.

Figure 3.1: Experimental Cell

Figure 3.2: Flow-cup Grid



3.1.2 Experimental Setup

Each cell was loaded from bottom to top with 1) a PVC liner, 2) a flow cup grid, 3) municipal solid waste, 4) nine tensiometer sheaths, 6) one irrigation hose, and 7) a PVC cover. The purpose of the liner was to prevent leakage of leachate out of the cell except through the drain holes and flow-cup grid tubes.

The first instrument placed in the cell was the flow-cup grid. One grid was placed at the bottom of each cell. The tubes were threaded through the holes drilled in the cell wall. No crimping of the tubes was observed. The grid was centered so that each side was approximately 30 cm from the adjacent cell wall. All tubes sloped downward from the cans to the holes in the cell wall, so drainage was not retarded. To further ensure free drainage, fine wire screen was used to line the inside of each can, and placed over the top of each can. The screen prevented any fine particles from migrating into the can and prevented large particles from plugging the can. Drainage from each cup was collected in a two litre PET container.

With the flow-cup grid in place municipal solid waste was added. The MSW used for the main experiment was collected in two standard compactor trucks from a residential area in West Edmonton during the second week of October, 1994. The waste was tipped onto the truck garage floor at Waste Management Inc.'s West Edmonton Landfill and Recycle Facility, where the experiment was conducted. Each cell was then filled using a small front end loader. Approximately 5 kg of the waste was set aside for the determination of moisture content and particle size.

The heterogeneous nature of the waste leads to many surface irregularities. The surface of each cell was smoothed using a ten kg tamper. Tensiometer sheaths were then put in place. Only three tensiometers per cell were used. In order to collect more representative suction head data, it was necessary to move the tensiometers to different locations in the cell during the experiment. The nine tensiometer sheaths placed in each cell facilitated this movement and protected the tensiometers from damage. The sheaths were constructed from 25 mm diameter, hollow, PVC tubing, cut into three different lengths of 30, 60 and 100 cm. Clusters of three sheaths of different heights were driven into the waste at three different locations in the cell. The middle cluster was located at the center of the cell, while the end clusters were approximately 40 cm from the cell walls. The distance between sheaths in each cluster was limited to a maximum of 10 cm. The placement of the sheaths in this manner allowed for a suction head profile of the waste to be determined at three separate locations in the cell. To prevent channeling of water down the side of the sheaths, plastic bags were placed around the sheaths.

Three tensiometers were placed in each cell, in the cluster furthest from the drain holes. Tensiometer readings were taken before water addition as the tensiometers were moved from cluster to cluster. Sheaths not containing tensiometers were covered with Styrofoam cups to prevent water from entering the open sheath.

Water was supplied to the cells through a network of hoses attached to a municipal water supply. A main hose, connected to the supply, was attached to a series of adjustable y-valves which allowed the water to be distributed to the eight cells. The valves allowed the moisture loading intensity for each cell to be adjusted (four cells were set to the high moisture loading rate, and four were set to the low level). Water was distributed over the surface area of the waste by conveying it through an irrigation hose laid on the surface of each cell. The spray from the hose uniformly wetted the surface of the cell. To further ensure uniform wetting, the irrigation hose was re-laid weekly. Water was added daily for 30 minutes. The 30 minute addition period is fairly representative of storms in this area (Hogg and Carr, 1985).

To prevent evaporation, a sheet of polyethylene was placed over each cell after loading was complete. This covered the entire surface of the cell and was draped over the tensiometers. The sheet was only removed when tensiometer readings were taken, which amounted to less than five minutes a day for each cell. After the experimental setup was completed, the cells were tipped to ensure adequate drainage. Wooden blocks supported the cells on a five percent slope. The first addition of water occurred ten days after the setup was completed. This allowed for all instrumentation to equilibrate and the waste in the cells to settle.

Before daily water addition, tensiometer data, flow-cup grid data and total leachate discharge volume was recorded. The flow-cup grid data and leachate volume were recorded both before and after water addition. This was necessary because leachate discharged continued between the periods of water addition. The main experiment ran from October 24, 1994 until January 15, 1995, a period of 104 days. The data gathered during that time is statistically analyzed using the methods discussed in the following section.

3.1.3 Statistical Methods

The instrumentation used for the main experiment provides both a direct and indirect measure of channeling in the cells (section 3.1.1). The statistical methods used to analyze tensiometer data are discussed below.

Tensiometers provide an indirect measure of channeling because they record suction head and not a volume of water flowing through channels. However, the data can be used to test the channeling hypothesis by testing if moisture flows through the waste as a uniform, horizontal moisture front, as would be expected if homogeneous matrix flow occurs (section 2.1). However, the actual flow mechanism (e.g., Darcian or channel flow) cannot be tested with this data because it is an indirect method of measuring channeling. To test if the moisture front is uniform the readings of tensiometers at the same level in the waste are compared. If one or two of the three tensiometers at the same level read zero and the remaining do not the null hypothesis can be rejected. This is valid for any time after the start of water addition.

The one sided t-distribution is used to compare the number of times all tensiometers on one level read zero with the number of times they are non-zero for the entire period of water addition. The null hypothesis, that the moisture front is uniform, is rejected if the number of times all tensiometers are saturated is not significant compared to the number of times all are not saturated. This is evaluated at the 95% confidence interval. The random variable in this analysis is the proportion of number of days all tensiometers at the same level are not saturated to the number of days all are saturated. The t-test may be used with the following assumptions: 1) the random variable is normally distributed, 2)random variables are independent, and 3) the variance of the populations are equal.

Though there may be some correlation in the random variable (i.e. all tensiometers are likely to be saturated if all were saturated on the previous day, assuming uniform moisture movement), independence is assumed to simplify calculations. The normality of the random variable may be verified using histograms and normal probability plots, however, because the t-distribution is fairly robust the results are insensitive to the assumption (Box et. al., 1978).

Flow-cup grid data is also used to test the channeling hypothesis. The hypothesis can be divided into two sub-hypotheses which test if moisture moves uniformly through the waste, and test the actual flow mechanism. These sub-hypotheses are:

A) Moisture does not flow as a uniform, horizontal, moisture front

B) Darcian flow is not the only flow mechanism occurring in the cells

The statistical methods used to analyze the flow-cup grid data are described below.

Sub-hypothesis A is tested using the discrete volume of leachate discharged from each flow cup as the random variable. If the discrete discharge from the flow cups do not equal one another at any time after water addition the null hypothesis (moisture flows through waste as a uniform front) can be rejected.

A one-way analysis of variance test (ANOVA) is used to test the hypothesis. The null hypothesis is rejected if the spatial variation in leachate discharge from the flow cups is greater than the temporal variation. This is evaluated at the 95% confidence interval. Since the discrete leachate discharge from any flow cup is independent of the other cups in the cell, independence of the random variable can be assumed. This assumption is valid since ANOVA is fairly robust and relatively insensitive to violations of the assumption of normality and equal variance (Miller and Freund, 1985). Also, the assumptions of ANOVA can be approximately justified if the experiment is randomized (Box et. al., 1978), as is the case for the moisture movement and supplementary experiments conducted. Therefore, one-way ANOVA is used to test this hypothesis.

Sub-hypothesis B is tested using the mean discrete volume of leachate discharged by each cup in the grid over time. If the mean of the discharge does not increase over time the null hypothesis can be rejected. As mentioned in section 2.1.2, in the Darcian flow representation of moisture movement the flow rate through the waste increases as the moisture content of a porous matrix increases and capillary pressure is reduced (this is described mathematically by equation 3). Therefore, the flow rate out of the cells should increase with time as more water is added.

This sub-hypothesis is tested using a difference of means test. If the means of the discharge of each flow cup do not increase significantly over time at the 95% confidence level the null hypothesis can be rejected. Differences of mean volumes of less than 1 ml between consecutive time periods are considered insignificant. This value is chosen because it is the smallest reading of leachate volume to occur, and the small value biases the analysis against rejecting the null hypothesis. The random variable must be normally distributed to use the difference of means test (Beyer, 1968). Though the distribution of discrete leachate discharge is not normal, the means of the discrete readings, taken over a four day time period, can be assumed to be normally distributed due to the Central Limit Theorem. Because the leachate volumes may be influenced by the loading rate, this test is only tested on cells with a constant loading rate. This includes all the high infiltration intensity cells (cells 5 through 8). Also, flow-cups which read zero for the entire duration of water addition are not included in the analysis.

The results of the flow-cup grid data analysis and the tensiometer data analysis are used together to confirm the presence of channeling in the experimental cells, and thus both are used to confirm the main channeling hypothesis. The statistical tests, limitations and assumptions used to test hypotheses 2, 3, and 4, are discussed below.

As mentioned, the first factorial analysis tests the effects and interactions of infiltration intensity and compaction, while the second examines intensity and waste density. The loading rates and density changed with time and deviated from the high and low level settings and a botched factorial analysis was used (Box et. al., 1978). Table 3.2 shows the settings of both factorial analyses.

Table 3.2: Settings of Main Factors for Factorial Analyses

INFILTRATION INTENSITY AND COMPACTION		
Setting	Setting Value (coded parameter)	
	INFILTRATION INTENSITY	COMPACTION
HIGH	30 mm/hr. (1)	Compacted (1)
LOW	7 mm/hr. (-1)	Uncompacted (-1)
Low Intensity, Low Compaction Cells	10.8 mm/hr. (-0.67)	Uncompacted (-1)
Low Intensity, High Compaction Cells	11.1 mm/hr. (-0.64)	Compacted (1)
High Intensity, Low Compaction Cells	18.9 mm/hr. (0.03)	Uncompacted (-1)
High Intensity, High Compaction Cells	22.4 mm/hr. (0.39)	Compacted (1)

INFILTRATION INTENSITY AND DENSITY		
Setting	Setting Value (coded parameter)	
	INFILTRATION INTENSITY	DENSITY
HIGH	30 mm/hr. (1)	600 kg/m^3 (1)
LOW	7 mm/hr. (-1)	300 kg/m^3 (-1)
Low Intensity, Low Compaction Cells	10.8 mm/hr. (-0.67)	405 kg/m^3 (-0.30)
Low Intensity, High Compaction Cells	11.1 mm/hr. (-0.64)	478 kg/m^3 (0.18)
High Intensity, Low Compaction Cells	18.9 mm/hr. (0.03)	403 kg/m^3 (-0.32)
High Intensity, High Compaction Cells	22.4 mm/hr. (0.39)	478 kg/m^3 (0.18)

The settings shown in the table take into account the variable moisture loading rate and the change in density over the duration of the experiment. The only parameter which does not vary is compaction. As mentioned, a cell is considered compacted if it was packed with a hydraulic ram before the start of the experiment. No further compaction was applied when the experiment started, therefore, compaction does not vary over the duration of the experiment.

The use of a factorial design allows the effects and interactions of the factors on moisture movement to be quantified. The analysis is facilitated by characterizing moisture movement by discrete measurable quantities which include: 1) practical field capacity moisture content, 2) effective storage moisture content, 3) water added to reach practical field capacity, 4) water added to reach effective storage, 5) breakthrough time, 6) time to reach steady state, 7) initial unsaturated hydraulic conductivity, and 8) ultimate unsaturated hydraulic conductivity were examined. Water added to reach practical field capacity and water added to reach effective storage are included as supplementary variables which link the moisture contents with times but are not actual moisture movement variables (e.g., water added to reach practical field capacity is the amount of water added from the start of moisture loading to breakthrough time, increasing the initial moisture content of the waste to practical field capacity). All of the variables were chosen because they have been developed to illustrate the difference between matrix and a combination of matrix-channeled flow in previous studies (section 2.2.2). Therefore, it is possible to compare the values found in this experiment with other moisture movement studies.

3.2 MOISTURE MOVEMENT MODELING

The modeling component of the study involves the evaluation of existing models to predict moisture movement, as well as comparing the results generated by the highest ranking model to actual experimental results. Finally these model results are compared to the HELP model to determine which approach more accurately predicts measured moisture movement. The following section presents the method used for model evaluation.

3.2.1 Evaluation of Models

The models listed in section 2.3 were evaluated using a check list of important parameters developed from the literature review (Table 3.3). Their ability to model moisture movement through MSW depended on how they accounted for the parameters shown in Table 3.3. The parameters are subdivided into waste and flow characteristics, environmental conditions, operational conditions, and model output. Each parameter is equally rated, independent of category, because each is needed to either realistically represent the physical system (e.g., initial moisture content) or provide relevant information to a solid waste professional (e.g., head on liner). Therefore, the more checklist parameters accounted for by a model the higher the model ranked. Several different scoring methods were applied to the models. Table 3.4 shows the scores of the top seven models (fractured - porous media, and porous media models), as well as, the top ranking fractured media, and water balance model evaluated according to the checklist. The final rankings of all models are shown in Table 3.5.

Table 3.3: Checklist Parameters

1. WASTE AND FLOW CHARACTERISTICS
    - 1.1 models both saturated and unsaturated conditions
    - 1.2 models both imbibition and drying conditions
    - 1.3 models heterogeneous media
    - 1.4 accounts for channeled flow
    - 1.5 accounts for matrix flow

2. ENVIRONMENTAL CONDITIONS
    - 2.1 models variable infiltration intensity
    - 2.2 accounts for antecedent moisture conditions
    - 2.3 accounts for temperature effects (e.g., evaporation)
    - 2.4 accounts for biological effects (e.g., biodegradation, transpiration)

3. OPERATIONAL CONDITIONS
    - 3.1 accounts for initial moisture content
    - 3.2 accounts for varying particle size
    - 3.3 accounts for porosity
    - 3.4 accounts for channel orientation, diameter and length
    - 3.5 models both free drainage and pressure flow

4. MODEL OUTPUT
    - 4.1 gives average and peak leachate volume
    - 4.2 gives average and peak leachate flow rate
    - 4.3 gives breakthrough time
    - 4.4 gives duration of event
    - 4.5 gives leachate quality
    - 4.6 gives head on liner
    - 4.7 gives moisture profile of the waste
    - 4.8 gives leachate migration from the landfill
    - 4.9 gives water balance on landfill
    - 4.10 applicable for use over the entire landfill

Table 3.4: Scores of the Top Models Evaluated

CRITERIA (Refer to Checklist, Table 3.2, For Criteria Listing)

MODEL	1. Waste and Flow Characteristics					2. Environmental Conditions				3. Operational Conditions					4. Model Output										TOTAL
	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	4.10	
Fractured-Porous Media Model PREFLO (Workman and Skaggs, 1990)	√	√		√	√	√	√	√	√	√		√	√	√	√		√	√		√	√		√	√	19
Fractured-Porous Media Model MACRO (Jarvis, 1994)	√	√		√	√	√	√	√	√	√		√	√	√	√		√	√	√		√		√	√	19
Fractured-Porous Media Model (Gerke and vanGenuchten, 1993)	√	√		√	√		√			√	√	√	√	√	√	√	√	√	√	√	√			√	18
Porous Media Model (Connell and Bell, 1993)	√	√			√	√	√	√		√	√			√	√	√	√	√		√	√		√	√	17
Fractured-Porous Media Model (Hoogmoed and Bouma, 1980)	√	√		√	√		√		√	√			√	√	√		√	√		√	√		√	√	16
Fractured-Porous Media Model (Beven and Germann, 1981)	√			√	√	√	√			√			√		√	√	√	√		√	√		√	√	15
Fractured-Porous Media Model LASOMS (Chen and Wagenet, 1992)	√			√	√		√			√	√	√	√		√	√	√	√		√	√			√	15
Fractured Media Model (Nordqvist et. al., 1992)			√	√				√					√	√	√		√		√					√	9
Water Balance Model (Gee, 1981)	√	√					√			√		√			√								√	√	8

Table 3.5: Overall Model Rankings

MODEL TYPE AND AUTHOR	OVERALL RANK
Fractured - Porous Media Model Workman and Skaggs, 1990 - PREFLO	1
Fractured - Porous Media Model Jarvis, 1994 - MACRO	1
Fractured - Porous Media Model Gerke and van Genuchten, 1993	2
Porous Media Model Connell and Bell, 1993	3
Fractured - Porous Media Model Hoogmoed and Bouma, 1980	4
Fractured - Porous Media Model Beven and Germann, 1981	5
Fractured - Porous Media Model Chen and Wagenet, 1992 - LASOMS	5
Fractured - Porous Media Model Miller and Mishra, 1988	6
Porous Media Model Straub and Lynch, 1982	7
Fractured - Porous Media Model Edwards et. al., 1979	8
Porous Media Model Korfiatis et. al., 1984 - LANDFIL	9
Fractured - Porous Media Model Germann and Beven, 1985	10
Fractured - Porous Media Model Peters and Klavetter, 1988	11
Fractured - Porous Media Model Davidson, 1985	12
Fractured Media Model Nordqvist et. al., 1992	13
Porous Media Model Noble and Arnold, 1991 - FULFIL	14
Water Balance Model Gee, 1981 a	15
Fractured Media Model Evans and Huang, 1983	16

The PREFLO model by Workman and Skaggs and the MACRO model by Jarvis ranked highest overall (see Table 3.4 and 3.5). The PREFLO model was chosen for comparison to the HELP model instead of MACRO because 1) it explicitly considers the physical properties of the channels (e.g., diameter), 2) it does not model channeled flow as modified Darcian flow, and, 3) fewer estimates of empirical parameters need to be made for the use of this model (for example, no estimate of a macropore hydraulic conductivity is required). The PREFLO and HELP models are used to predict experimental results. The methods of comparison are described in the next section.

3.2.2 Comparison of Model Results

In order to determine how well both models predict moisture movement through MSW, the results are evaluated with respect to 6 discrete parameters which characterize continuous leachate discharge. These parameters, defined in the literature review, are breakthrough time, time to effective storage, peak leachate volume, time to peak, total leachate volume discharged, and duration of the leachate event. Model results are compared to each other and to measured results. These comparisons are used to test the modeling hypothesis. Hypothesis 5 is tested by comparing two sets of HELP model results to experimental results. The first set of results is generated by using HELP default input parameters. These values do not account for channeling. The second set of results is generated from input parameters developed to account for channeling. These parameters are obtained from the literature and experimental results (see section 3.3 on the experimental methods used to determine the input parameters). Hypothesis 6 is tested by comparing the results of both the HELP and PREFLO model to experimental results. The input parameters used for the PREFLO model are obtained from the literature and results of the moisture movement and supplementary experiments conducted because no default values exist for this model.

3.3 SUPPLEMENTARY EXPERIMENTS

In order to obtain data to calibrate the HELP and PREFLO models supplementary MSW experiments were conducted. These tests included initial moisture content determinations, Rosin-Rammler particle size analysis, moisture content - capillary pressure relationship, and channel size and flow pattern analysis.

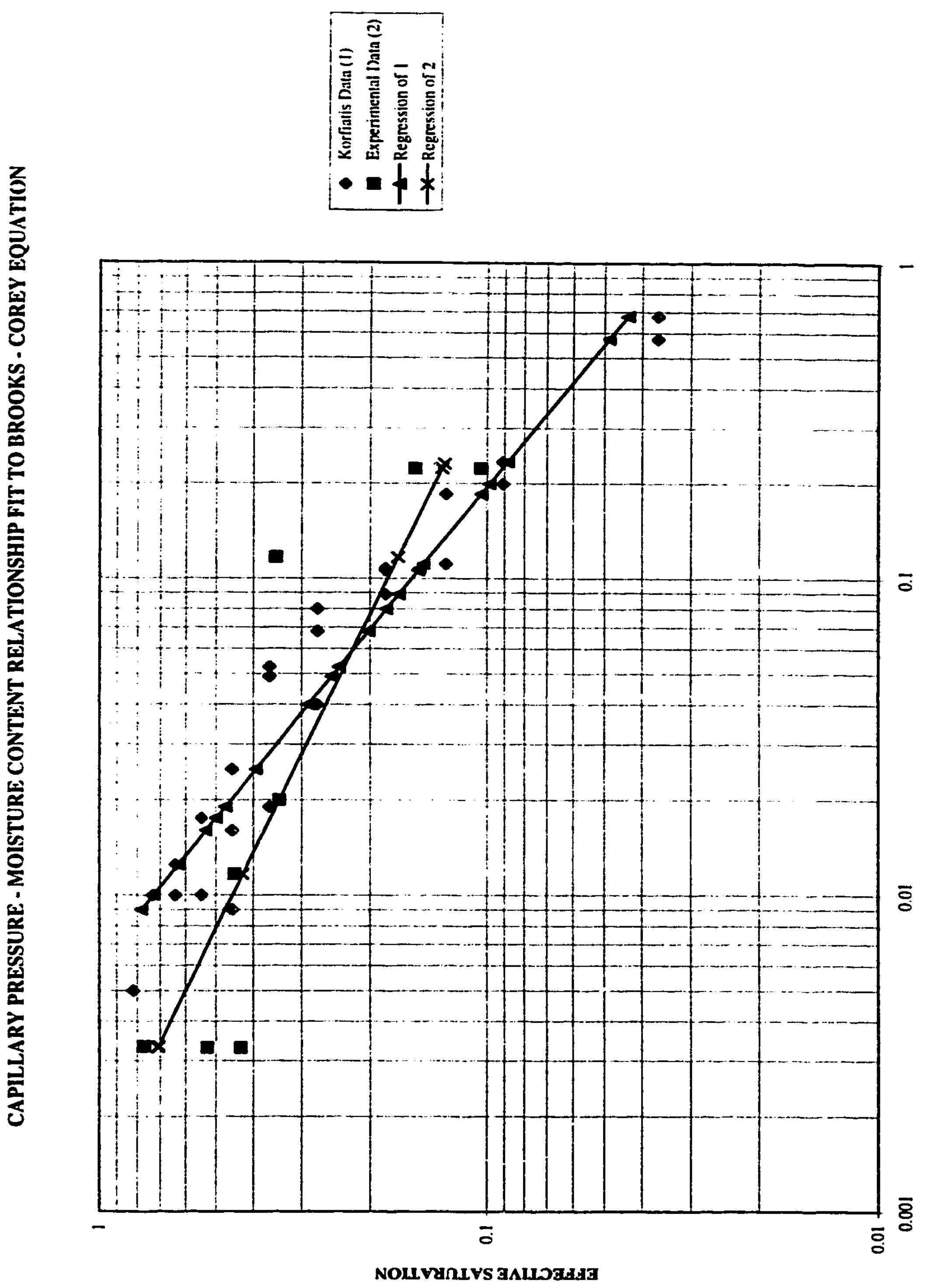
The initial moisture content data is used as input into both flow models. Initial moisture contents are determined with the same method used in previous studies (Carter, 1993; Zeiss and Major, 1993). Grab samples were taken from each cell used in the main experiment and weighed. They were then dried to constant weight at 103°C. The sample masses ranged between 1 and 3 kg. In order to get a representative moisture content the average from all grab samples was used as model input.

Rosin-Rammler particle size is used to verify that the waste used in the experiment is typical of waste used in other studies by comparing it to literature values. The analysis was conducted according to the method described by Hasselriis (1984). Like initial moisture content determinations, 1 - 3 kg grab samples from each cell used in the main experiment were analyzed.

The moisture content - capillary pressure relationship is used as input into the PREFLO model. This relationship was determined by following the method described by Carter, (1993) for determining the relationship in soil. However, the heterogeneity of the waste required a much larger scale setup. In order to obtain a representative sample of waste 90 to 120 kg must be used (Klee, 1993). Therefore, the experiment was conducted in sealed, 1.8 m high, 0.55 m diameter steel cylinders. Tensiometers were placed at three different levels in the waste to record capillary pressure. Water drained out of the cell through a drain spout at the bottom of the cell. With the initial moisture content recorded, water was added to the waste in the cell until saturation occurred. This saturation volume was recorded. The waste was then allowed to drain freely. The amount of water drained was recorded and subtracted from the saturation volume to determine the volumetric moisture content of the waste. Once free drainage had ceased, the tensiometers were read, and the average value recorded. The moisture content of the waste after free drainage has ceased is referred to as the field capacity. It corresponds to a capillary pressure of 0.33 bars. Negative pressure was then applied to the column with a peristaltic pump. Once drainage at the first pressure applied ceased, and the capillary pressure and moisture content were recorded, the suction was increased.

The range of negative pressures applied by the peristaltic pump was small; however, it was possible to supplement the data with data from moisture content determinations (both air dry and initial). This allowed for a curve to be completed. Although the data was unsuitable to use as model input because of the limited range of pressures used the curve created was compared to similar data from Korfiatis, 1984. The two data for the curves was fitted to the Brooks - Corey equation (see Figure 3.3). The large values of the r^2 parameters of the regression ($r^2 = 0.92$ for Korfiatis data, and $r^2 = 0.76$ for the experimental data), showed that Brooks - Corey could well represent the moisture content - capillary pressure relationship in MSW. Therefore, the Brooks - Corey equation, along with parameters found from previous moisture movement studies (e.g., Zeiss and Major, 1993) were used as input into the model.

Figure 3.3: Data From Moisture Content - Capillary Pressure Curve Supplementary Experiment Fitted to the Brooks-Corey Equation



Channel diameter and length are required as input into the PREFLO model. Therefore, these parameters were determined through supplementary experiments. Also, the pattern of moisture flow through these channels was also examined to show the actual patterns of channeling in pilot scale cells.

The first channeling experiment was performed in 1.8 m by 0.55 m diameter steel cells with cross-sectional areas of 0.26 m^2. Approximately 35 kg of waste was loaded into each of the two cells used for the experiment. The diameter and shape of the channels was found by filling up the channels with plaster of Paris, similar to the method given in Vermeul et. al., 1993. Plaster of Paris was poured over the top of the waste in the cell as well as introduced through a 25 mm hollow PVC tube which had been driven into the waste. The plaster of Paris was diluted sufficiently so that it had a consistency similar to water, and flowed through the waste much like water. The plaster was allowed to cure for one month. Waste was peeled off the plaster in layers, and casts of the channels were formed. The number, diameter and length of each channel cast was recorded and the average equivalent diameter, and percentage pore area vs. total area were calculated (results shown in Table 3.6). These parameters were used as input into PREFLO.

Table 3.6: Physical Properties of Channels Determined from Supplementary Experiment

Layer Number	Number of Pores in Layer	Average Pore Depth (cm) (St. Dev.)	Average Equivalent Pore Radius (cm) (St. Dev.)	Average Pore Area (cm^2) (St. Dev.)	Pore Filled Area
1	10	4.5 (6.8)	1.8 (1.5)	16.9 (28.3)	6.6%
2	13	3.3 (1.8)	1.8 (0.4)	10.7 (5.5)	4.7%
3	20	3.6 (1.4)	2.0 (0.7)	13.4 (10.1)	10.5%
4	22	3.5 (1.6)	1.7 (0.6)	10.3 (7.6)	8.9%
5	5	4.8 (1.3)	3.6 (1.4)	45.8 (32.2)	8.9%
AVERAGE	14 (7)	3.7 (2.9)	1.9 (1.0)	14.8 (17.2)	8.0%

Through the use of plaster of Paris typical channel shape, diameter and length are found. However, the experiment does not indicate how moisture moves through the waste, and, specifically what pattern and through what cross-sectional area flow occurs. This information is needed to estimate the number of channels which actively convey flow and are not simply "dead end" pores (Freeze and Cherry, 1979). Therefore, a tracer test was performed. White latex primer, with a consistency more similar to water than plaster of Paris, was used to trace the flow path. One pilot scale cell (cell 2, low infiltration intensity, high compaction) was used for this experiment. A one metre square was marked off in the middle of the cell. The waste in the square was removed in 10 to 20 cm lifts, ten minutes after primer addition. The areas of the cross-section marked by the tracer were recorded (Table 3.7), as well as their approximate location in the 1 m square. This data, which was supplemented by pictures of each layer (see Figure 3.4), is used to correct the percentage pore area listed in Table 3.6 to reflect only the area taken up by active pores. Therefore, the dead end pore area is neglected. The average pore area (8.0%) is multiplied by the average area marked by the tracer (26%) to estimate the average active pore area. This value (2.0%) is used as input into the PREFLO model.

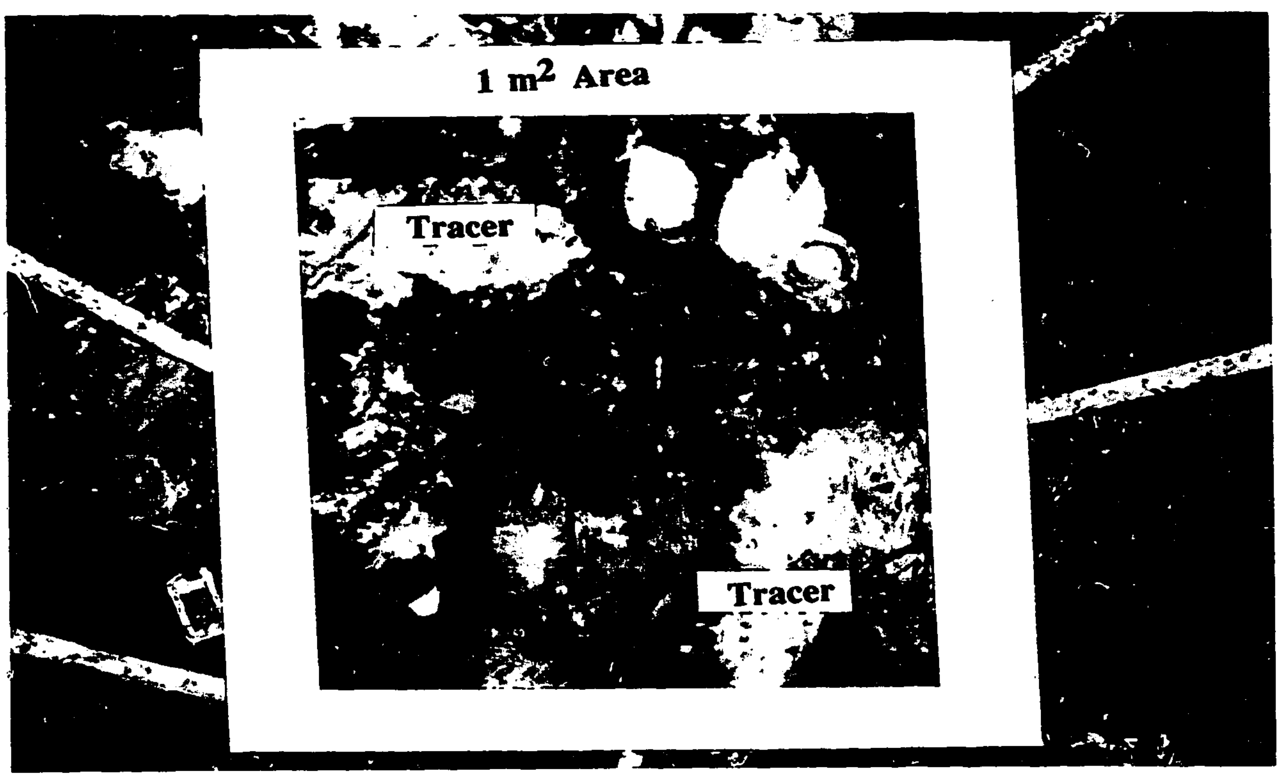
Table 3.7: Flow Area Estimated from Tracer Test

LAYER NUMBER	TRACER MARKED AREA NUMBER	AREA (m^2)	TOTAL TRACER MARKED AREA
1 (surface of cell)	1	1	100%
2	1	0.08	33%
	2	0.20	
	3	0.05	
3	1	0.2	38%
	2	0.06	
	3	0.12	
4	1	0.03	3%
5	1	0.08	15%
	2	0.07	
6	1	0.23	
	2	0.20	43%
AVERAGE (excluding top layer)		0.20	26%

Note: Top level is excluded in average because it does not reflect pore area through which tracer flows because tracer is applied evenly over this layer

The experimental methods for the supplementary experiments allow the experimentally derived input parameters for both models to be determined. The models are calibrated with these parameters, and the predictions generated are used to test the modeling hypotheses (hypotheses 5 and 6). In addition to these methods, the experimental methods used in the setup and design of the moisture movement experiment have been discussed, as well as the statistical methods used to analyze the data generated from this experiment. The results of the statistical analysis is used to test the hypotheses.

Figure 3.4: Sample Cross-Section for Supplementary Channel Flow Experiment



4 RESULTS AND ANALYSIS

In order to test each hypothesis all experimental and simulation results are analyzed according to the methods previously described. The results of all experiments and simulations, as well as analysis are presented in this chapter.

4.1 MOISTURE MOVEMENT EXPERIMENTAL RESULTS

Data and summary statistical results are presented in this section. First, the waste characteristics such as initial moisture content, particle size, and density are presented. The experimental results, including the moisture movement figures are also shown. Tensiometer and flow-cup grid data are presented and used to evaluate the channeling hypothesis. Lastly, the results from the main moisture movement experiment are used in a factorial analysis to evaluate each operational condition hypotheses (hypotheses 2, 3, and 4).

4.1.1 Experimental Cell Results

Initial moisture contents, Rosin-Rammler particle size, and initial and final heights and densities are presented in Table 4.1 for the eight experimental cells. The initial moisture contents and Rosin-Rammler parameters are similar to those found in the literature (Table 2.3). Table 4.1 shows large changes in density and height over time. It is interesting to note that a low compaction cell, cell 3, has the highest density at the end of the experiment. In fact, at the end of the experiment cells 3 and 5 had densities comparable to the high compaction cells. Figures 4.1 to 4.4 show the density increases and height decreases rapidly after the waste is initially placed in the cell. The change in density and height is greater in the low compaction cells. The density of the low compaction cells increases approximately 60% over the test, while the density of the high compaction cells increases by only 17%. This may indicate the effectiveness of the compaction applied to the high compaction cells, as there was little void space into which the waste could settle because the waste was packed more tightly.

Table 4.1: Experimental Cell Data

	Low Intensity Cells				High Intensity Cells				All Cells	
PARAMETER	Low Compaction Cells		High Compaction Cells		Low Compaction Cells		High Compaction Cells		Avg.	St. Dev.
	Cell 1	Cell 3	Cell 2	Cell 4	Cell 5	Cell 7	Cell 6	Cell 8		
Initial Moisture Content (v/v)	0.069	0.091	0.114	0.111	0.083	0.076	0.108	0.117	0.096	0.019
Rosin-Rammler Xo (cm)	7.0	4.5	7.0	9.0	8.0	7.0	9.0	7.0	7.3	1.4
Rosin-Rammler n (-)	1.28	1.30	1.31	1.31	1.27	1.29	1.31	1.30	1.30	0.02
Initial Height (m)	1.05	1.10	1.05	1.05	1.05	1.00	1.00	1.00	1.04	0.04
Final Height (m)	0.68	0.64	0.95	0.90	0.65	0.62	0.78	0.86	0.76	0.13
Initial Density (kg/m^3)	267	353	445	432	323	298	420	458	375	73
Final Density (kg/m^3)	413	607	492	504	522	484	539	532	512	55

Figure 4.1: Change in Waste Bulk Density Over Time for Low Compaction Cells

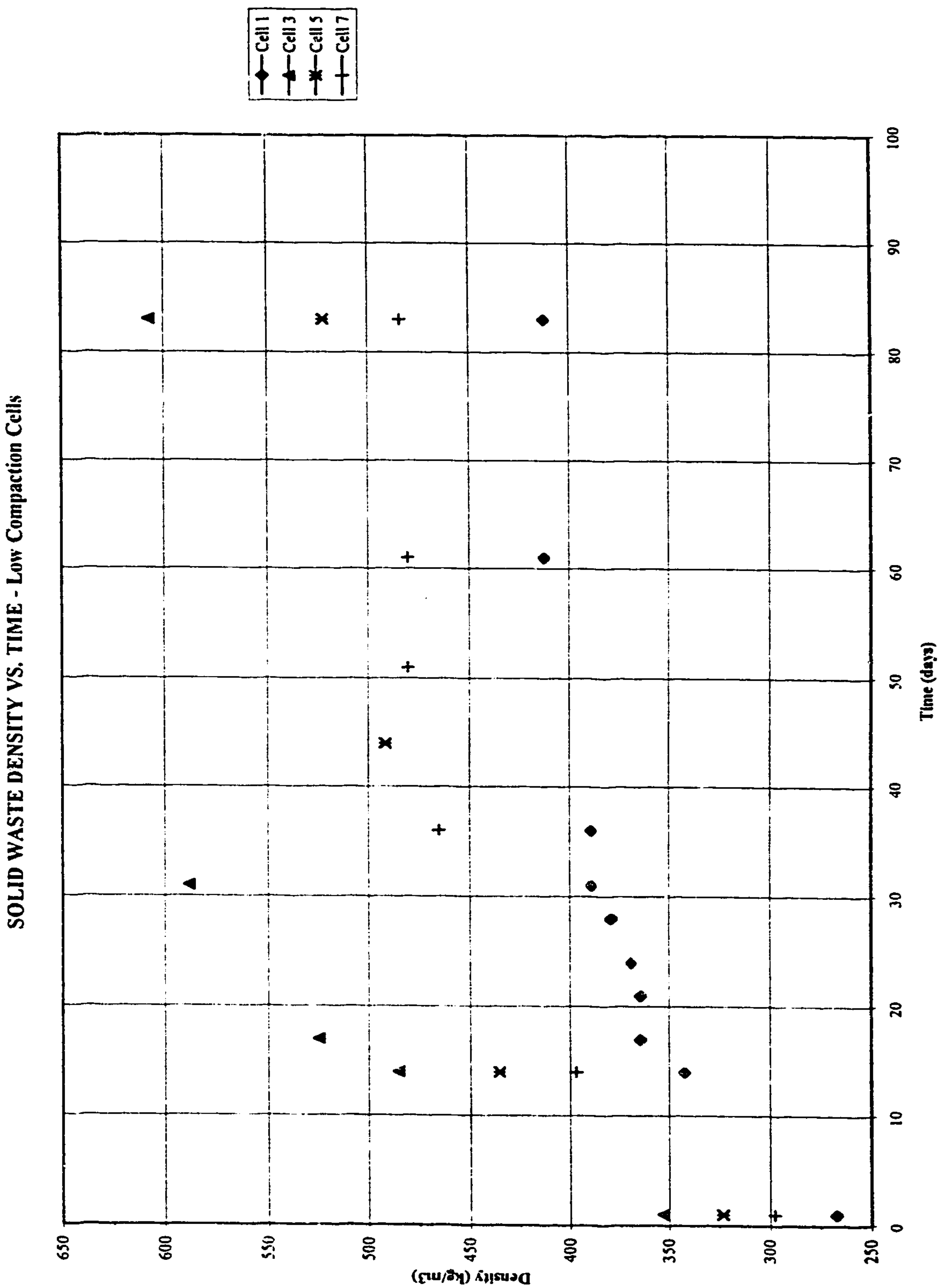


Figure 4.2: Change in Waste Bulk Density Over Time for High Compaction Cells

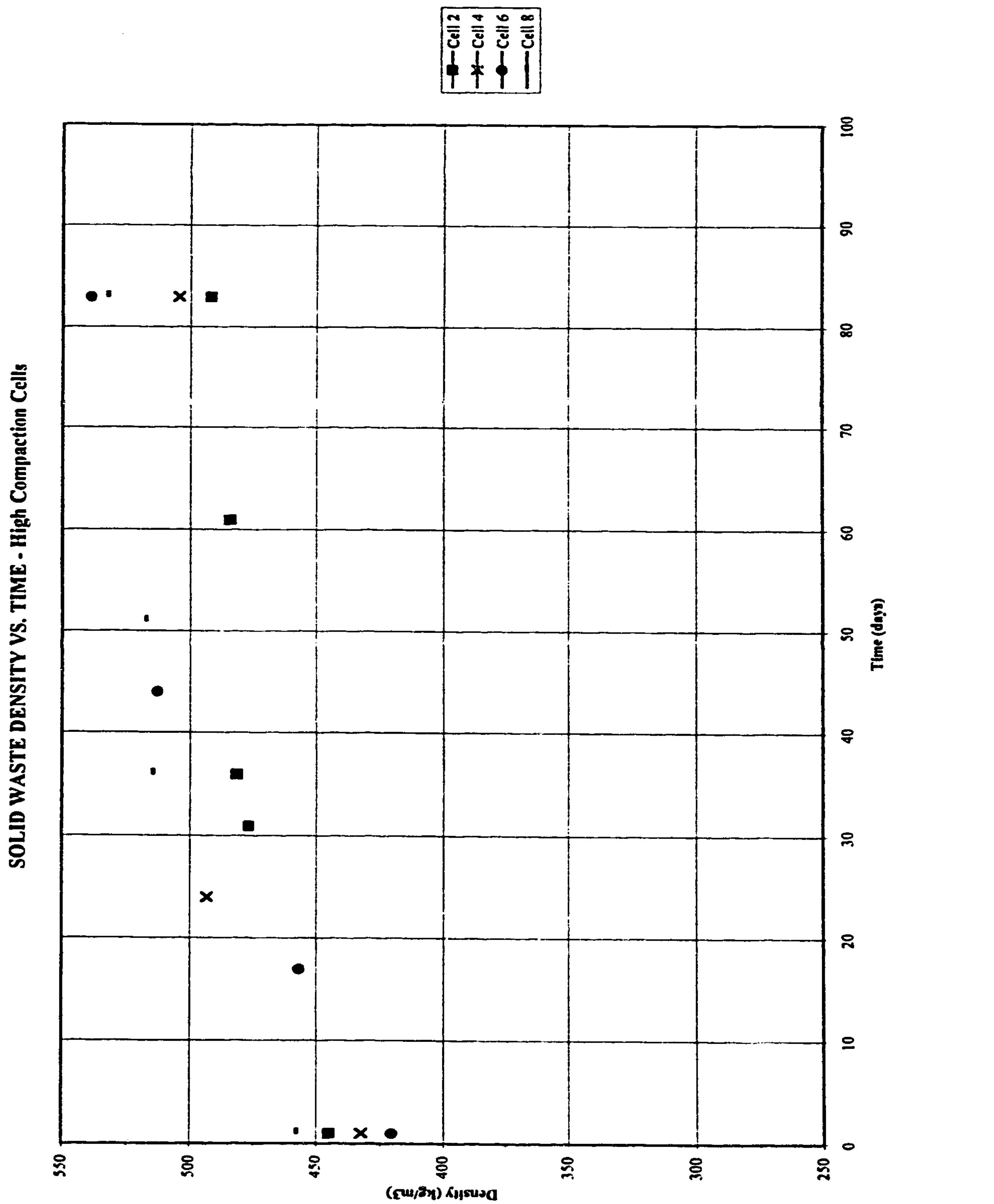


Figure 4.3: Change in Waste Height Over Time for Low Compaction Cells

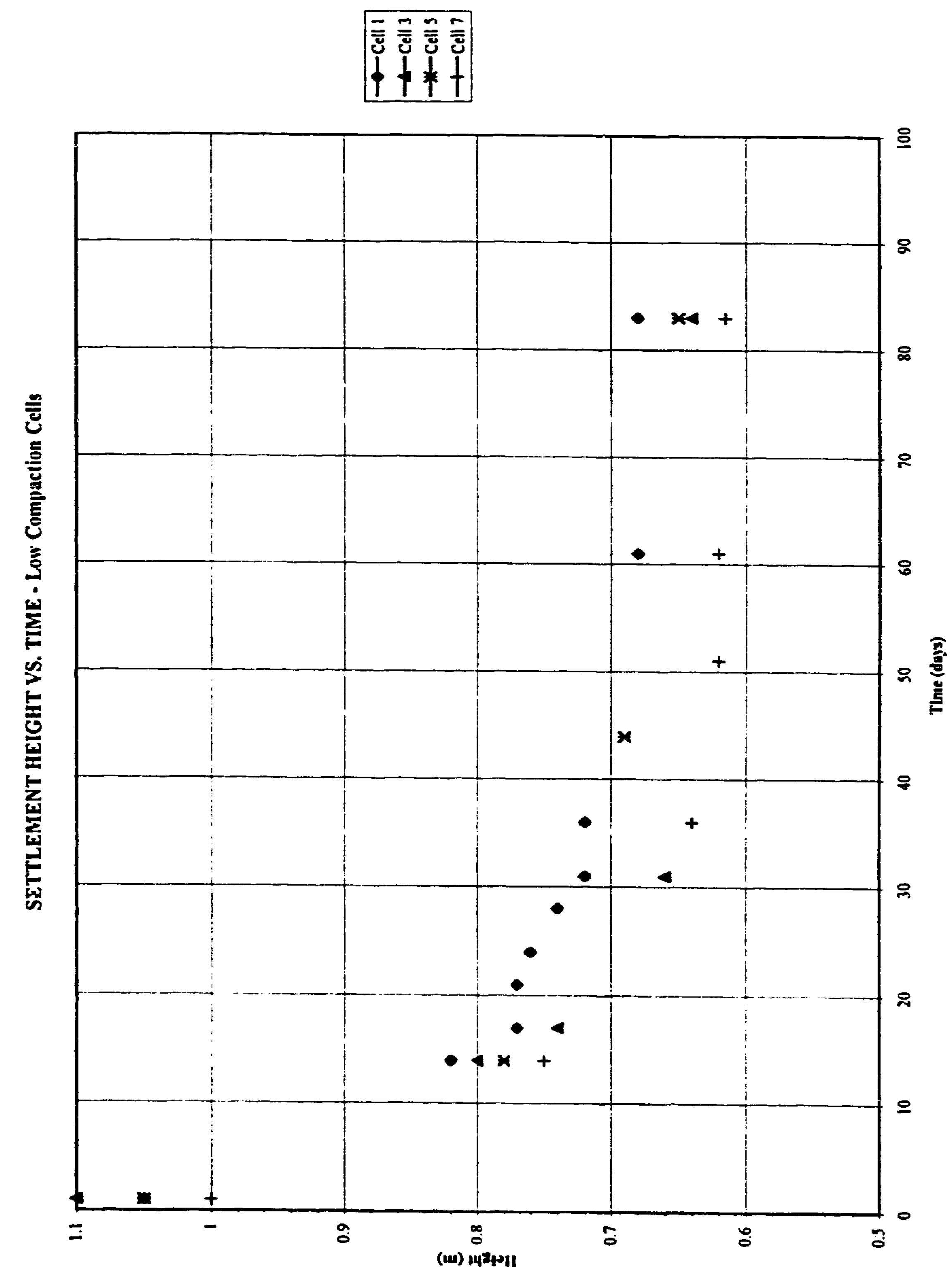
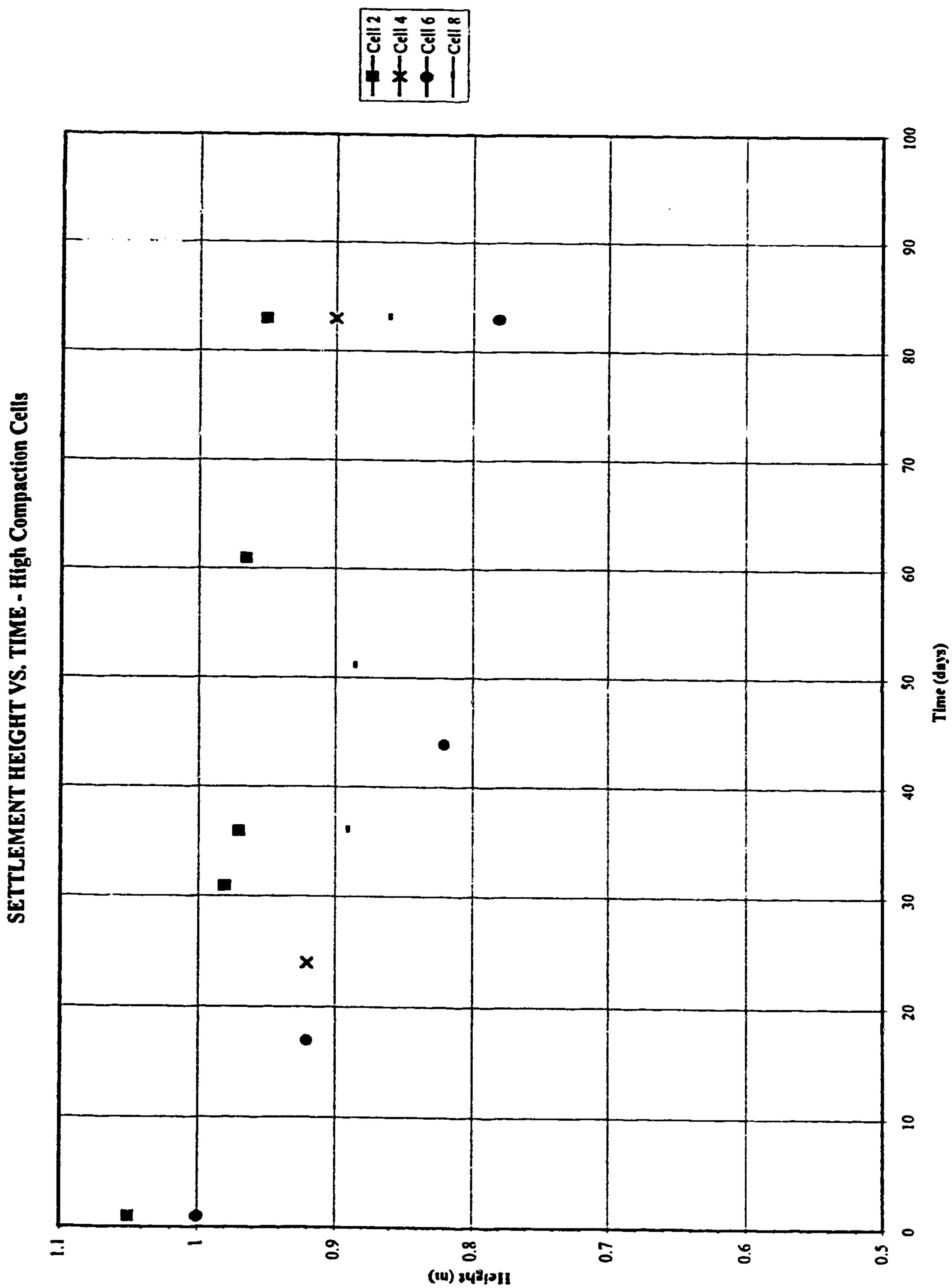


Figure 4.4: Change in Waste Height Over Time for High Compaction Cells



Discrete infiltration, storage and discharge curves for the main moisture movement experiment are given in Figures 4.5 to 4.12. Cumulative curves are shown in Figures 4.13 to 4.20. These figures show that leachate is discharged soon after water is first added to the cells (a total of 100 ml of leachate is discharged from cells 2 to 5 and 7 and 8 in the days before water is added, due to settlement of the waste squeezing out moisture). Generally, these curves show that high infiltration intensity cells discharge a greater amount of leachate more quickly than low infiltration intensity cells. Also, high compaction cells store more moisture than low compaction cells. This is also shown in Table 4.2 which presents the moisture movement variables: practical field capacity (PFC), effective storage (ES), water added to reach practical field capacity (W_{PFC}) and effective storage (W_{ES}), breakthrough time (t_{bt}), time to effective storage (t_{ES}), and initial and ultimate unsaturated hydraulic conductivity (K_{us} initial and K_{us} ultimate).

Figure 4.5: Discrete Infiltration, Discharge and Storage for Low Infiltration Intensity, Low Compaction Cell 1

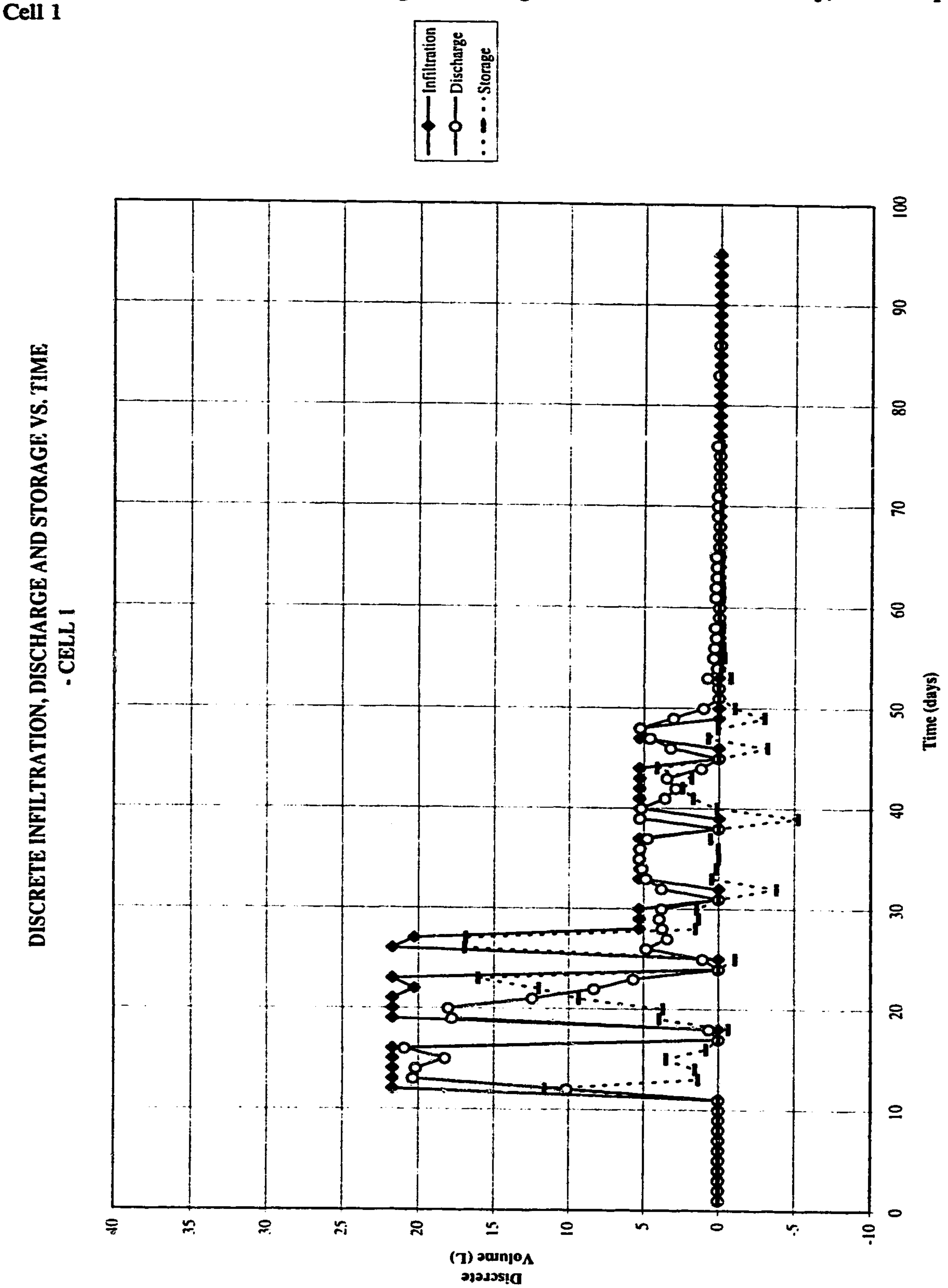


Figure 4.6: Discrete Infiltration, Discharge and Storage for Low Infiltration Intensity, Low Compaction Cell 3

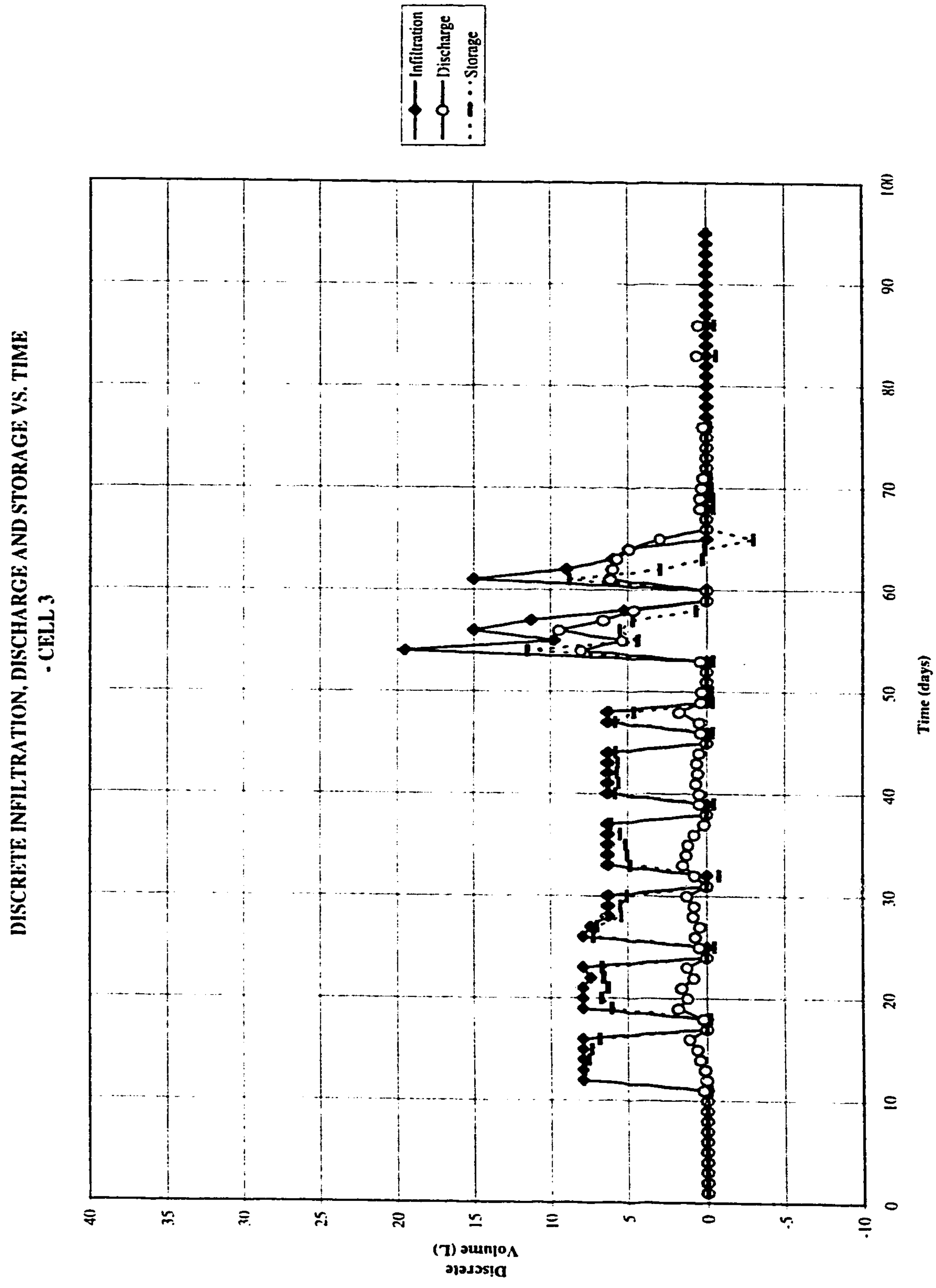


Figure 4.7: Discrete Infiltration, Discharge and Storage for Low Infiltration Intensity, High Compaction Cell 2

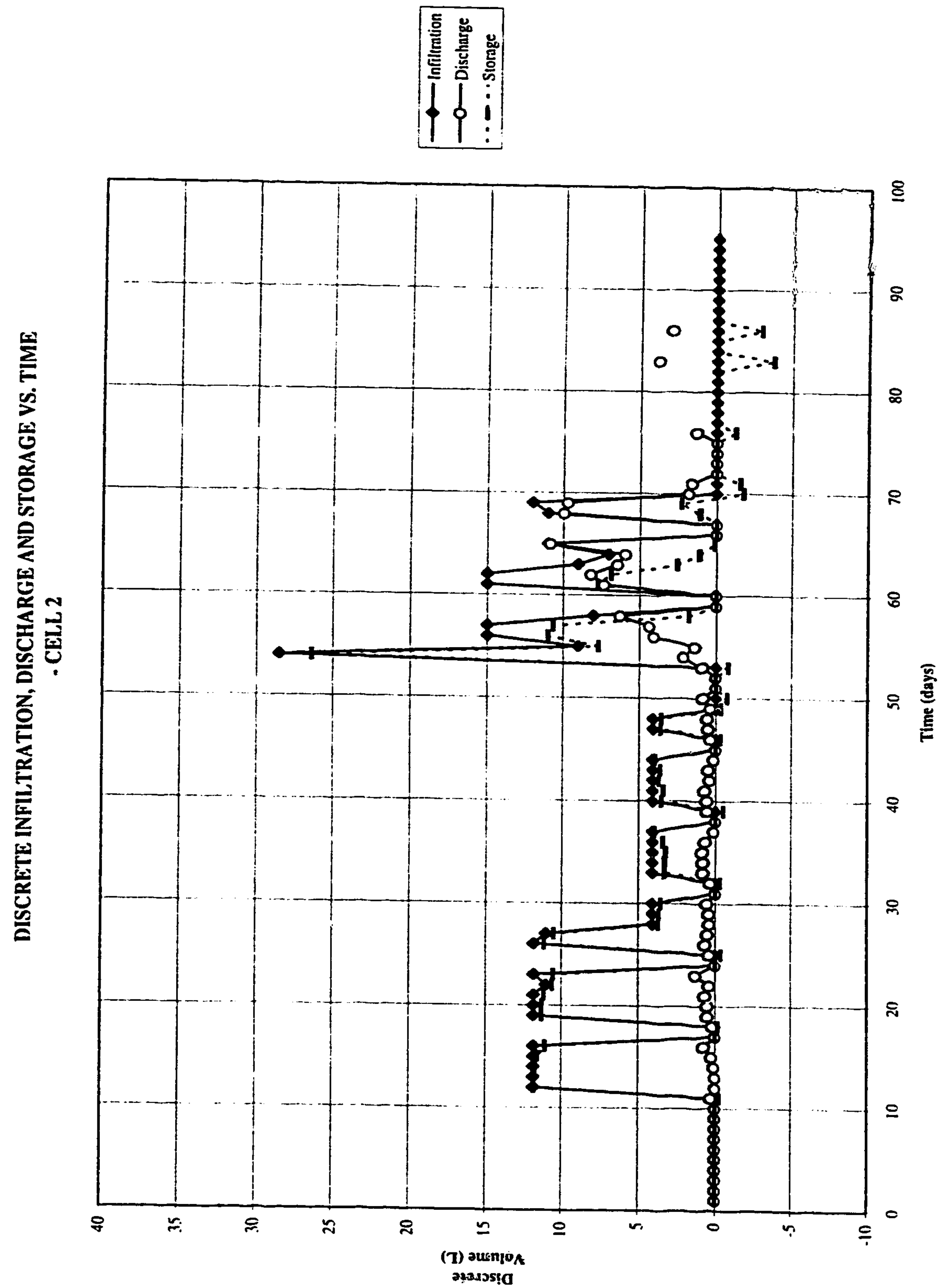


Figure 4.8: Discrete Infiltration, Discharge and Storage for Low Infiltration Intensity, High Compaction Cell 4

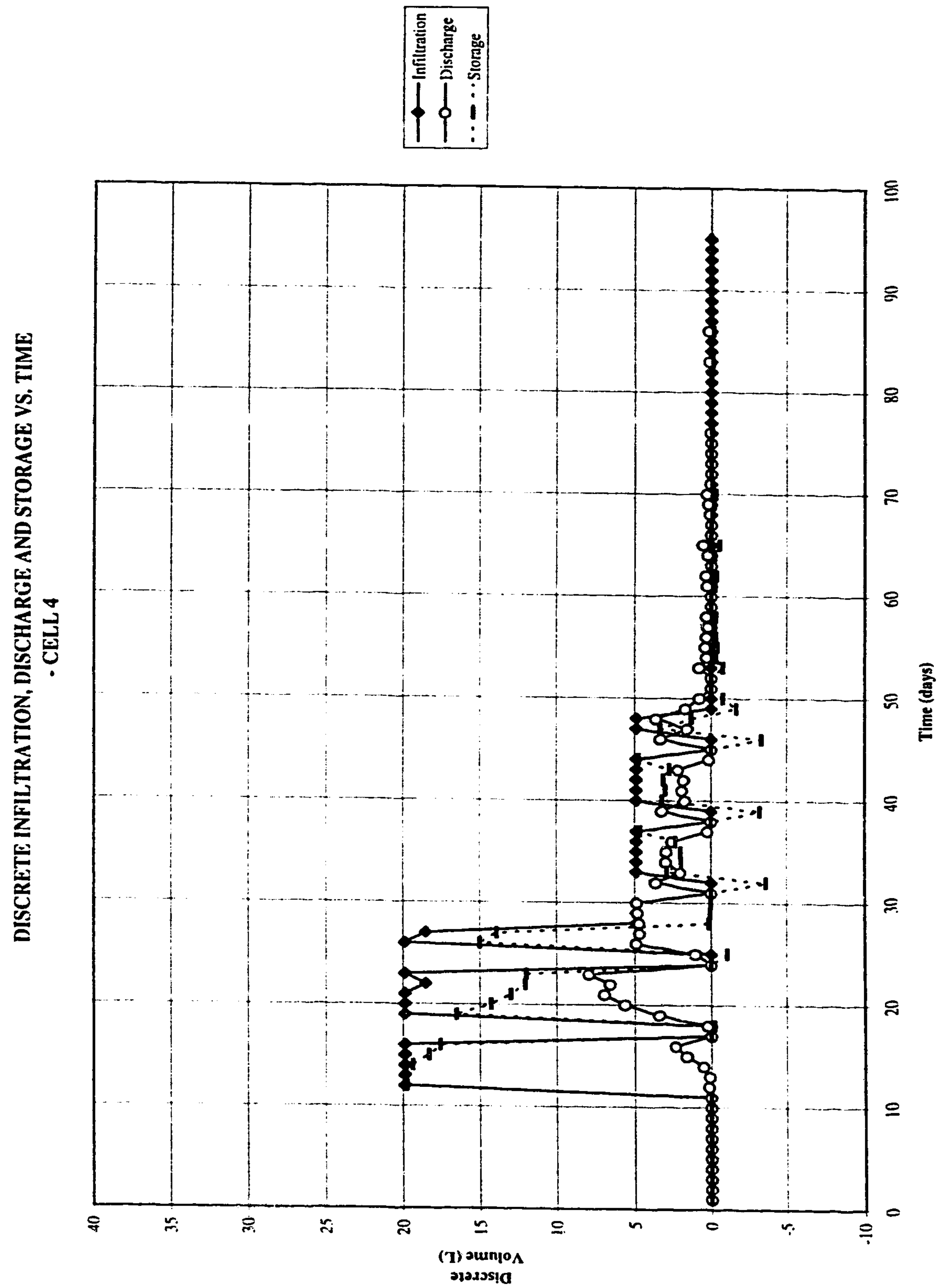


Figure 4.9: Discrete Infiltration, Discharge and Storage for High Infiltration Intensity, Low Compaction Cell 5

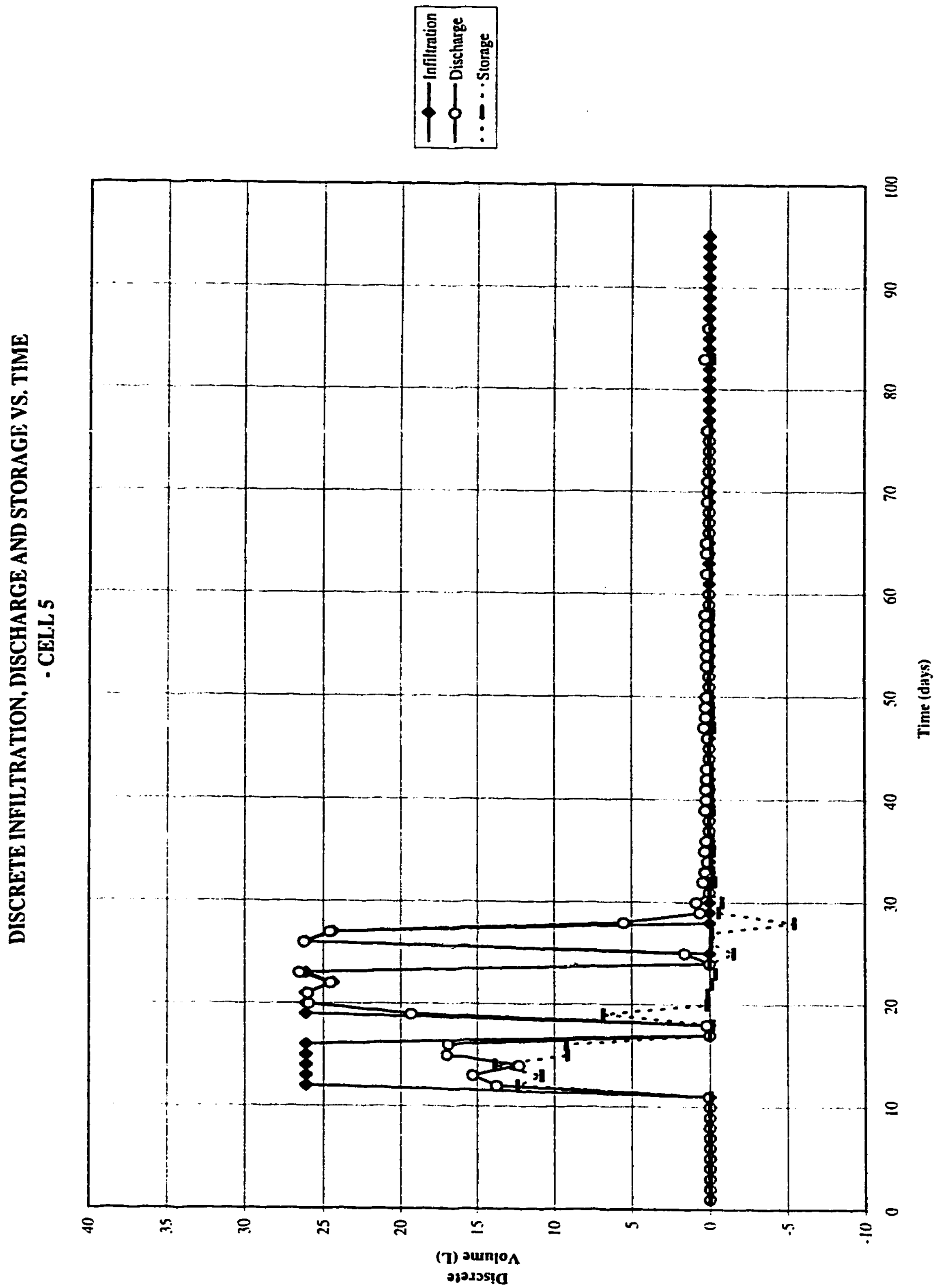


Figure 4.10: Discrete Infiltration, Discharge and Storage for High Infiltration Intensity, Low Compaction Cell 7

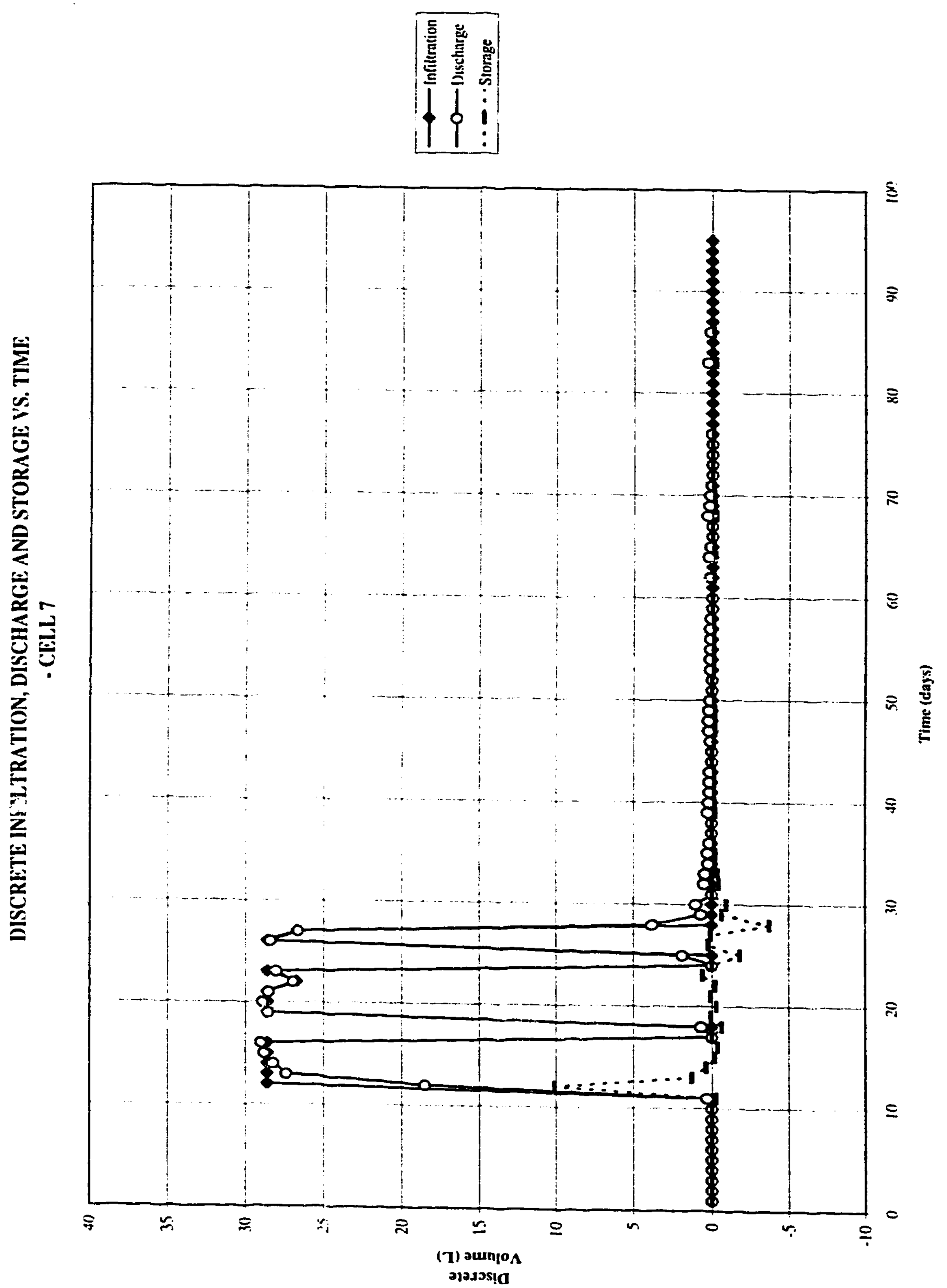


Figure 4.11: Discrete Infiltration, Discharge and Storage for High Infiltration Intensity, High Compaction Cell 6

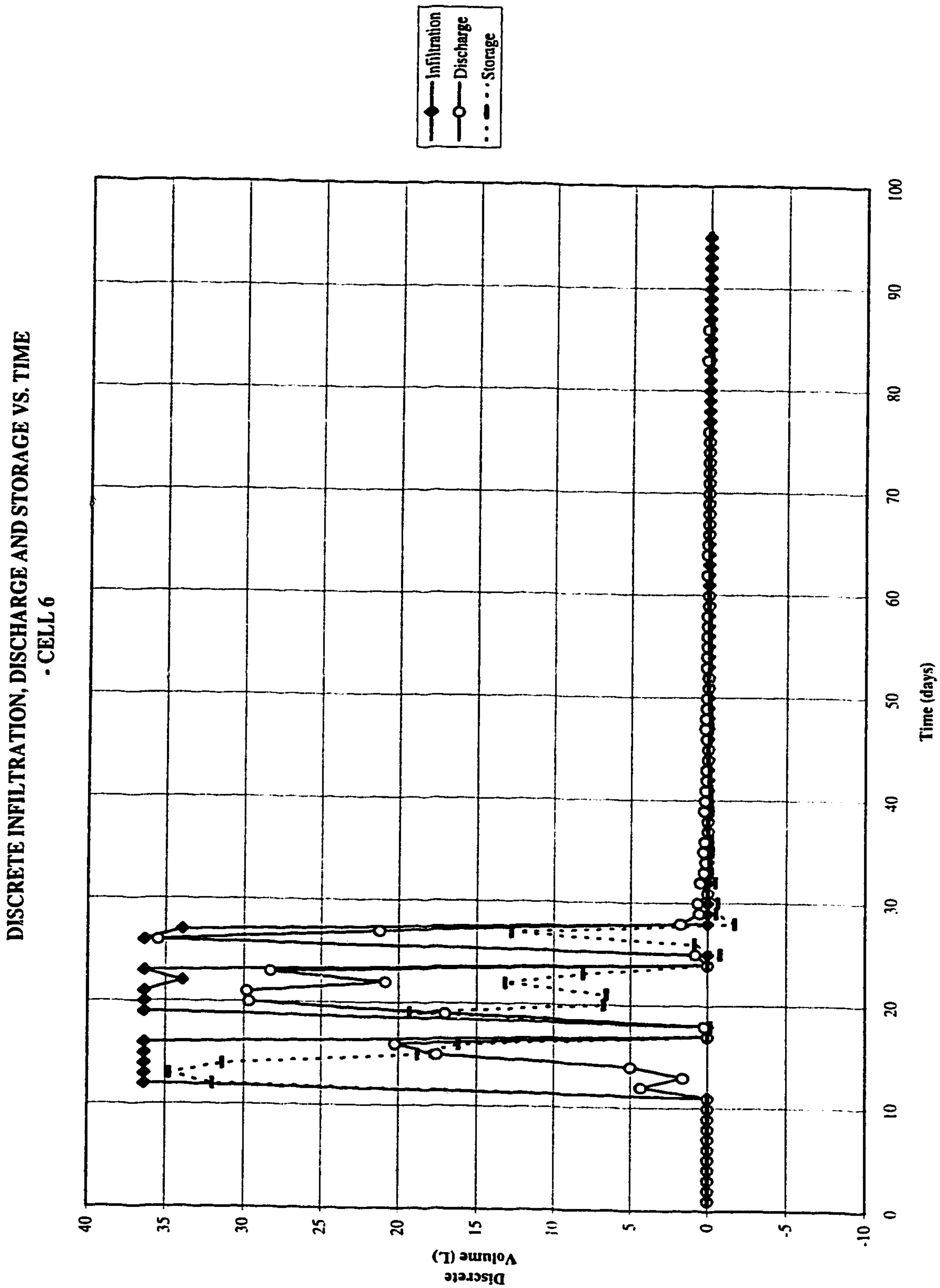


Figure 4.12: Discrete Infiltration, Discharge and Storage for High Infiltration Intensity, High Compaction Cell 8

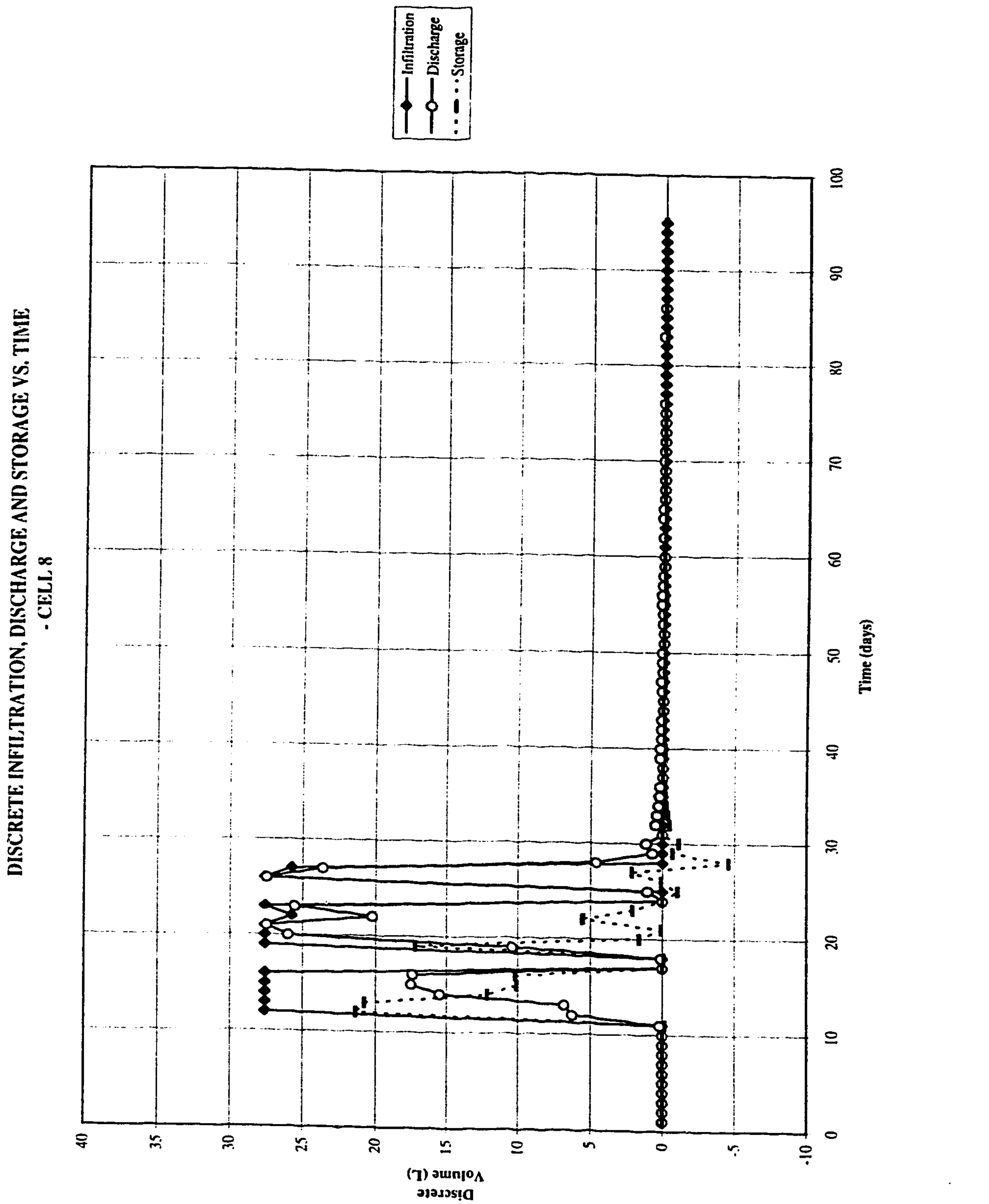


Figure 4.13: Cumulative Infiltration, Discharge and Storage for Low Infiltration Intensity, Low Compaction Cell 1

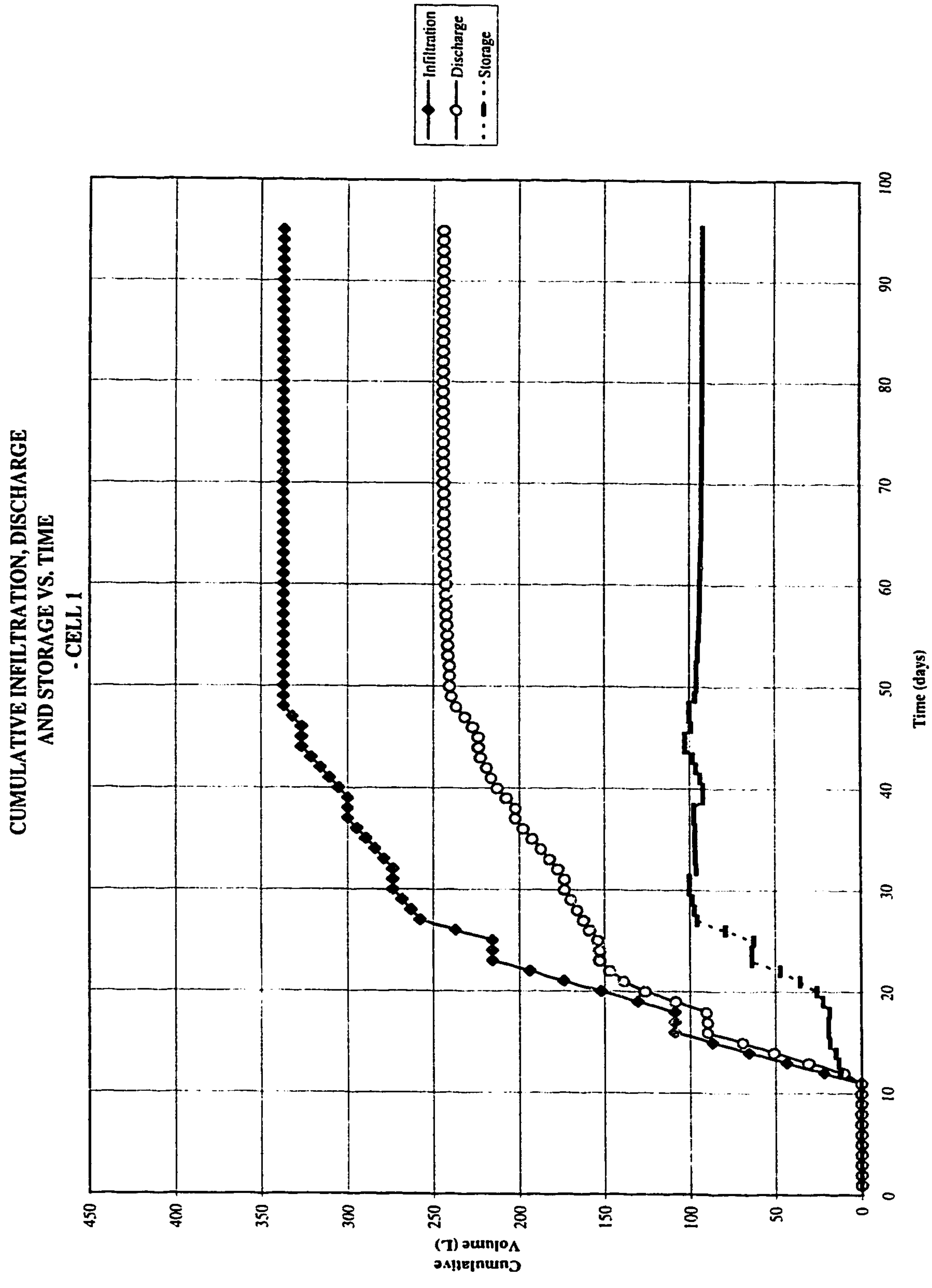


Figure 4.14: Cumulative Infiltration, Discharge and Storage for Low Infiltration Intensity, Low Compaction Cell 3

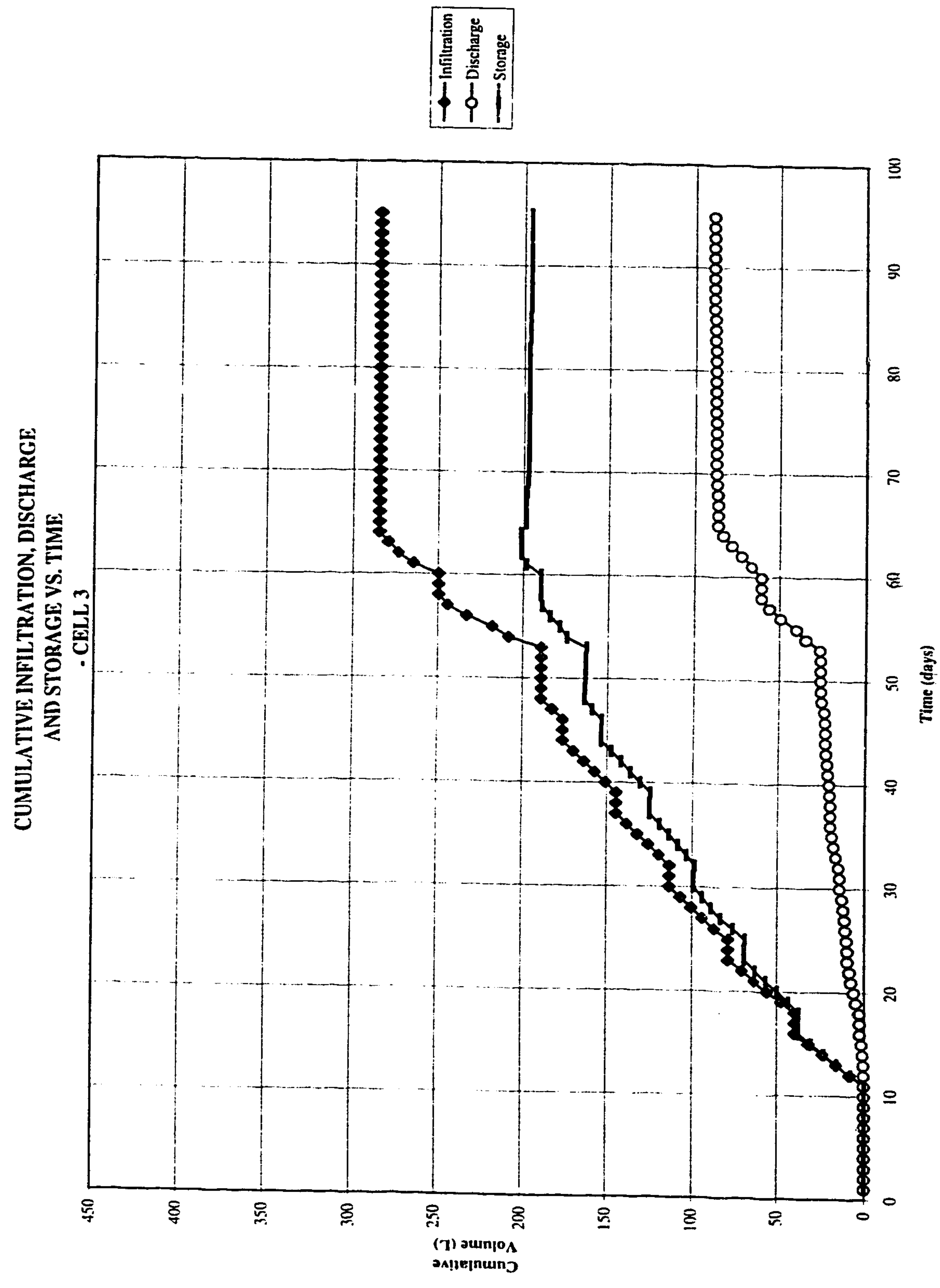


Figure 4.15: Cumulative Infiltration, Discharge and Storage for Low Infiltration Intensity, High Compaction Cell 2

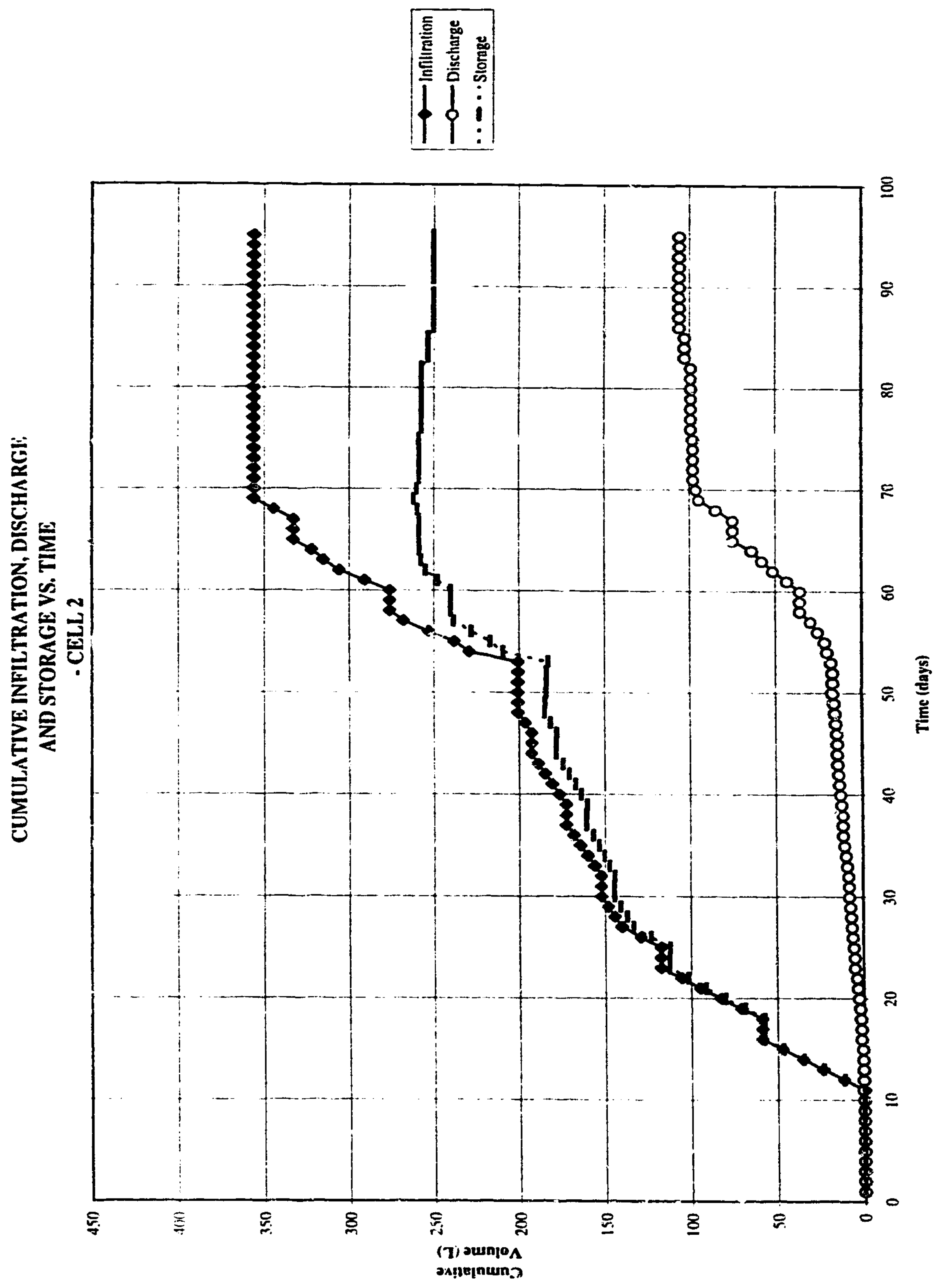


Figure 4.16: Cumulative Infiltration, Discharge and Storage for Low Infiltration Intensity, High Compaction Cell 4

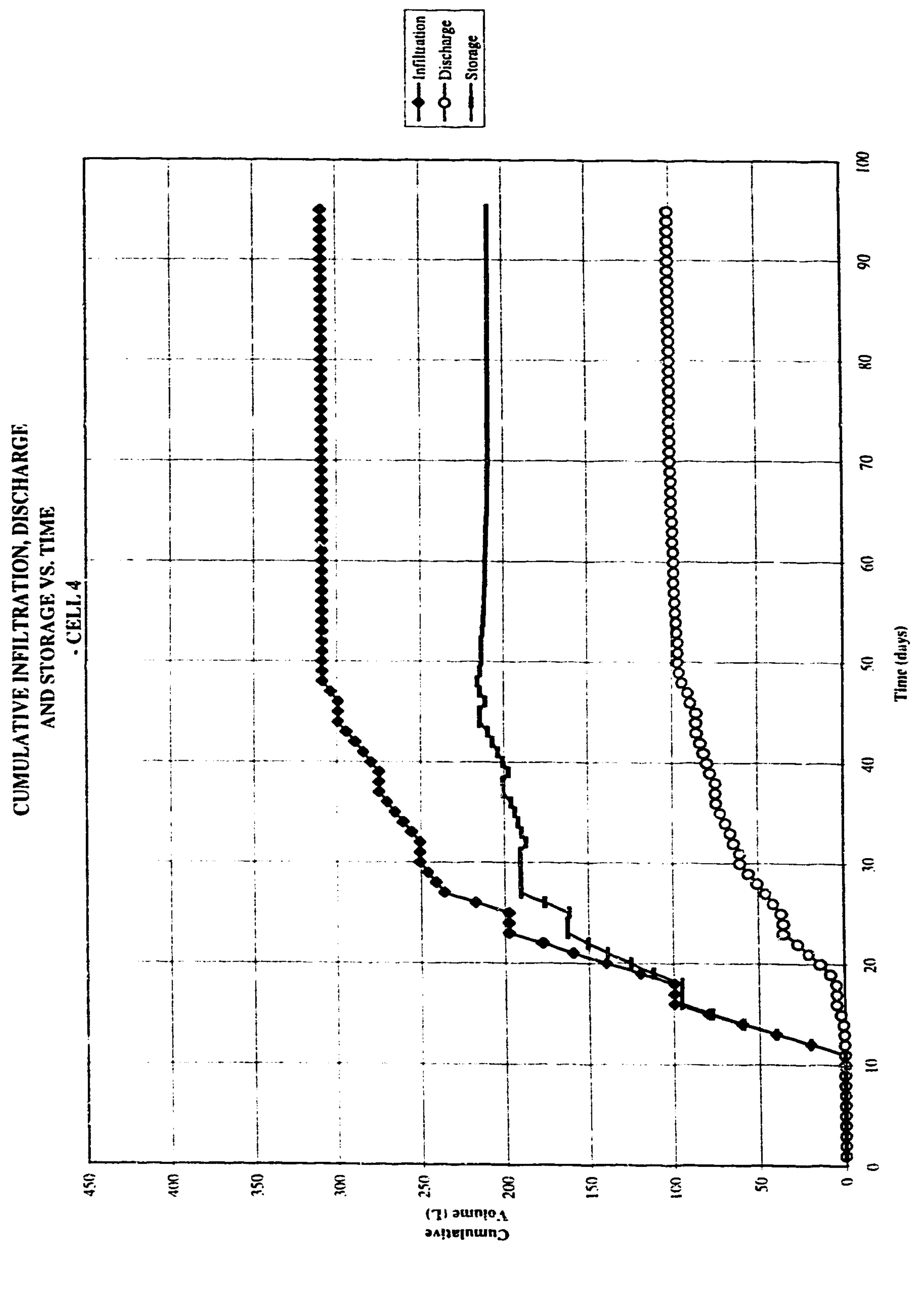


Figure 4.17: Cumulative Infiltration, Discharge and Storage for High Infiltration Intensity, Low Compaction Cell 5

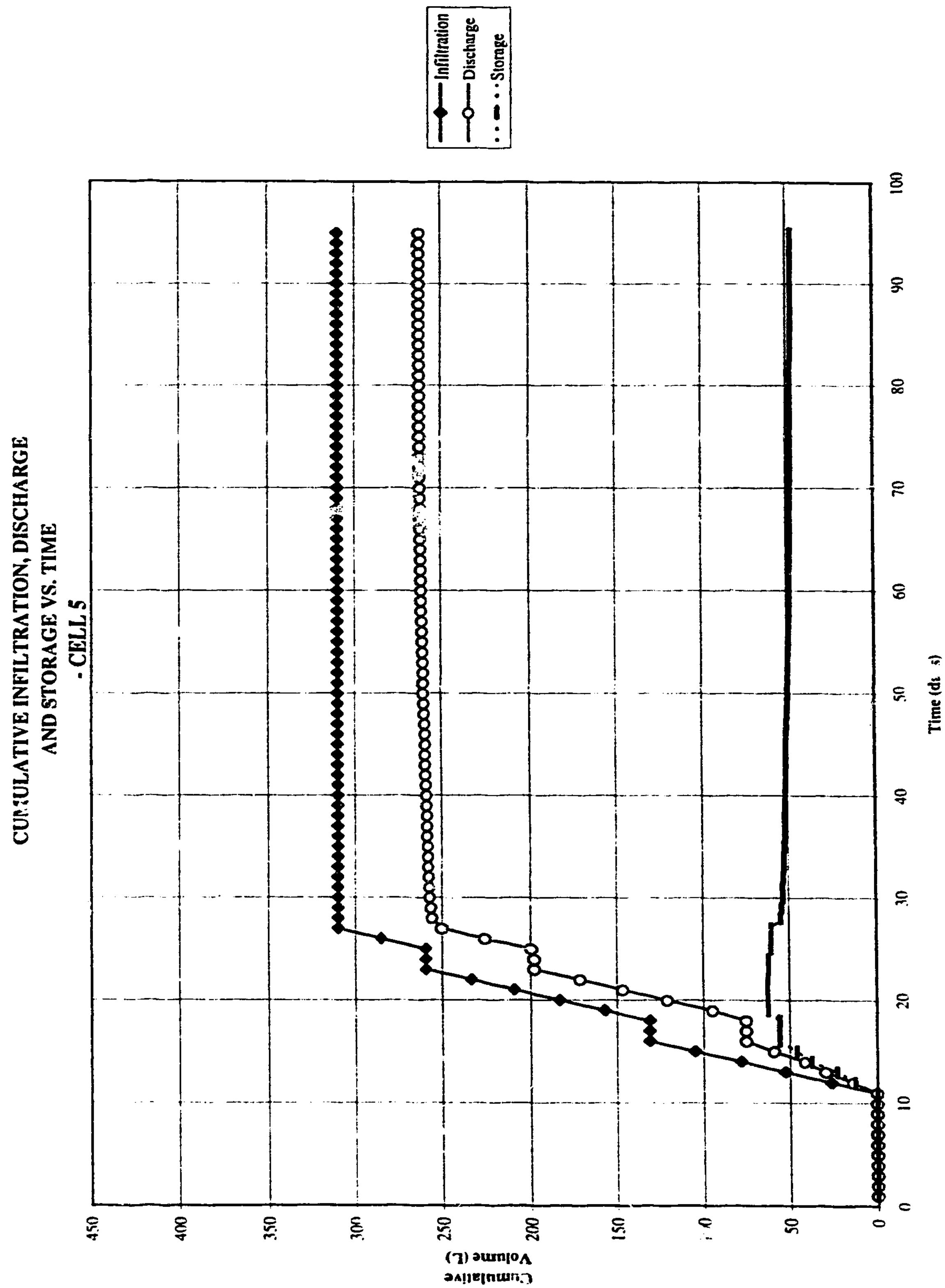


Figure 4.18: Cumulative Infiltration, Discharge and Storage for High Infiltration Intensity, Low Compaction Cell 7

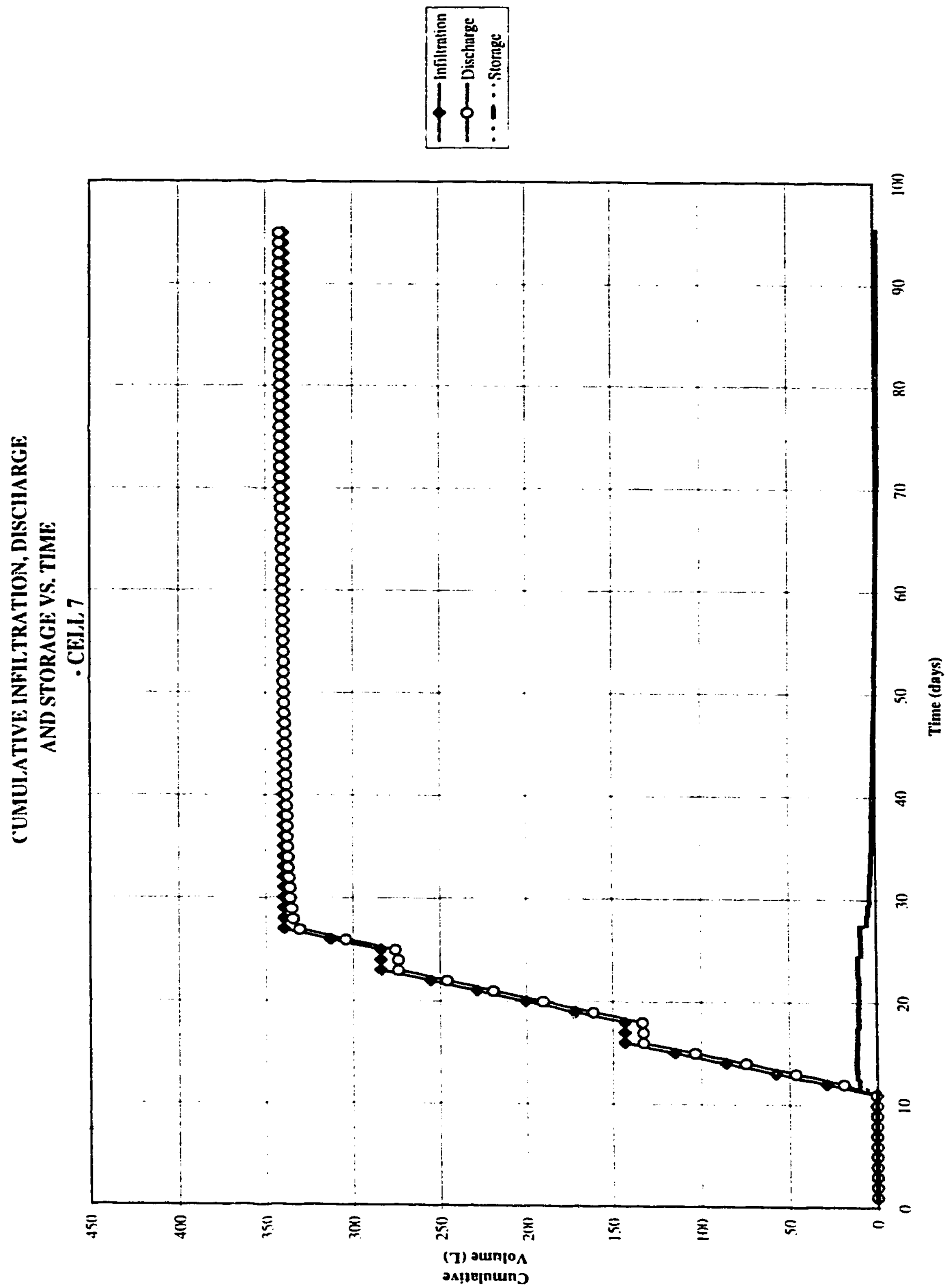


Figure 4.19: Cumulative Infiltration, Discharge and Storage for High Infiltration Intensity, High Compaction Cell 6

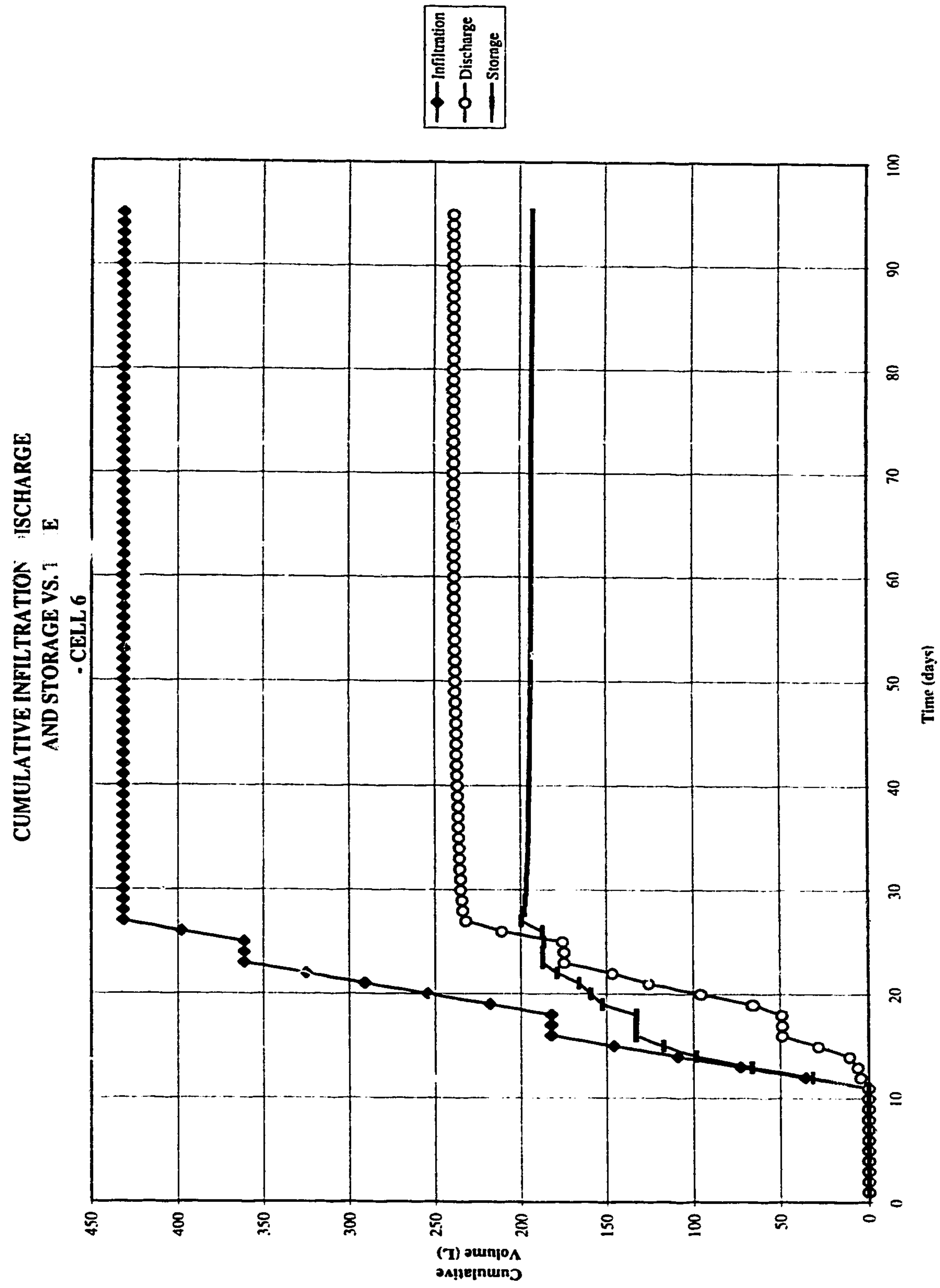


Figure 4.20: Cumulative Infiltration, Discharge and Storage for High Infiltration Intensity, High Compaction Cell 8

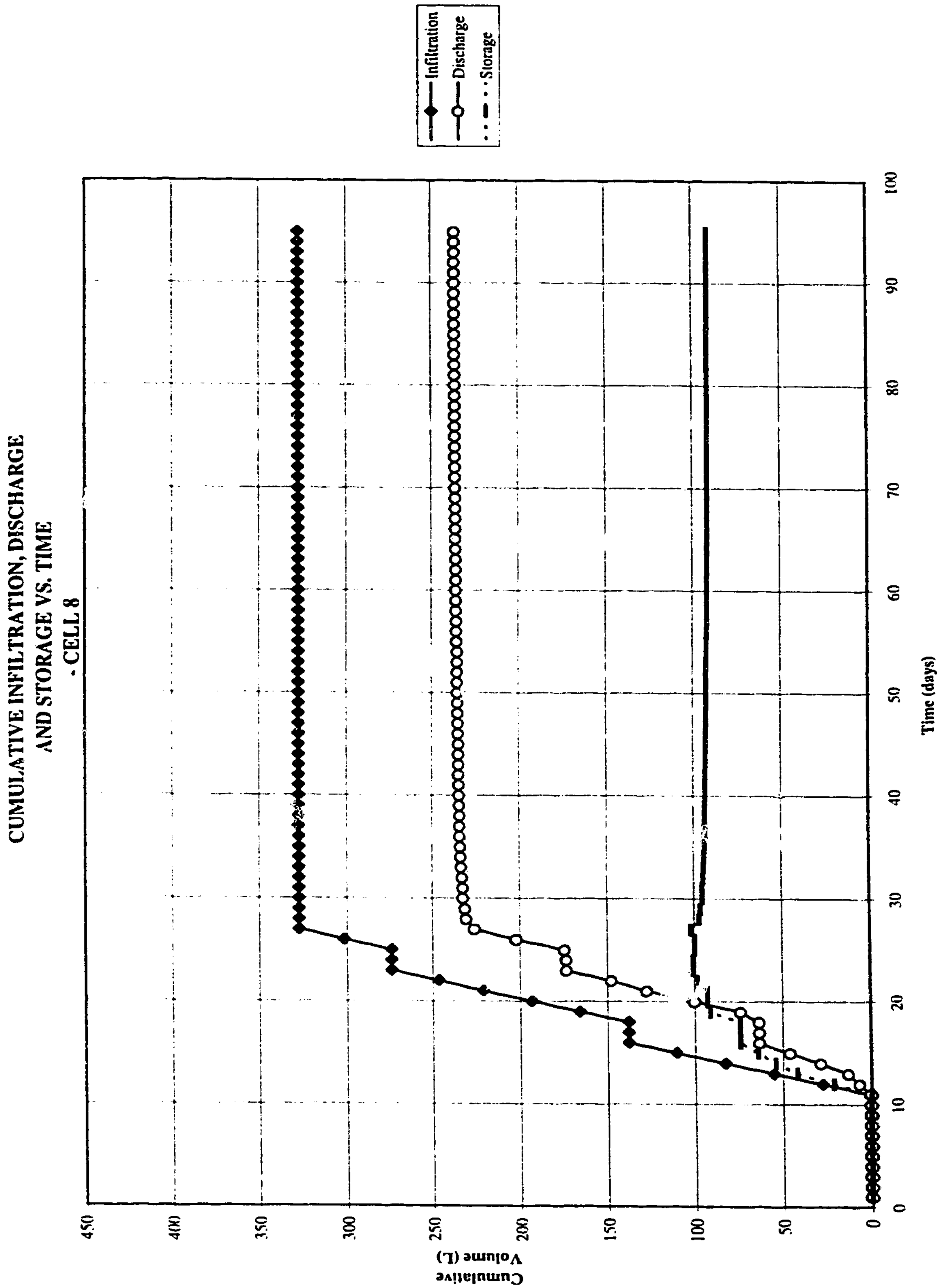


Table 4.2: Values of Moisture Movement Variables

	Low Intensity Cells				High Intensity Cells				All Cells	
PARAMETER	Low Compaction Cells		High Compaction Cells		Low Compaction Cells		High Compaction Cells		Avg.	St. Dev.
	Cell 1	Cell 3	Cell 2	Cell 4	Cell 5	Cell 7	Cell 6	Cell 8		
PFC (v/v)	0.090	0.130	0.133	0.132	0.113	0.105	0.126	0.133	0.120	0.016
ES (v/v)	0.146	0.287	0.238	0.200	0.144	0.107	0.195	0.171	0.186	0.057
W_{PFC} (L)	14.9	6.7	8.2	14.0	18.1	19.6	25.6	19.2	15.8	6.2
W_{ES} (L)	285	285	333	246	183	86	398	302	265	95
t_{bt} (minutes)	15	1485	2880	30	15	15	20	15	559	1069
t_{ES} (days)	23	54	53	18	9	2	15	15	24	19
K_{us} initial (cm/s)	4.84 E-2	4.77 E-4	2.99 E-4	2.70 E-2	4.67 E-2	4.47 E-2	4.00 E-2	5.29 E-2	3.26 E-2	2.12 E-2
K_{us} ultimate (cm/s)	2.09 E-6	2.43 E-6	4.42 E-6	1.98 E-6	1.05 E-5	1.13 E-5	1.48 E-5	1.11 E-5	7.33 E-6	5.13 E-5

The results in Table 4.2 also indicate the nature of the flow through the cells. As stated, Darcy's Law is used to describe laminar flow through a porous media (section 2.1.2). The media can be either heterogeneous or homogeneous, however, flow is not Darcian if the flow regime is turbulent (Bouwer, 1978). If the flow through the experimental cells is turbulent, Darcian flow is not the only moisture movement mechanism at work in the cells, therefore, channeled flow must be occurring. The flow regime occurring in the cells can be determined from the values of initial unsaturated hydraulic conductivity (K_{us} initial) shown in Table 4.2 by calculating the Reynolds number (equation 2). If the Reynolds number is greater than 10 the flow is not laminar, therefore, not Darcian.

Recall from section 2.1.2 the Reynolds number is calculated from the following equation:

$$Re = (\rho * q * d)/\mu \qquad (2)$$

where: ρ = the density of the fluid flowing through the pore (M/L^3)

q = the specific discharge; flow rate per unit area, or flux (L/T)

d = the diameter of the pore (L)

μ = the absolute viscosity of the fluid (M/L/T)

All variables of this equation are known or can be estimated for the experimental cells. Water is assumed to be at 10°C (this was the average temperature of the room in which the experiment was performed), therefore, the density (ρ) and the absolute viscosity (μ) can be set to correspond to this temperature. The value of q is set to K_{us} initial. Recall from equation 3 (section 2.1.2) that these values are equal if the hydraulic gradient is unity. The hydraulic gradient in the cells is greater than unity because the suction head in the waste is greater than zero (unsaturated conditions). Therefore, K_{us} initial is an underestimate of q. By setting the value of Re to 10, which is the limit of Darcian flow, the diameter of the pore can be calculated. If the calculated pore diameter is less than the average pore diameter found from the supplementary experiment (Table 3.6) the flow is turbulent, so channeled flow must occur. Table 4.3 shows the values of the diameters calculated using equation 2.

Table 4.3: Calculated Pore Diameters Using Critical Reynolds Number

Average Pore Diameter Found From Supplementary Experiment (cm)			3.8		
Water Density at 10°C (kg/m^3)			1000		
Dynamic Viscosity of Water at 10°C (Ns/m^2)			1.31E-3		
Critical Reynolds Number			10		
Cell Number	K_{us} initial (cm/s)	Calculated Diameter (cm)	Critical Diameter (cm)	Flow Regime	Darcian Flow
1	4.84E-2	2.7	3.8	Turbulent	No
2	4.77E-4	275	3.8	Laminar	Yes
3	2.99E-4	438	3.8	Laminar	Yes
4	2.70E-2	4.9	3.8	Laminar	Yes
5	4.67E-2	2.8	3.8	Turbulent	No
6	4.47E-2	2.9	3.8	Turbulent	No
7	4.00E-2	3.3	3.8	Turbulent	No
8	5.29E-2	2.5	3.8	Turbulent	No
Average	3.26E-2	4.0	3.8	Laminar	Yes

Table 4.3 shows that for cells 1 and 5 through 8 the calculated pore diameter is smaller than the experimental diameter, and therefore, flow through these cells is turbulent. It should be noted that this analysis is based on the assumption that moisture is moving through only one pore. In reality there are a great number of pores which make up the porous matrix, as well as a number of macropores. The diameters, both calculated and critical, would have to be increased to show that moisture moves through more than one pore. However, this analysis does show that turbulent flow is possible, and that Darcian flow may not be the only flow mechanism in the cells.

Also, Table 4.2 shows that the average K_{us} initial is 3.86E-2 cm/s. This value is in the range of saturated hydraulic conductivities found in the literature (Table 2.3). However, the moisture contents at practical field capacity are much smaller than the porosity values listed in Table 2.3 (the average of practical field capacities listed in Table 4.2 is 0.12 , while the average porosity of the values listed in Table 2.3 is 0.49). This shows that the waste in the cells is unsaturated, yet, the rate at which leachate is flowing through the waste is comparable to the saturated hydraulic conductivity determined for MSW by other experimenters. However, the initial moisture content, and Rosin-Rammler particle size of the waste in the cells (Table 4.1) is consistent with the literature values, so the waste used in the experiment is comparable to the waste examined by others. This indicates that flow through the waste may not be Darcian alone, because the leachate flow rate is greater than would be calculated if Darcy's Law (equation 3). were used, and the apparent unsaturated hydraulic conductivity at practical field capacity (K_{us} initial), is in the same range as the saturated hydraulic conductivity values found in the literature, where Darcian flow was assumed.

Furthermore, the results of the tracer test (Table 3.7) show that, on average, only 26% of the cross-sectional area of the waste conveys flow. Also, the areas marked by the tracer were not adjacent to each other but on opposite sides of the area (Figure 3.4). However, if the media were homogeneous and the flow was Darcian, a more uniform distribution of the tracer would be expected as tracer would flow evenly through the waste. As Zeiss and Major conclude, the small cross-sectional area of flow, and the unconnected active flow areas indicate channeled flow and contradict vertical one-dimensional Darcian flow (Zeiss and Major, 1993).

These results show the waste and flow characteristics observed in the cells used for the main experiment. The examination of these results shows that channeled flow may occur in the experimental cells. The channeling hypothesis can also be tested using the tensiometer and flow-cup grid data. The analysis of this data is presented below.

4.1.2 Tensiometer Results

The analysis of the tensiometer data is used to test the channeling hypothesis (hypothesis 1). Tensiometer data is shown for all cells in Figures 4.21 through 4.28. As noted on the figures the first tensiometer readings occur on day 12, which is when moisture loading for each cell started (twelve days after loading). Water addition was discontinued at different times for each cell, and steady state was reached at different times as well. The discussion below highlights general tensiometer trends for each cell. This is followed by summary statistics for each channeling sub-hypothesis, as well as a discussion of the analysis.

First the low infiltration intensity, low compaction cells (cells 1 and 3) are considered (Figures 4.21 and 4.22). The figures show the tensiometer readings in centibars. Some general patterns are seen in the figures. For cell 1 water addition is stopped on day 48. For both the top and middle levels, there are few occasions where all tensiometers are reading zero simultaneously. The tensiometer readings generally decrease as water is added, indicating that the area around the tensiometer is becoming wetter, however, for the most part the tensiometers for the top and middle level remain consistently unsaturated. Steady state is reached on day 35, and except for the bottom level, not all tensiometers read zero at that time.

Cell 3 is a replicate of cell 1, however, steady state occurred later than cell 1. Water addition was discontinued on day 64. Numerous non-zero readings are evident on all levels over the entire test duration, with few occasions of simultaneous saturation of tensiometers on the same level. This indicates that the moisture front is not uniform. As with cell 1, there is a general wetting of the tensiometers with time.

The low infiltration intensity, high compaction cells are cells 2 and 4. The tensiometer data for these cells is presented in Figure 4.23 and 4.24. Some differences between replicates can be observed by examining the figures. Water addition for cell 2 continued until day 69. For the duration of water addition all tensiometers on each level read zero simultaneously on numerous occasions. Most tensiometers, on all levels, read zero for the entire test duration except for certain days when non-zero values were read. Therefore, the moisture front may not be uniform, although it is difficult to observe this from the figure.

Water addition for cell 4, the replicate of cell 2, was discontinued on day 48. Unlike cell 2, numerous non-zero readings are evident, specifically for the middle and bottom level of the waste. Also, there are few occasions of simultaneous zero readings, specifically for the middle level tensiometers. This indicates that the moisture front is not uniform.

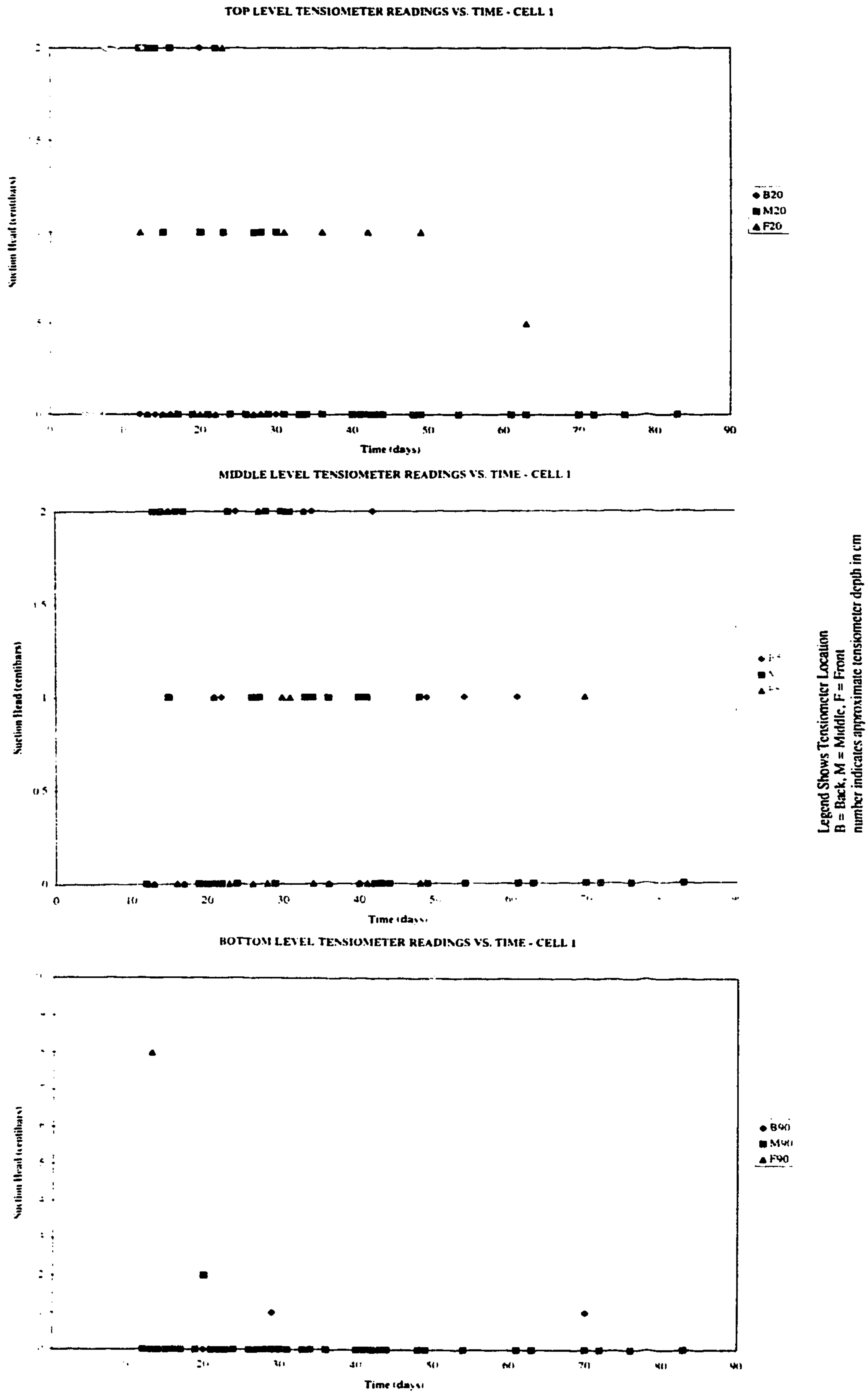
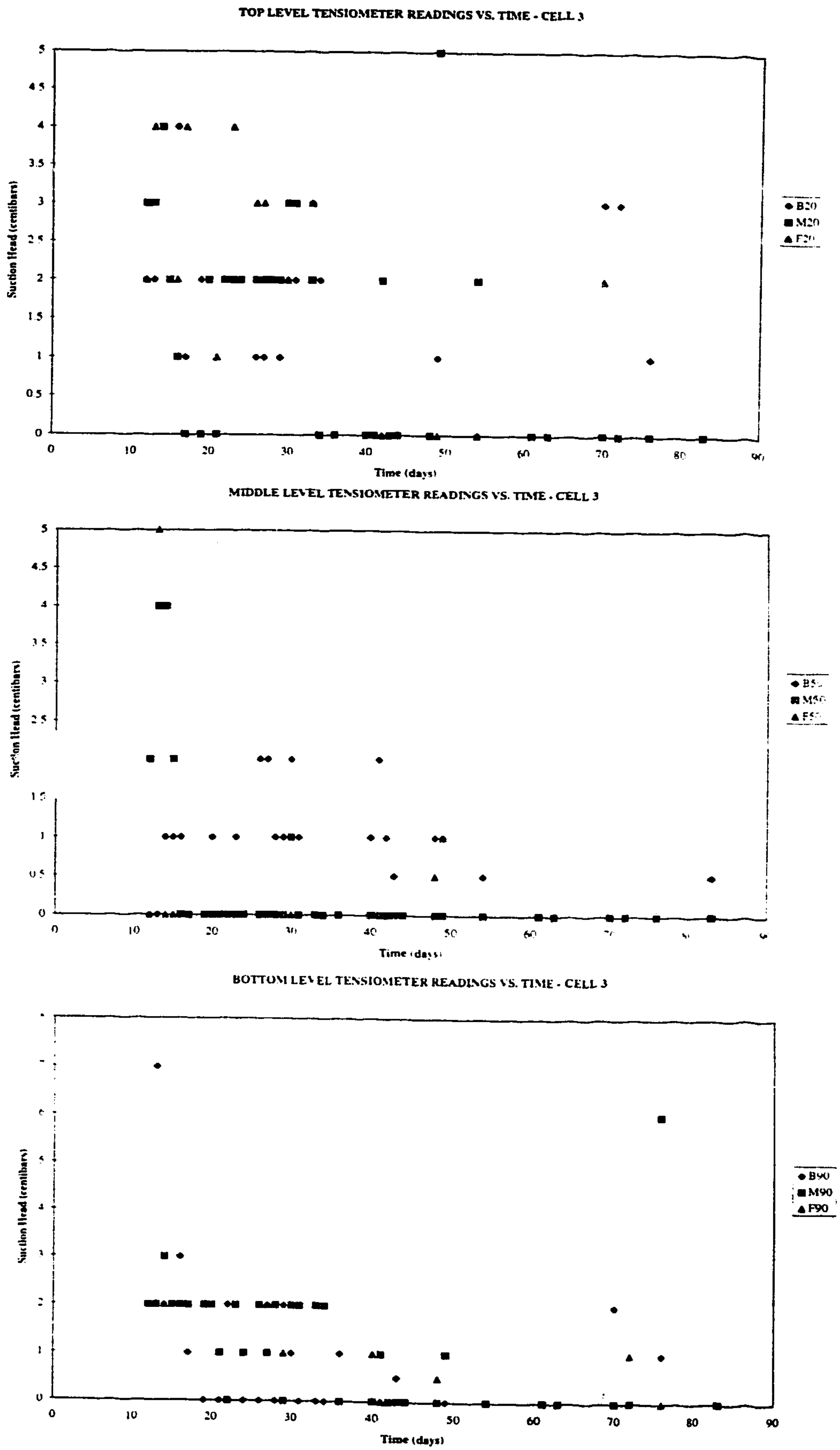


Figure 4.21: Tensiometer Readings for Cell 1 - Low Infiltration Intensity, Low Compaction ((a) top level, (b) middle level, (c) bottom level)



Legend Shows Tensiometer Location
B = Back, M = Middle, F = Front
number indicates approximate tensiometer depth in cm

Figure 4.22: Tensiometer Readings for Cell 3 - Low Infiltration Intensity, Low Compaction ((a) top level, (b) middle level, (c) bottom level)

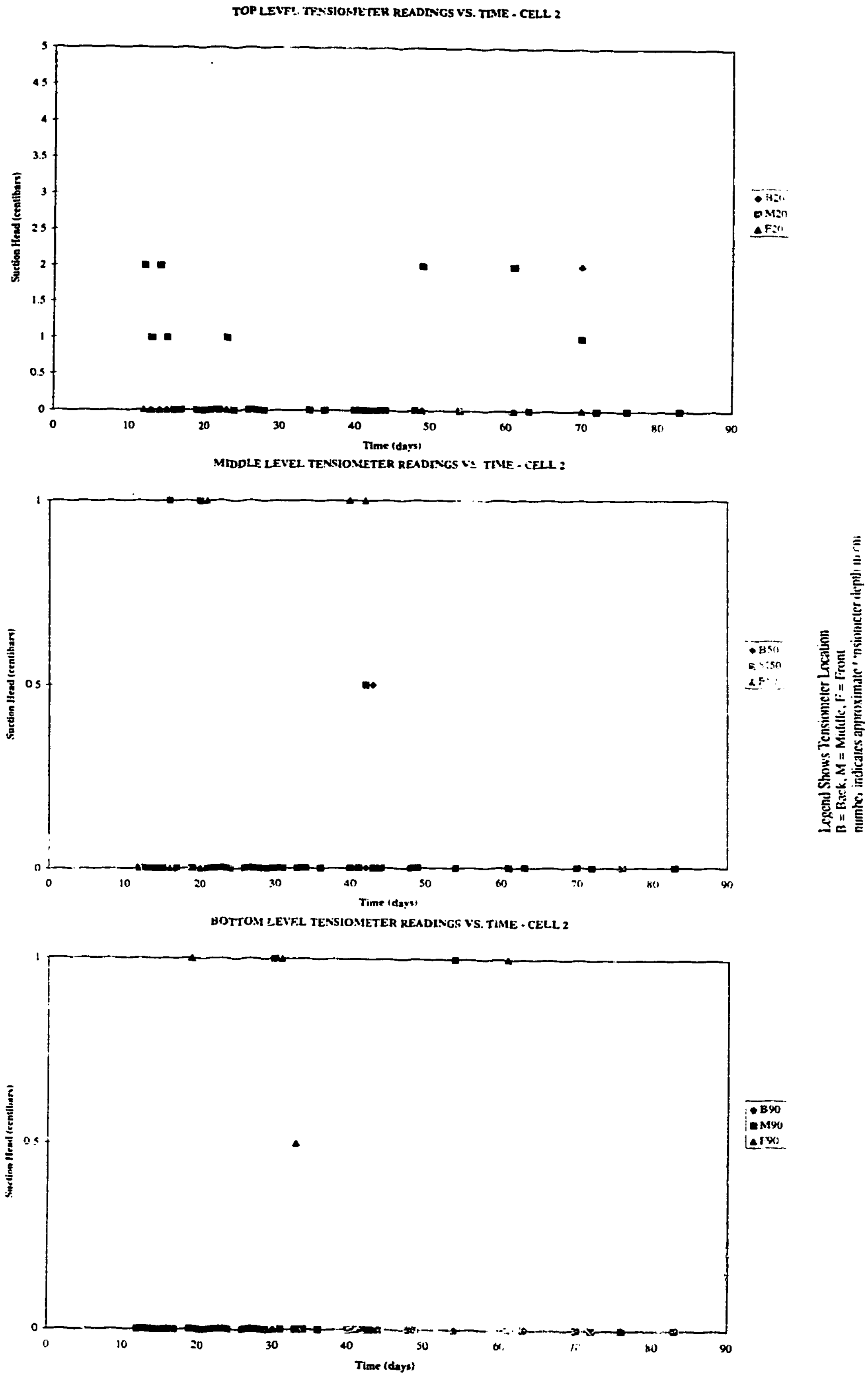
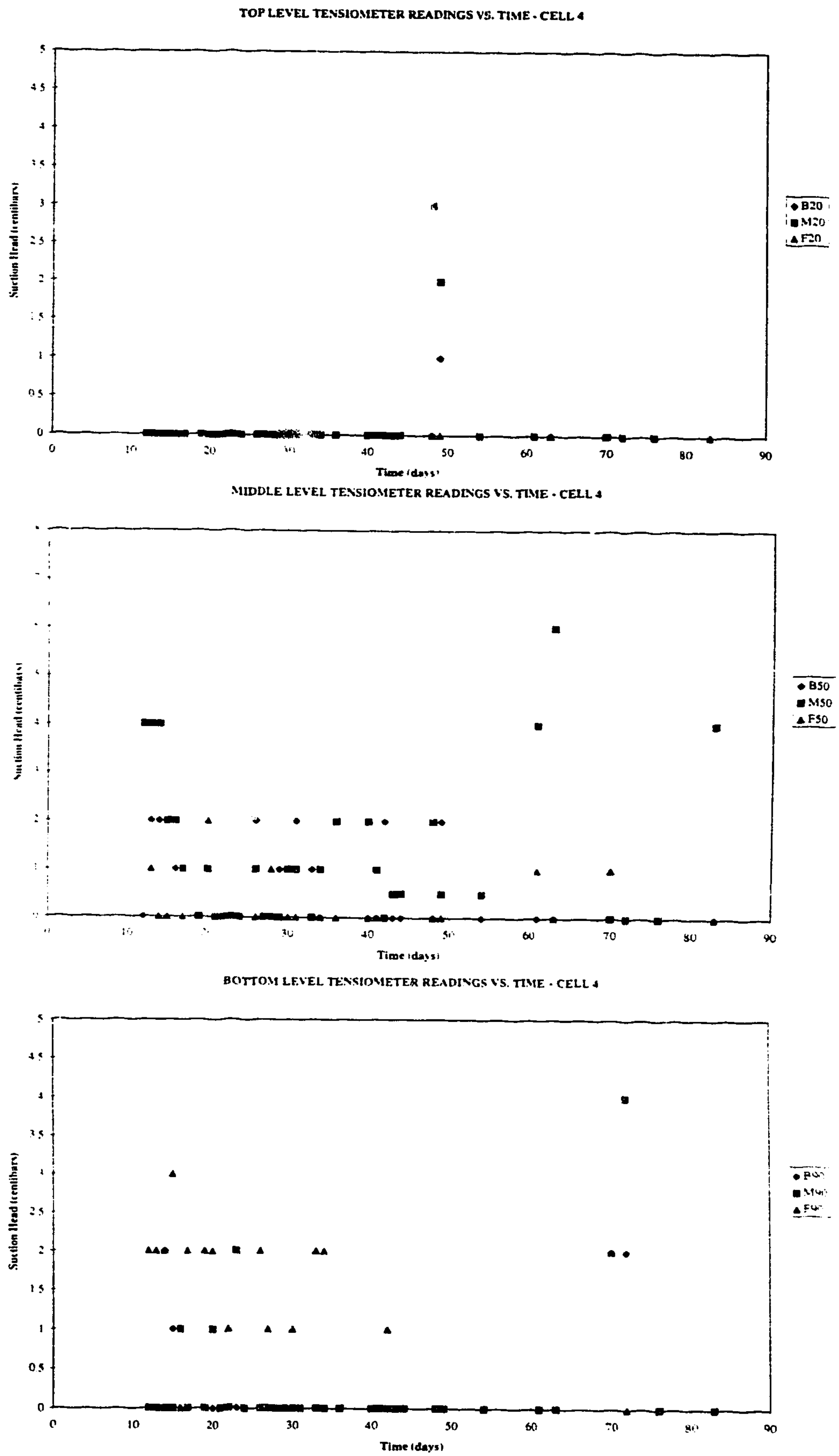
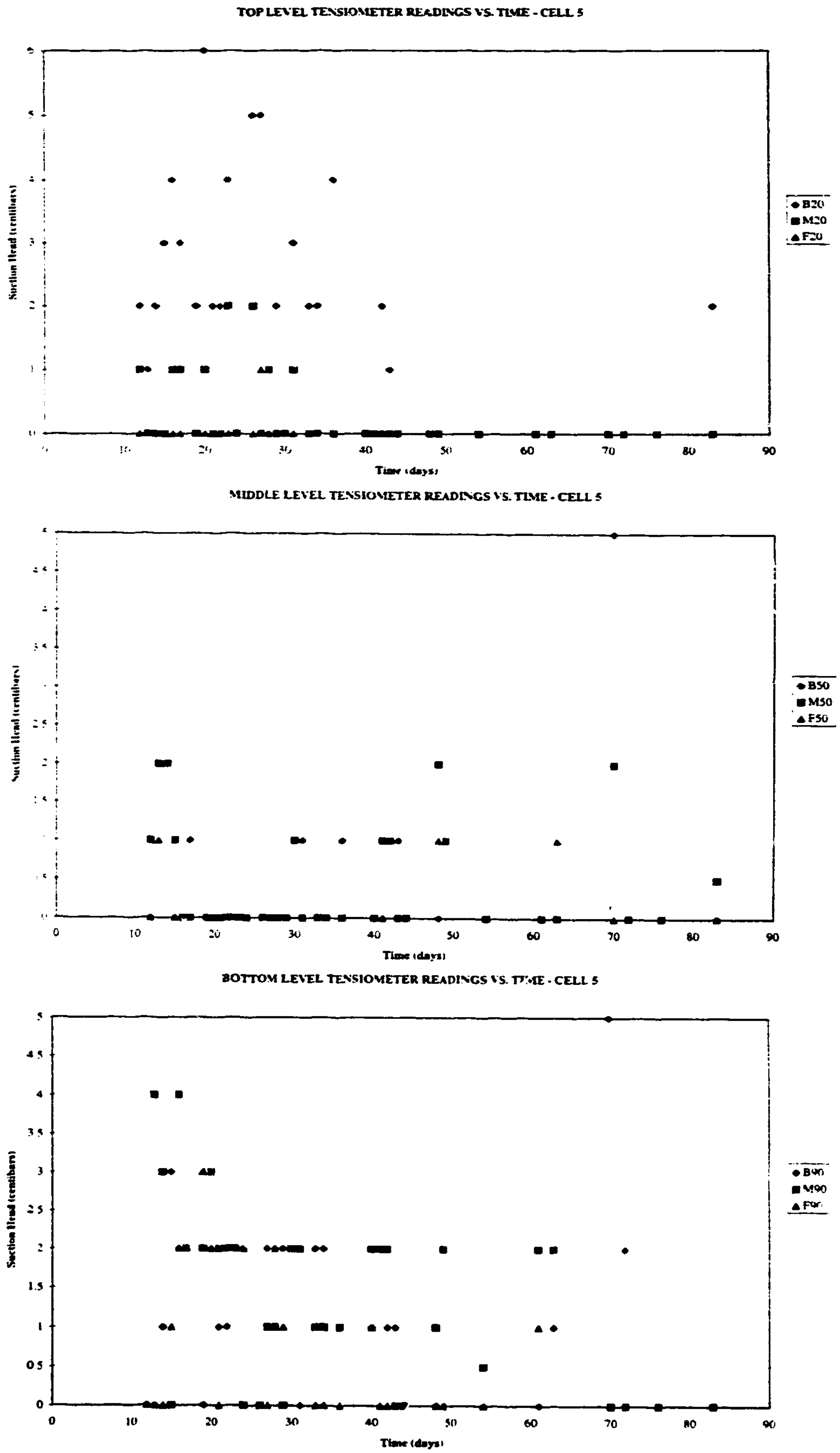


Figure 4.23: Tensiometer Readings for Cell 2 - Low Infiltration Intensity, High Compaction ((a) top level, (b) middle level, (c) bottom level)



Legend Shows Tensiometer Location
B = Back, M = Middle, F = Front
number indicates approximate tensiometer depth in cm

Figure 4.24: Tensiometer Readings for Cell 4 - Low Infiltration Intensity, High Compaction ((a) top level, (b) middle level, (c) bottom level)



Legend Shows Tensiometer Location
B = Back, M = Middle, F = Front
number indicates approximate tensiometer depth in cm

Figure 4.25: Tensiometer Readings for Cell 5 - High Infiltration Intensity, Low Compaction ((a) top level, (b) middle level, (c) bottom level)

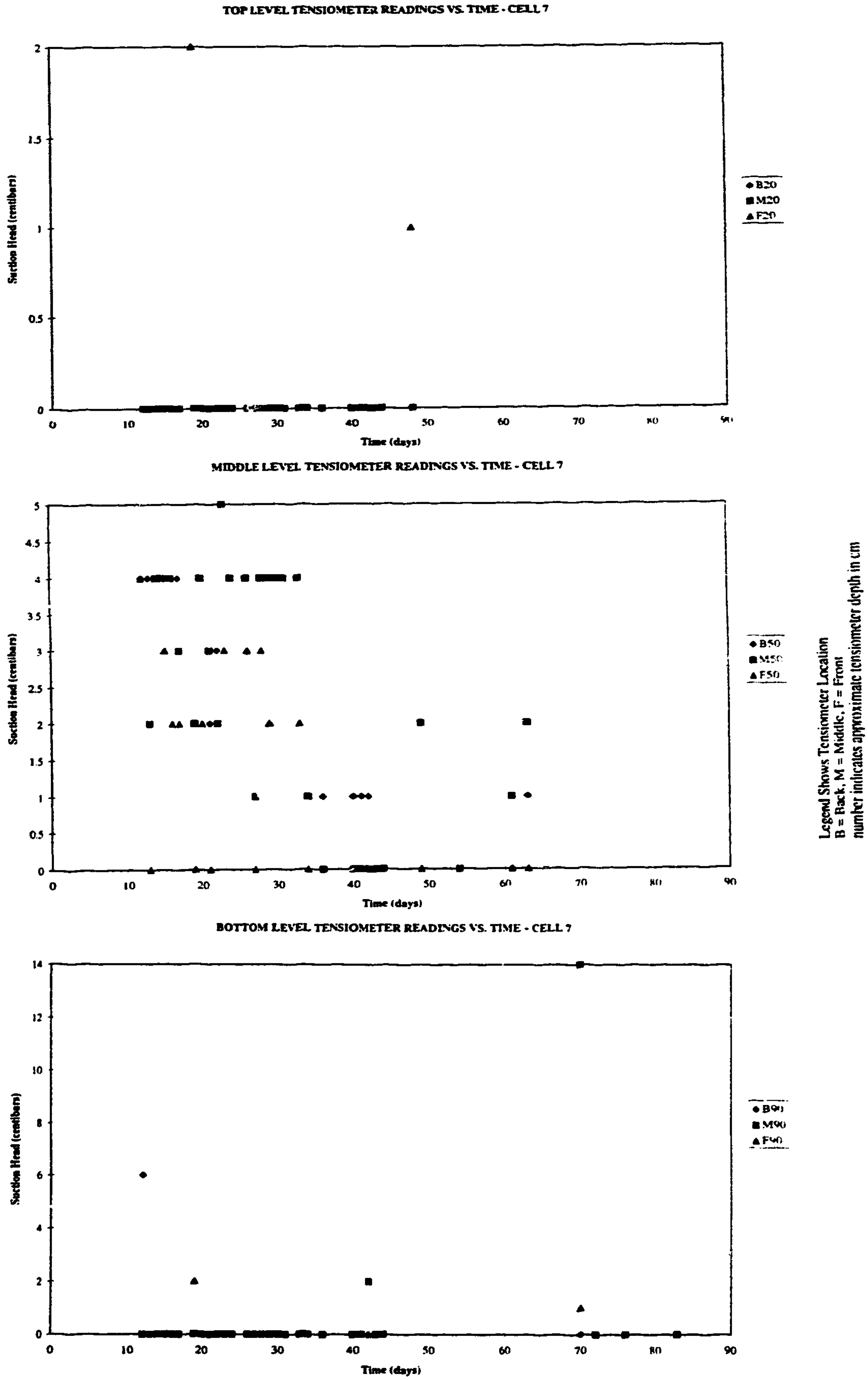
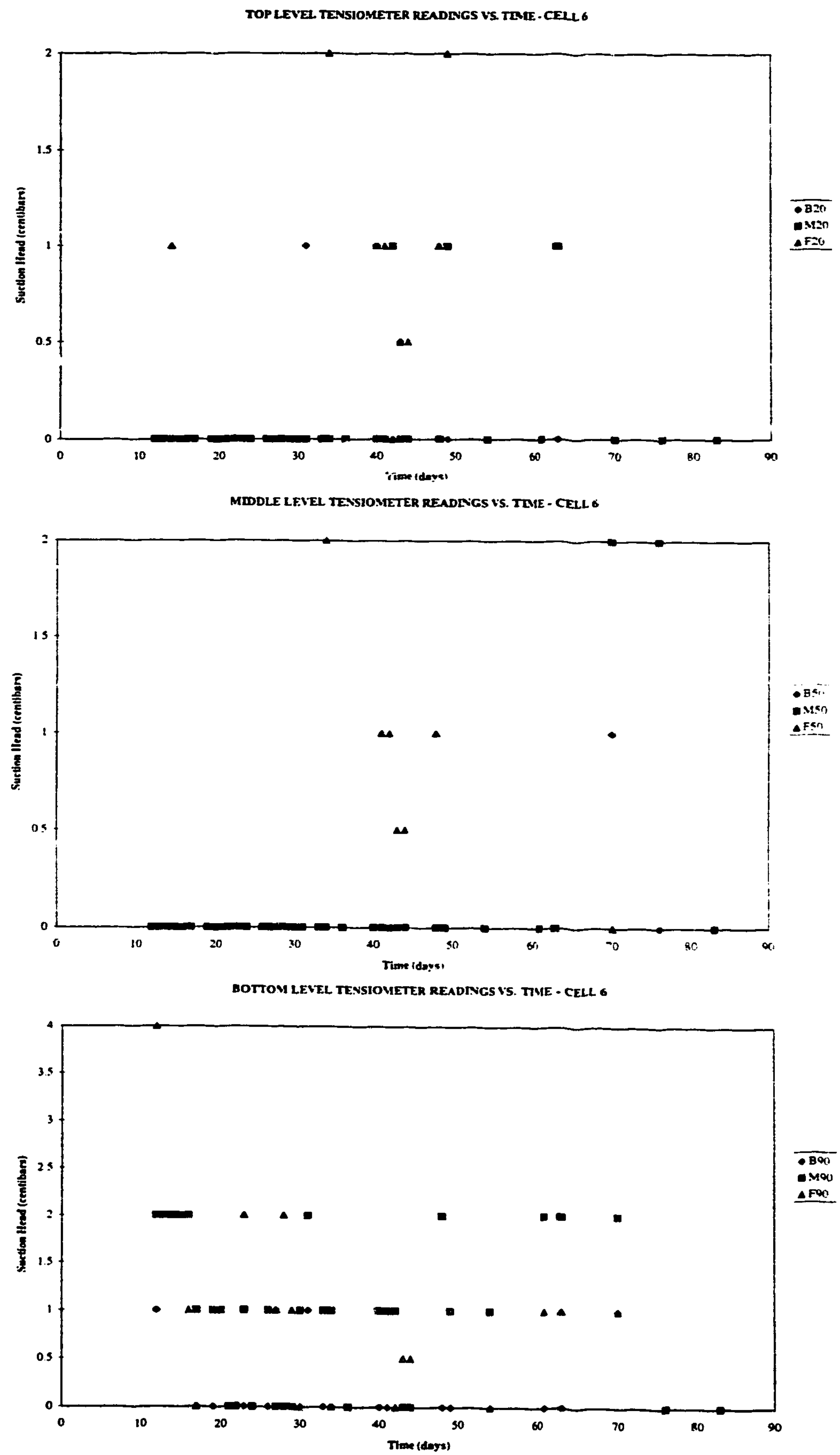
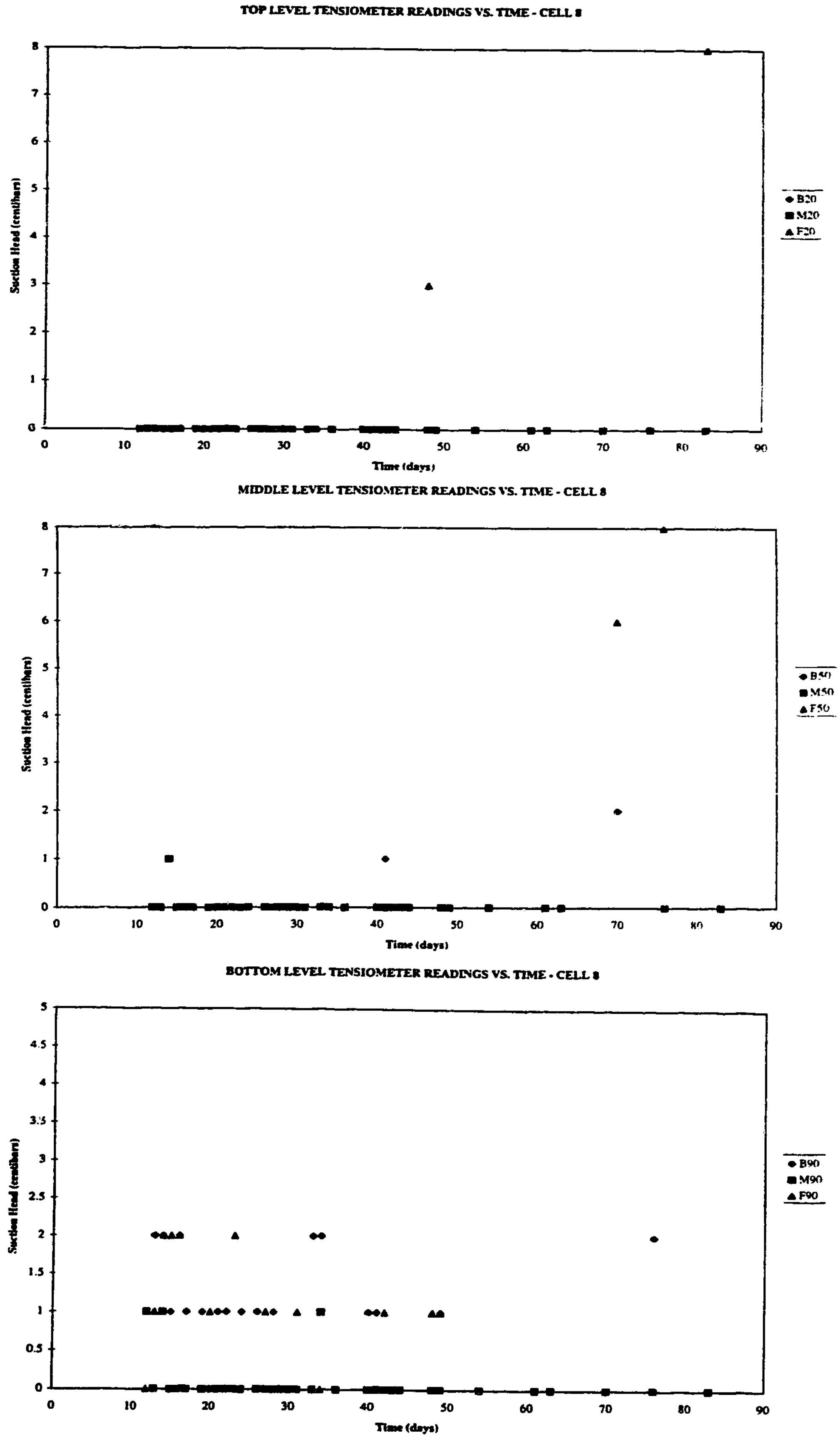


Figure 4.26: Tensiometer Readings for Cell 7 - High Infiltration Intensity, Low Compaction ((a) top level, (b) middle level, (c) bottom level)



Legend Shows Tensiometer Location
B = Back, M = Middle, F = Front
number indicates approximate tensiometer depth in cm

Figure 4.27: Tensiometer Readings for Cell 6 - High Infiltration Intensity, High Compaction ((a) top level, (b) middle level, (c) bottom level)



Legend Shows Tensiometer Location
B = Back, M = Middle, F = Front
number indicates approximate tensiometer depth in cm

Figure 4.28: Tensiometer Readings for Cell 8 - High Infiltration Intensity, High Compaction ((a) top level, (b) middle level, (c) bottom level)

The tensiometer data for the high infiltration intensity, low compaction cells (cells 5 and 7) is shown in Figures 4.25 and 4.26. More similarities may be found between these cells than between replicate low infiltration intensity cases. For cell 5 water addition ceased on day 28. At all levels, especially the top and bottom levels, numerous non-zero readings occur during the period of water addition. In fact, few simultaneous zero readings for tensiometers on the same level occur. This indicates that the moisture front is not uniform. The tensiometer data of cell 5, therefore, is a good illustration of the effects of channeling on moisture movement through MSW with respect to the capillary pressure of the waste column.

Water addition for cell 7 was also discontinued on day 28. The middle level tensiometer data show numerous non-zero readings during moisture loading, with simultaneous non-zero readings occurring. However, few non-zero readings are shown in the other two levels. Therefore, the data of the middle level, shows a non-uniform moisture front, however, it is more difficult to determine this from the data at the other levels.

The tensiometer data for high infiltration intensity, high compaction cells (cell 6 and 8) are shown in Figures 4.27 and 4.28. As the figures highlight, the behavior of the tensiometers of these cells is similar. First, cell 6 was loaded with moisture for 16 days, with water addition being discontinued on day 28. Only the bottom level tensiometers show consistent non-zero readings during water addition, with few occasions of simultaneous zero readings. Again, this data shows the wetting front is non-uniform, and indicates that channeling may occur.

Moisture loading for cell 8 also ceased on day 28. The tensiometer data of cell 8 shows that numerous non-zero readings occur at the bottom level. Again, there are few occasions during moisture loading where all tensiometers read zero simultaneously. As with cell 6 this indicates a non-uniform wetting front and suggests that channeling may occur.

The examination of the tensiometer data shows that the moisture front moving through the cells is non-uniform. This indicates that the waste cannot be considered homogeneous, and flow through channels may occur. Again, channeled flow cannot be confirmed with this data because it gives an indirect measure of channeled flow (section 3.1.3). In addition to the graphs, statistical tests of tensiometer data indicate that the moisture front is non uniform and channeling may take place in pilot scale cells. The number of days in which tensiometers read non-zero capillary pressures are compared with the total number of days that all read zero to determine if the moisture front is non uniform. If the number of days is not significantly different (see section 3.1.3 for significance criteria), the null hypothesis, that moisture flows uniformly through the waste can be rejected. Table 4.4 shows the number of significant cases listed by level. The number of cases is equal to the number of cells, except where tensiometers on a level in one cell all equaled zero, or all equaled non-zero. These cases were not included in the analysis.

Table 4.4: Summary Statistics of Tensiometer Data

Cases are significant if the total number of days when some tensiometers at the same level read non-zero is significantly greater than the number of days where all tensiometers at the same level read zero

Cases are significant at the 95% level, evaluated using a one sided t-test

CONDITION	NUMBER OF SIGNIFICANT CASES BY TENSIOMETER LEVEL			TOTAL NUMBER SIGNIFICANT	PERCENT SIGNIFICANT
	TOP	MIDDLE	BOTTOM		
Low Intensity Low Compaction (Cells 1 and 3)	2 of 2	2 of 2	1 of 2	5 of 6	83%
Low Intensity High Compaction (Cells 2 and 4)	0 of 2	1 of 2	1 of 2	2 of 6	33%
High Intensity Low Compaction (Cells 5 and 7)	1 of 1	1 of 1	1 of 2	3 of 4	75%
High Intensity High Compaction (Cells 6 and 8)	1 of 1	1 of 1	0 of 1	2 of 3	67%
Low Intensity (Cells 1,3,2, and 4)	2 of 4	3 of 4	2 of 4	7 of 12	58%
High Intensity (Cells 5,7,6, and 8)	2 of 2	2 of 2	1 of 3	5 of 7	71%
Low Compaction (Cells 1,3,5, and 7)	3 of 3	3 of 3	2 of 4	8 of 10	80%
High Compaction (Cells 2,4,6, and 8)	1 of 3	2 of 3	1 of 3	4 of 9	44%

In approximately 63% of the cases, shown above, the null hypothesis can be rejected. Therefore, in more than half of the cases statistical tests show that moisture moves non-uniformly through the waste. This is consistent with the heterogeneous composition of MSW discussed in the literature review (section 2.2.2). As mentioned, a non-uniform moisture front shows that waste is heterogeneous, and it may also indicate that channeling occurs, because channeled flow also results in a non-uniform moisture front through the waste. The table also shows that more non-zero cases occur in high infiltration intensity and low compaction cells, which would suggest channeling may be more prevalent in these cells (cells 5 and 7). This is consistent with the figures which show numerous tensiometers reading non-zero for the duration of water addition, specifically for cells 5 and 7 (also cells 1 and 3). This also agrees with existing theory discussed in the literature review (section 2.1), which states that channeling is likely to occur with high intensity loading. The effect of compaction on moisture movement is shown in the table, as 80% of the cases in low compaction cells are significant. Once again this is consistent with theory as less densely compacted material should have larger pore spaces which could act as channels to convey flow. The statistical analysis, therefore, agrees well with both the experimental data shown in Figures 4.21 to 4.28, and shows that moisture moves non-uniformly through municipal solid waste. Flow-cup grid data is also used to examine moisture movement. The data and summary results of the statistical tests for the flow-cup data are presented in the following section.

4.1.3 Flow-Cup Grid Results

Flow-cup grid data is shown in Table 4.5. The average, and maximum number of flow-cups discharging during water addition is given in this table, as is the number discharging at steady state. Any volume of leachate collected in the flow-cup container is considered discharge.

Table 4.5: Percentage Number of Flow-Cups Discharging During Water Addition

CONDITION	CELL NUMBER	PERCENTAGE NUMBER OF FLOW-CUPS DISCHARGING		
		AVERAGE	MAXIMUM	EFFECTIVE STORAGE
Low Intensity Low Compaction	Cell 1	40	83	50
	Cell 3	12	83	50
Low Intensity High Compaction	Cell 2	31	67	67
	Cell 4	26	58	0
High Intensity Low Compaction	Cell 5	26	83	33
	Cell 6	12	50	8
High Intensity High Compaction	Cell 7	17	42	0
	Cell 8	11	42	8

This table shows that the average number of flow-cups discharging is less than 50% of the number of flow-cups in each cell. Also, the maximum number discharging for each cell is less than 100%, so at no time during water addition do all flow-cups discharge at the same time. This is also true at effective storage (steady state).

In addition to Table 4.5, statistical tests on flow-cup data also support the presence of channeling. The first channeling sub-hypothesis is tested using ANOVA to determine if more spatial variability exists in the discharge of each flow-cup in a cell than temporal variability. The summary statistics for this test are presented in Table 4.6.

Table 4.6: Number of Significant Cases from ANOVA Analysis (Sub-hypothesis A)

Cases are Significant if the variation in leachate discharge between flow-cups is greater than the variation in leachate discharge of each flow-cup over time (e.g., significant if spatial variation greater than temporal variation)

CONDITION	NUMBER OF SIGNIFICANT CASES	RANGE OF PROBABILITY ($P_{significant}$ = 5%)
Low Intensity Low Compaction (Cells 1 and 3)	2 of 2	< 1%
Low Intensity High Compaction (Cells 2 and 4)	2 of 2	< 1%
High Intensity Low Compaction (Cells 5 and 7)	2 of 2	2.5% to < 1%
High Intensity High Compaction (Cells 6 and 8)	1 of 2	12% to < 1%
Low Intensity (Cells 1,3,2 and 4)	4 of 4	< 1%
High Intensity (Cells 5,7, 6 and 8)	3 of 4	12% to < 1%
Low Compaction (Cells 1,3,5 and 7)	4 of 4	2.5% to < 1%
High Compaction (Cells 2,4,6, and 8)	3 of 4	12% to < 1%

Generally, the null hypothesis, that moisture moves uniformly through waste, can be rejected in seven of the eight cells. These results clearly indicate that moisture is not moving uniformly through the waste since the difference in discharge between flow-cups is greater than the difference in discharge over time of each flow-cup.

If moisture moved uniformly through the waste the spatial difference in leachate discharge would be less than the temporal discharge. This agrees well with the tensiometer data. Also, the table shows that the one non-significant case occurs under high infiltration intensity, high compaction conditions.

Though high compaction conditions would be expected to encourage more uniform moisture movement, high infiltration intensity should increase channeling, and therefore, lead to less uniform moisture movement. This unexpected result may be due to the nature of the testing method. The ANOVA analysis compares the temporal variance with the spatial variance. The value of the temporal variance depends on the range of leachate discharge volumes as well as the number of readings taken, with smaller values of variance resulting from more readings. The leachate discharge volumes were similar for each cell, typically ranging from 0 to 800 ml per flow-cup. However, the duration of water addition was different between high intensity and low intensity cells. Since the high intensity cells had shorter moisture loading periods, fewer readings were taken, so the temporal variance for these cells was larger than the temporal variance of the low intensity cells. The larger temporal variance was similar to the spatial variance, and as a result the difference between the two was non-significant. This is also shown by examining the range of probabilities listed in the table. The low intensity cases have much smaller probabilities than the high intensity cases. Again, this is a result of the analysis and should not be interpreted as more uniform moisture movement occurs in high infiltration intensity cells. Other than this occurrence, the results show that moisture movement through solid waste does not move as a uniform front. Therefore, channeling sub-hypothesis A is supported.

The second channeling sub-hypothesis was tested using a difference of means test similar to that used for tensiometer data (section 3.1.3). A summary of the statistical analysis is presented in Table 4.7. As mentioned, only cells with constant loading rate are analyzed using this test, so only high infiltration intensity cells are examined. Also, flow-cups which remained zero for the duration of the moisture loading period were not used in the analysis. The number of significant cases refers to the cases where the null hypothesis is rejected.

Table 4.7: Number of Significant Cases from Difference of Means Test (Sub-hypothesis B)
Cases are significant if flow-cup discharges do not significantly increase with time
Significance evaluated at the 95% level

CONDITION	CELL NUMBER	NUMBER OF SIGNIFICANT CASES	AVERAGE SIGNIFICANT (%)
High Intensity	Cell 5	10 of 12	83%
Low Compaction	Cell 7	5 of 6*	83%
High Intensity	Cell 6	5 of 6	83%
High Compaction	Cell 8	6 of 6	100%

Note: * Two out of 6 flow-cups discharge significantly less leachate over the duration of water addition

These results clearly show that micropore flow is not the only flow mechanism in the cells. Again, it should be noted that only high infiltration intensity cells are used in the analysis because the moisture loading rate of these cells did not vary with time. As a result the occurrence of channeling may be greater than would be expected if low intensity cells were used. The number of times the null hypothesis is rejected is similar for both high and low compaction cells, with a greater rejection rate occurring in the high compaction cells. This counters the literature which states that less channeling should occur in highly compacted waste (Schroeder et. al., 1994). However, the number of significant cases to the total number of cases is high for all cells so this is probably coincidental. The summary table (Table 4.7) clearly show that channeling is a dominant mechanism in the pilot scale cells, and therefore, channeling sub-hypothesis B is supported by this analysis.

The flow-cup data and summary tables presented above, support each of the channeling sub-hypotheses, and thus, the main hypothesis that channeling occurs in pilot scale cells. The tensiometer results also support the channeling hypothesis. Therefore, it can be confidently stated that channeling occurs and is a significant mechanism in the pilot scale experimental cells. With the first hypothesis proven the environmental and operational condition hypotheses may be examined. This discussion is presented in the following section.

4.1.4 Factorial Analysis of Environmental and Operational Condition Hypotheses

The environmental and operational condition hypotheses (hypotheses 2, 3 and 4) states that infiltration intensity, compaction, and waste density affect practical field capacity, effective storage, breakthrough time, time to steady state, and initial and ultimate hydraulic conductivity at the conditions tested. The statistics for the analysis are shown in Table 4.8 through Table 4.10.

Table 4.8: Table of Main Effects and Probability of Infiltration Intensity, Compaction, and Waste Density on Moisture Movement Variables

($P_{significant}$ = 5.0%)

Significant Cases Underlined

VARIABLE	INFILTRATION INTENSITY		COMPACTION		WASTE DENSITY	
	Main Effect	P (%)	Main Effect	P (%)	Main Effect	P (%)
Practical Field Capacity (v/v) st.dev.= 0.0103	-0.0040	76%	0.0211	16%	0.0816	<u>0.2%</u>
Effective Storage (v/v) st.dev.= 0.0381	-0.1403	<u>2.5%</u>	0.0668	17%	0.2233	<u>0.4%</u>
Water added to reach Practical Field Capacity (L) st.dev.= 4.9	-8	18%	8	18%	32	<u>0.3%</u>
Water added to reach Effective Storage (L) st.dev.= 40.5	-123	<u>3.9%</u>	199	<u>0.8%</u>	667	<u>≤ 0.1%</u>
Breakthrough Time (minutes) st.dev.= 802	-2475	<u>3.8%</u>	458	61%	1773	9.1%
Time to Effective Storage (days) st.dev.= 11.8	-57.5	<u>0.8%</u>	14.8	35%	50.8	<u>1.5%</u>
Initial unsaturated hydraulic conductivity (cm/s) st.dev.= 0.0141	0.0628	<u>1.6%</u>	-0.0094	55%	-0.0364	7.8%
Ultimate unsaturated hydraulic conductivity (cm/s) st.dev.= 1.1E-6	1.9E-5	<u>≤ 0.01%</u>	-5.3E-7	70%	-2.1E-6	16%

Table 4.9: Table of Interactions and Probability for Infiltration Intensity-Compaction, and Infiltration Intensity-Waste Density on Moisture Movement Variables

($P_{significant}$ = 5.0%)

Significant Cases Underlined

VARIABLE	INFILTRATION INTENSITY - COMPACTION INTERACTION		INFILTRATION INTENSITY - DENSITY INTERACTION	
	Interaction	P (%)	Interaction	P (%)
Practical Field Capacity (v/v) st.dev.= 0.0103	-0.0013	80%	-0.0091	80%
Effective Storage (v/v) st.dev.= 0.0381	0.0758	16%	0.2474	<u>0.3%</u>
Water added to reach Practical Field Capacity (L) st.dev.= 4.9	-9	16%	-38	<u>0.2%</u>
Water added to reach Effective Storage (L) st.dev.= 40.5	232	<u>0.4%</u>	781	<u>≤ 0.1%</u>
Breakthrough Time (minutes) st.dev.= 802	-416	60%	-1743	9.6%
Time to Effective Storage (days) st.dev.= 11.8	20.7	17%	81.5	<u>0.3%</u>
Initial unsaturated hydraulic conductivity (cm/s) st.dev.= 0.0141	0.0032	80%	0.0146	32%
Ultimate unsaturated hydraulic conductivity (cm/s) st.dev.= 1.1E-6	-1.5E-6	29%	-8.1E-6	<u>0.3%</u>

Table 4.10: Summary Table of Significance of Main Effects on Moisture Movement Variables

VARIABLE	INTENSITY	COMPACTION	DENSITY	INTENSITY - COMPACTION INTERACTION	INTENSITY - DENSITY INTERACTION
Practical Field Capacity	Not Significant	Not Significant	Significant	Not Significant	Not Significant
Effective Storage	Significant	Not Significant	Significant	Not Significant	Significant
Water added to reach Practical Field Capacity	Not Significant	Not Significant	Significant	Not Significant	Significant
Water added to reach Effective Storage	Significant	Significant	Significant	Significant	Significant
Breakthrough Time	Significant	Not Significant	Not Significant	Not Significant	Not Significant
Time to Effective Storage	Significant	Not Significant	Significant	Not Significant	Significant
Initial unsaturated hydraulic conductivity	Significant	Not Significant	Not Significant	Not Significant	Not Significant
Ultimate unsaturated hydraulic conductivity	Significant	Not Significant	Not Significant	Not Significant	Significant

This summary shows that in this analysis infiltration intensity had a significant effect on effective storage, water added to reach effective storage, breakthrough time, time to reach steady state, and initial and unsaturated hydraulic conductivity. This is also reflected in the discrete loading figures (Figures 4.5 to 4.12). Low intensity cells 1 through 4 reach effective storage, much later than the high intensity cells. Also, more water has to be added to these cells to reach effective storage, than the high intensity cells (this can also be seen in the cumulative discharge Figures 4.13 to 4.20). Since more water is added, and because there is a similar total volume in the high intensity and low intensity cells, the low intensity cells have a higher effective storage moisture content. The breakthrough time is also affected significantly by the intensity. Since channeling has been shown to occur more often and to a greater extent in high intensity cells this result is not surprising. By examining the discrete loading figures the effect of intensity on breakthrough time is also apparent. Low intensity cells 2 and 3 take three and two days respectively to reach breakthrough. The breakthrough time of the other cells is in the order of minutes (15 to 20 minutes for all other cells). This shows that intensity has a significant effect on breakthrough time. Also, initial unsaturated hydraulic conductivity is significantly affected by intensity. Recall that this variable depends on the breakthrough of moisture movement through the waste, with larger breakthrough times resulting in smaller conductivities. Since channeling occurs more in higher intensity cells, breakthrough times are smaller, and initial hydraulic conductivities are greater for high intensity cells. Ultimate unsaturated hydraulic conductivity is dependent on the flow rate through the waste at steady state. Since more channeling occurs in high intensity cells the flow rate through the waste in these cells is greater than through low intensity cells. This is also shown by the moisture movement figures, as the discharge of the high intensity cells is greater than that of the low intensity cells.

The results in Table 4.8 show that compaction has an effect only on the water added to reach effective storage. This is evident by examining the moisture movement figures, in particular, the high infiltration intensity cells (Figures 4.17 to 4.20). The compacted cells (6 and 8) reach effective storage later than the uncompacted cells (5 and 7). Therefore, more water is added to these cells. This is more difficult to observe in the low intensity cells because of the variation in the loading rates and the difference in the time to reach effective storage between replicates. This is consistent with theory, as compaction acts to increase the volume of waste exposed to moisture by opening plastic bags and by flattening particles. Therefore, more water would have to be added to reach effective storage. This implies that compaction should also have a significant effect on the effective storage moisture content. The results in Table 4.8 show that while compaction acts to increase the effective storage moisture content of the waste (the main effect is positive) it is not statistically significant in this analysis.

Table 4.8 shows that density significantly affects practical field capacity, effective storage, water added to reach practical field capacity, water added to reach effective storage, and time to reach effective storage. This agrees with the moisture movement data presented in the figures since a difference in the variables listed above is noticeable between high and low density cells. The density of the waste in the high compaction cells was increased both by compaction and by adding more waste. Therefore, the capacity to store water was greater in these cells because they had more waste. Therefore more water was added to reach the practical field capacity and effective storage moisture contents. The results of the compaction analysis show that the actual ripping of bags and flattening of particles caused by the compaction process had little significant effect on the moisture movement variables. However, the increase in density caused by the addition of more waste is significant on the parameters listed above.

The interaction of infiltration intensity and compaction is significant only for water added to reach effective storage. This is consistent with the previous results because both the main effects of intensity and compaction significantly affect this variable. Theory also supports this result because low infiltration intensity (less channeling) coupled with highly compacted waste (more pore volume exposed to moisture, flatter particles) should require more water added before effective storage is reached.

Unlike the interaction of infiltration intensity and compaction, the intensity-density interaction significantly affects a number of variables. Effective storage is significantly affected by the interaction, as is water added to reach effective storage. This can also be seen in the figures, as less water is added to reach effective storage in high intensity, low compaction cells than low intensity, high compaction cells. The same is true for water added to reach practical field capacity. Time to reach effective storage is also significantly affected by the interaction. Again this is evident from the moisture movement graphs. Ultimate unsaturated hydraulic conductivity is significantly affected by the intensity-density interaction, however, initial unsaturated hydraulic conductivity is not. This may be due to the change in density with time. The greater difference in density near the end of the test, combined with infiltration intensity may have had a greater affect on the flow rate at the end of the test, than on the flow at the beginning of the experiment. As a result the intensity-density interaction is only significant with respect to the ultimate unsaturated hydraulic conductivity.

The factorial analysis of the moisture movement data shows that infiltration intensity significantly affects the largest number of moisture movement variables examined. Waste density and the intensity density interaction also affect a number of the variables examined. Compaction, and the intensity-compaction interaction, only significantly affect the volume of water added to reach effective storage. This shows that the operational and environmental conditions tested do affect, to different degrees, moisture movement through municipal solid waste.

The experimental results for moisture movement, and channeling have been presented and discussed, and the hypotheses related to this data have been supported through the data analysis. The two final hypotheses are tested through the use of both moisture movement and modeling results. The modeling results and analysis, as well as the discussion and testing of the hypotheses is presented in the following section.

4.2 MOISTURE MOVEMENT MODELING RESULTS

The results and summary statistics from the HELP and PREFLO model simulations are presented in this section to evaluate the two modeling hypotheses (hypotheses 5 and 6).

4.2.1 HELP Model Results

In order to test the modeling hypothesis which states that simulating channeling allows for more accurate prediction of moisture movement than not considering channeling, HELP model simulations were conducted. The HELP default values were used as model input to neglect the effects of channeling (Table 4.11). It should be noted that the values of saturated hydraulic conductivity used in the channeling simulations are fitting parameters derived by using the Campbell equation (equation 6) and the values for initial unsaturated hydraulic conductivity and practical field capacity moisture content (Table 4.2). The saturated hydraulic conductivity values (denoted K_s') do not, therefore, have any physical significance, but are used as model input so the apparent hydraulic conductivity found in the experiment (K_{us} initial) will be used by HELP to determine the leachate flow rate (drainage modeled using equation 7, section 2.1.2).

No leachate discharge was predicted by the simulations which used HELP default input parameters. Graphical results for cell are shown in Figure 4.29 (figures for the other cells are not included because all graphs appear the same with no leachate discharged). This is due to the low initial moisture contents of the cells as well as the high default field capacity moisture content of the HELP model. Obviously, any simulations in which channeling is considered will lead to better prediction of moisture movement provided some leachate is generated.

The data for moisture movement simulations with experimentally derived input parameters are in much better agreement with experimental moisture movement than the results derived from HELP default parameters (Figures 4.30 to 4.37). Simulated discharge does not start with water addition, as is the case of measured discharge, instead a delay of a few days is experienced, particularly in the low infiltration intensity cells. However, unlike the measured leachate discharge the simulated discharge responds rapidly to the moisture loading, and after a short time period the simulated leachate is equal to the infiltration. This results in a greater than measured volume of leachate produced. The exception is the two high intensity, low compaction cells. The simulated discharge for these cells is less than the measured discharge. This is due mainly due to the lag between the start of precipitation and the start of the simulated leachate discharge. This lag is most likely due to the low initial moisture contents of these cells. More moisture must be added to these cells to reach field capacity and, therefore, the start of drainage. The additional moisture loading required delays the start of leachate discharge. Also, unlike the experimental cells, the simulations stop discharging leachate as soon as water addition has ended. This indicates that the simulated cells are at steady state with some moisture content above field capacity, and because of the large hydraulic conductivity, are able to drain to field capacity as soon as moisture loading stops. While the simulation results using experimentally derived input data are a significant improvement over the default data simulations, the input parameters can be "fine tuned" to get a more accurate prediction of moisture movement.

Table 4.11: Input Parameters for HELP Simulations

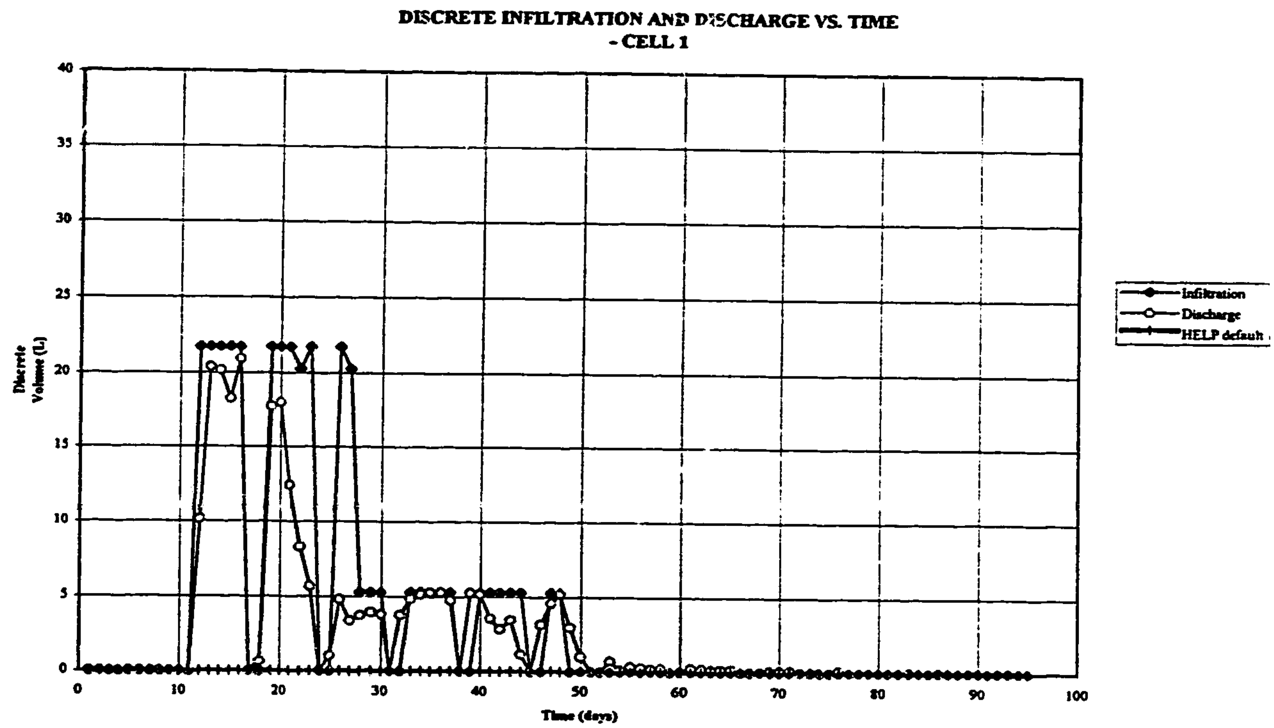
Input Parameter	Low Infiltration Intensity				High Infiltration Intensity			
	Low Compaction		High Compaction		Low Compaction		High Compaction	
	INPUT PARAMETERS COMMON TO ALL HELP SIMULATIONS							
	Cell 1	Cell 3	Cell 2	Cell 4	Cell 5	Cell 7	Cell 6	Cell 8
Layer Thickness (cm)	84	82	99	94	81	77	92	92
Initial Moisture Content (v/v)	0.077	0.091	0.114	0.111	0.083	0.077	0.108	0.117
	HELP DEFAULT VALUES FOR INPUT PARAMETERS							
Porosity (v/v)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Field Capacity (v/v)	0.292	0.292	0.292	0.292	0.292	0.292	0.292	0.292
Wilting Point (v/v)	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077
Saturated Hydraulic Conductivity K_s' (cm/s)	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3
	EXPERIMENTALLY DERIVED INPUT PARAMETERS (CALIBRATION)							
Porosity* (v/v)	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Field Capacity (v/v)	0.090	0.130	0.133	0.132	0.113	0.105	0.126	0.133
Wilting Point ** (v/v)	0.016	0.022	0.023	0.023	0.020	0.018	0.022	0.023
Saturated Hydraulic Conductivity ^ K_s' (cm/s)	5.2E+3	4.1E+1	2.2E+1	2.1E+2	1.0E+3	2.0E+3	4.2E+2	2.3E+2
	INPUT PARAMETERS OPTIMIZED THROUGH SENSITIVITY ANALYSIS							
Porosity (v/v)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Field Capacity (v/v)	0.136	0.195	0.199	0.198	0.097	0.089	0.189	0.200
Wilting Point ** (v/v)	0.024	0.034	0.035	0.034	0.017	0.015	0.033	0.035
Saturated Hydraulic Conductivity ^ K_s' (cm/s)	1.0E+5	8.2E+1	4.4E+1	4.2E+2	2.0E+3	4.0E+3	8.4E+2	4.6E+2

* previous experimental value from Zeiss and Uguccioni (1995)

** wilting point used to ensure a pore size distribution index of 0.65 (previous experimental value from Zeiss and Uguccioni, 1995)

^ obtained from backcalculating using the Brooks-Corey equation and experimental values of K_{us} initial and practical field capacity

Figure 4.29: Sample of Discrete and Cumulative Leachate Volume Predicted From Default HELP Simulations - Cell 1



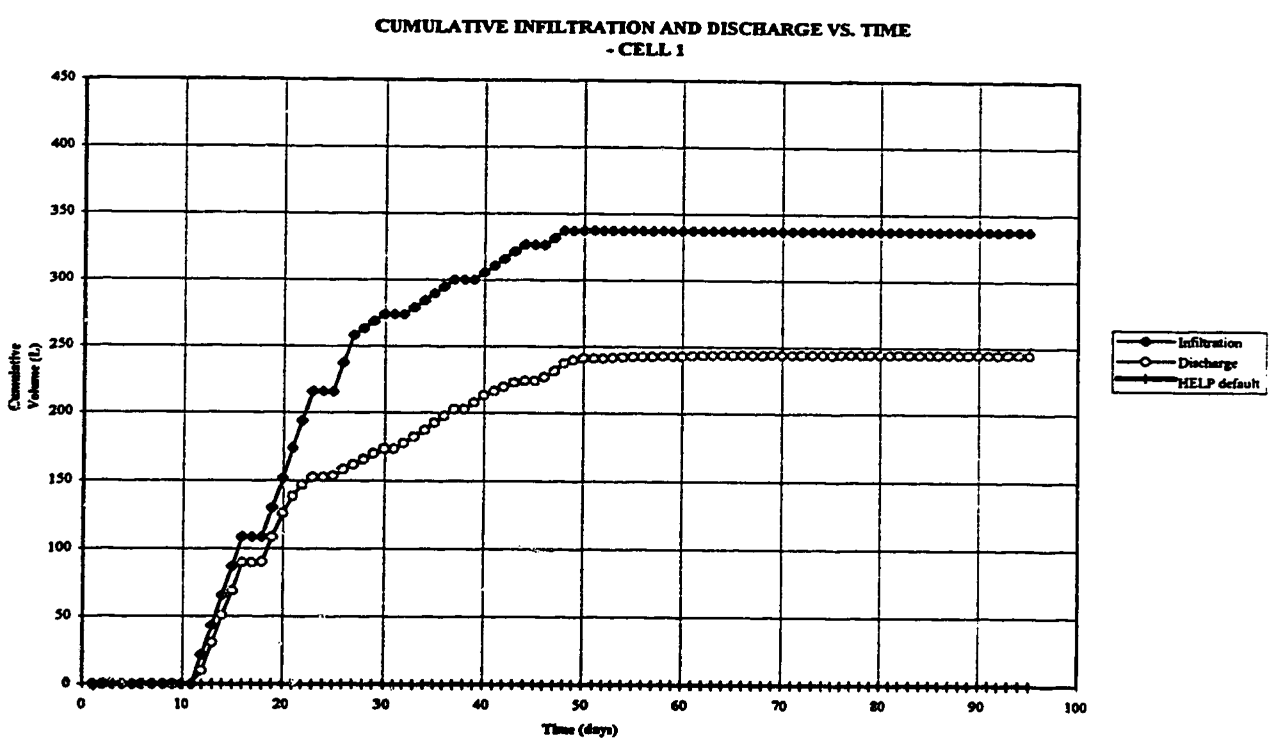
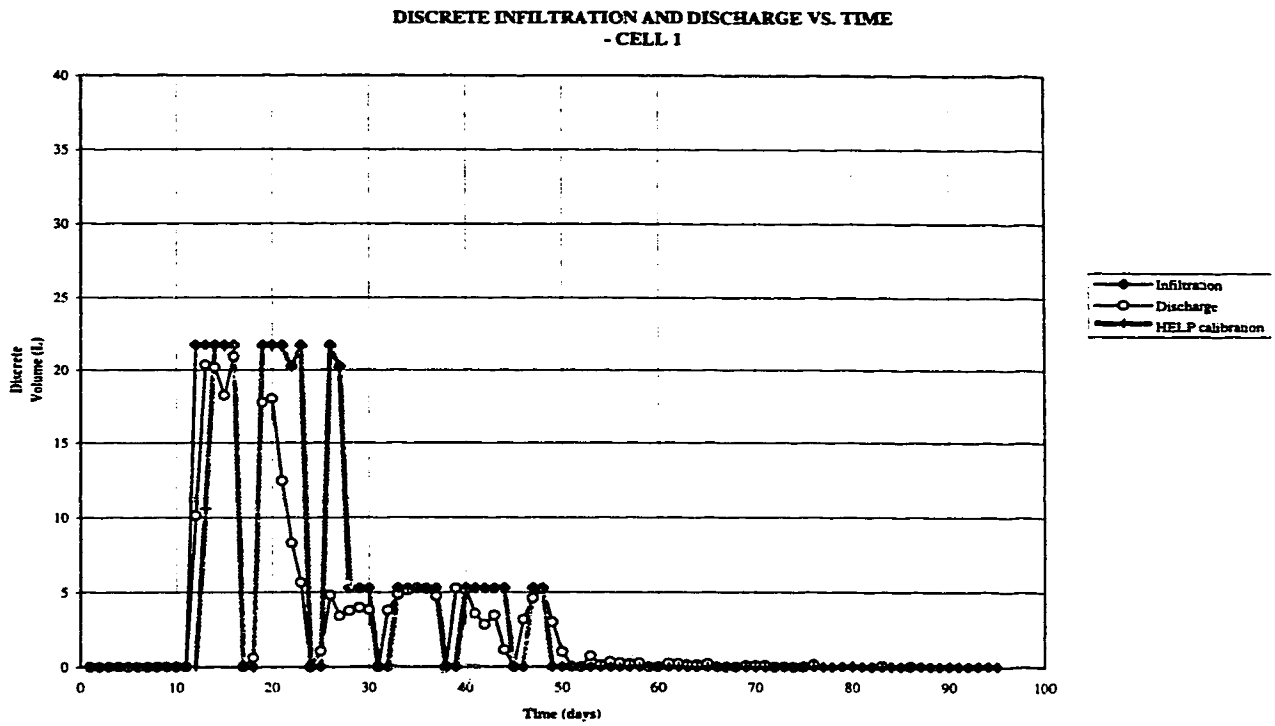


Figure 4.30: Discrete Leachate Volume Predicted From Calibrated HELP Simulations for Low Infiltration Intensity, Low Compaction Cells (Cells 1 and 3)



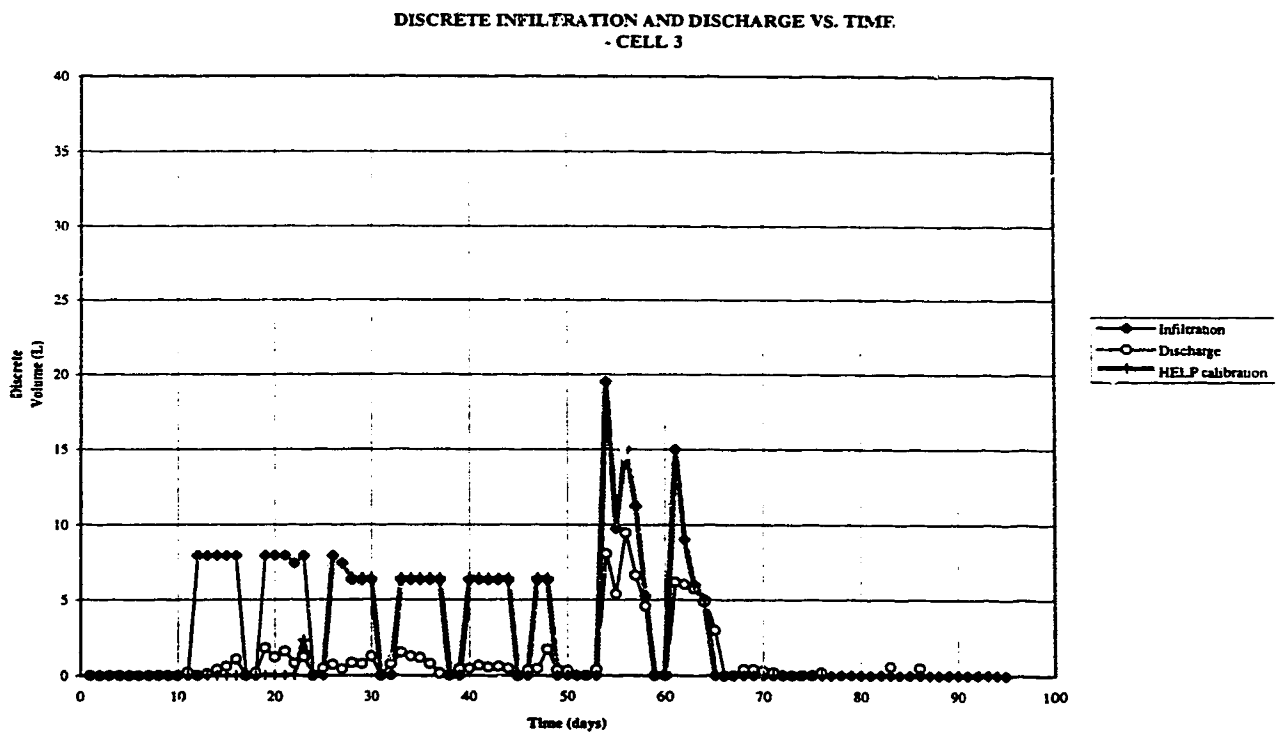
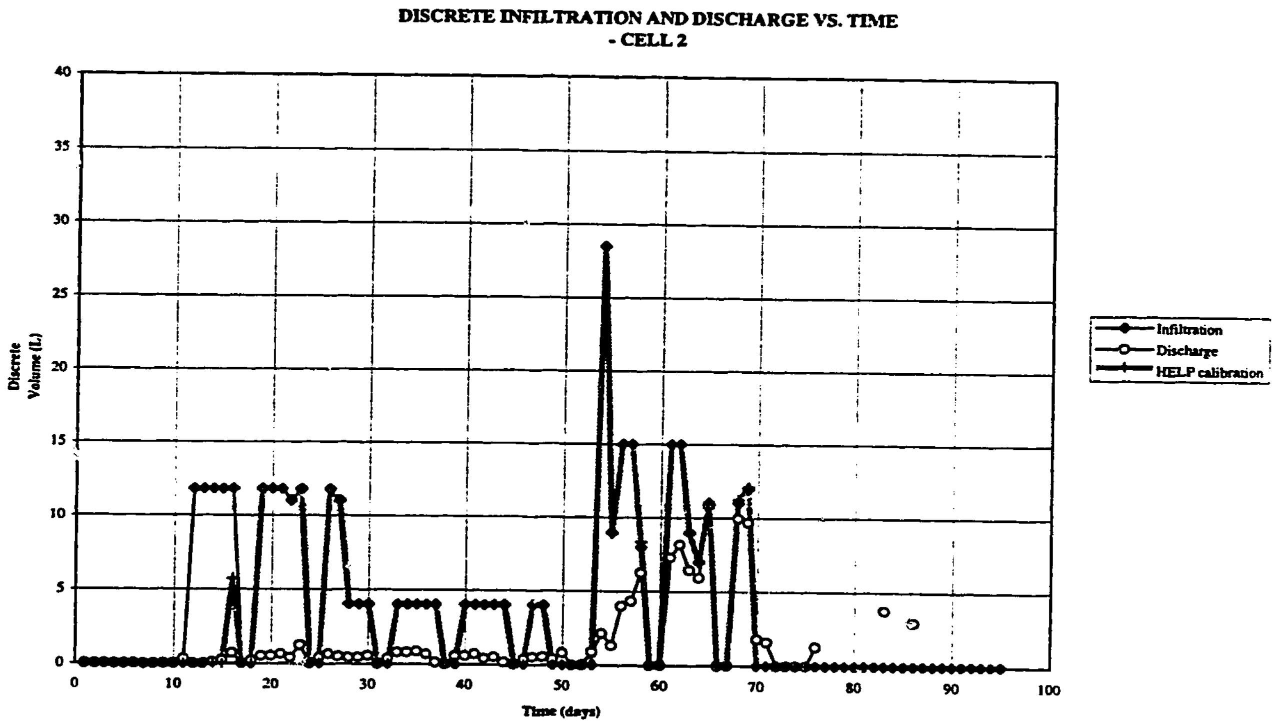


Figure 4.31: Discrete Leachate Volume Predicted From Calibrated HELP Simulations for Low Infiltration Intensity, High Compaction Cells (Cells 2 and 4)



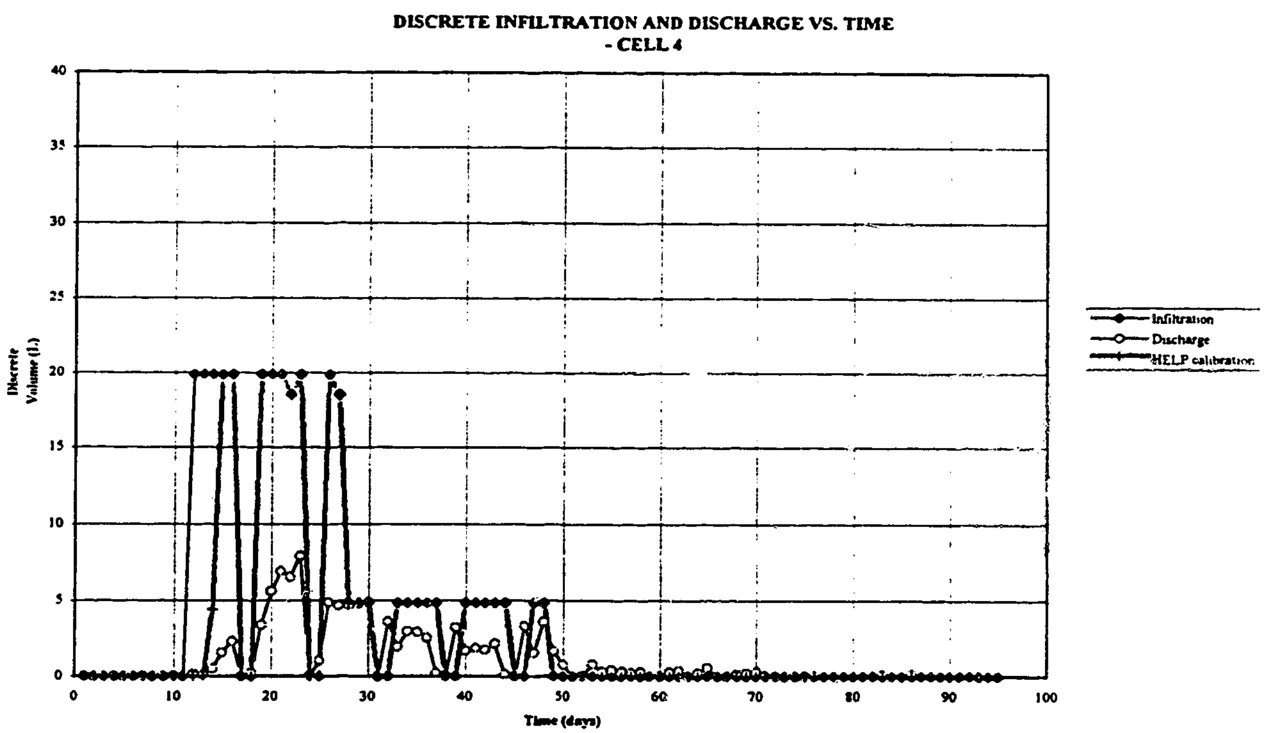
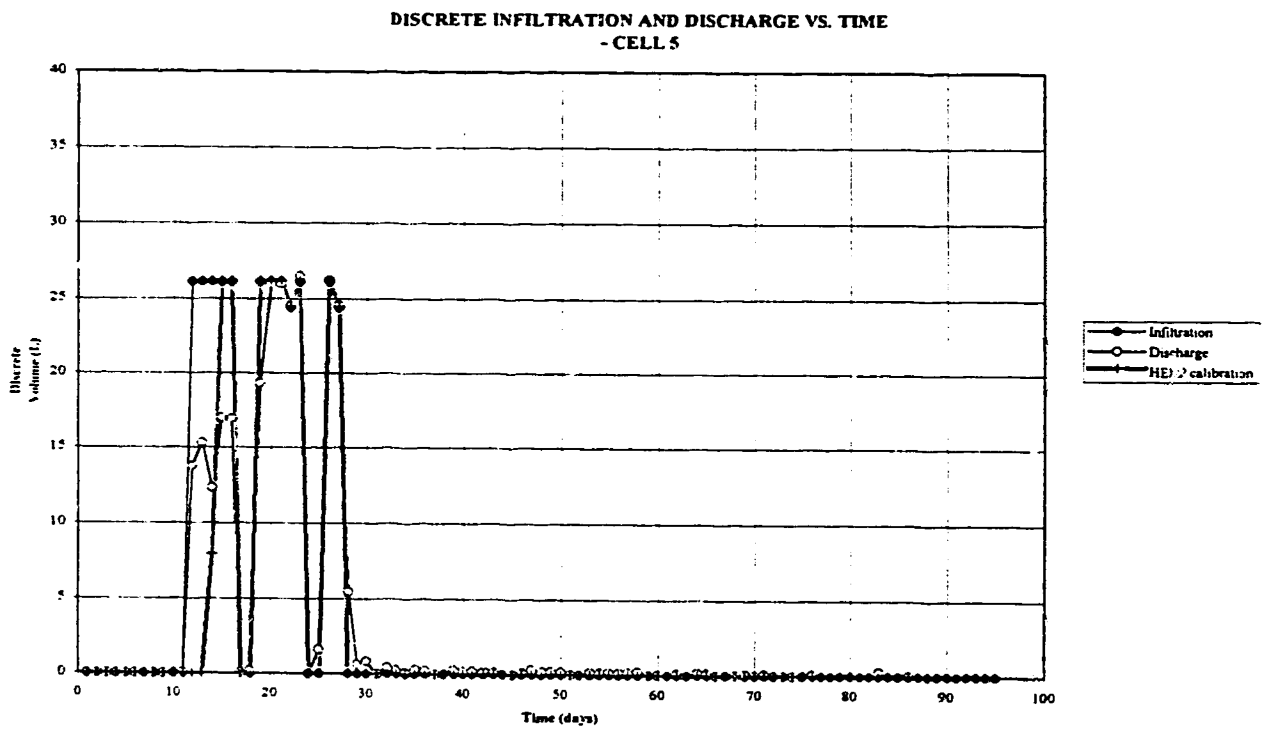


Figure 4.32: Discrete Leachate Volume Predicted From Calibrated HELP Simulations for High Infiltration Intensity, Low Compaction Cells (Cells 5 and 7)



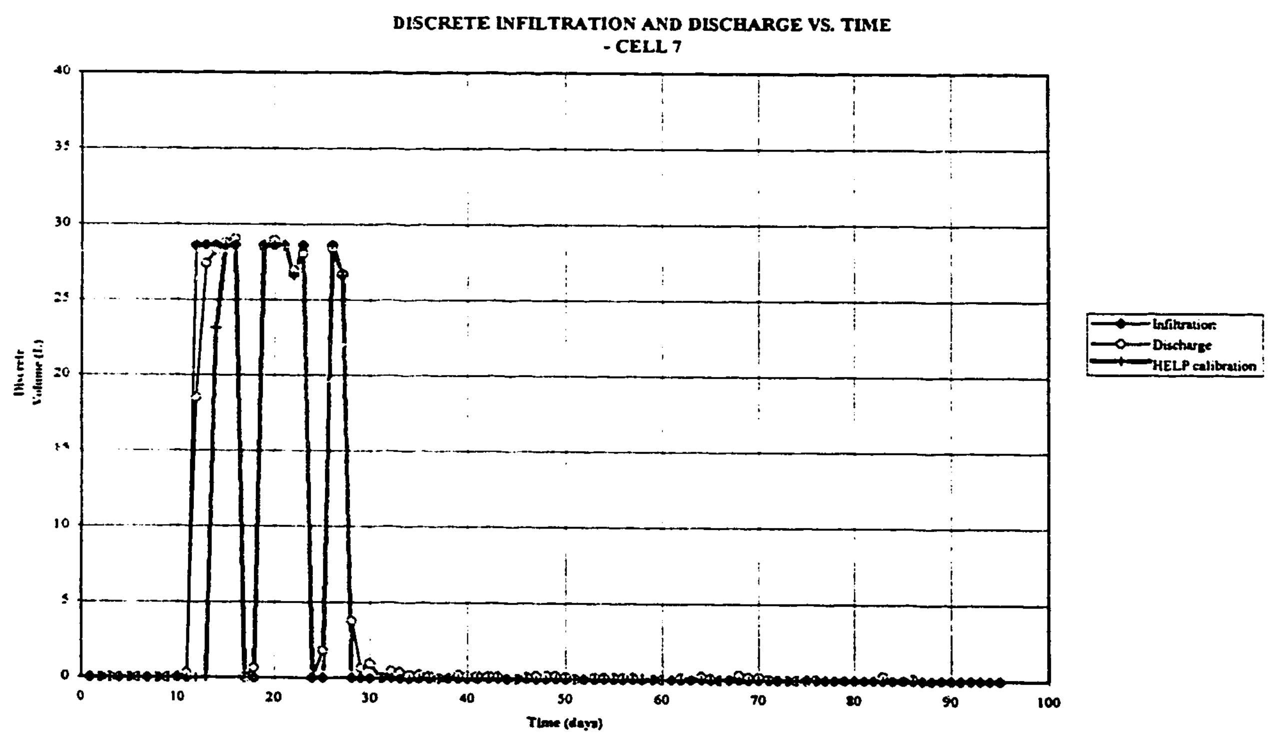
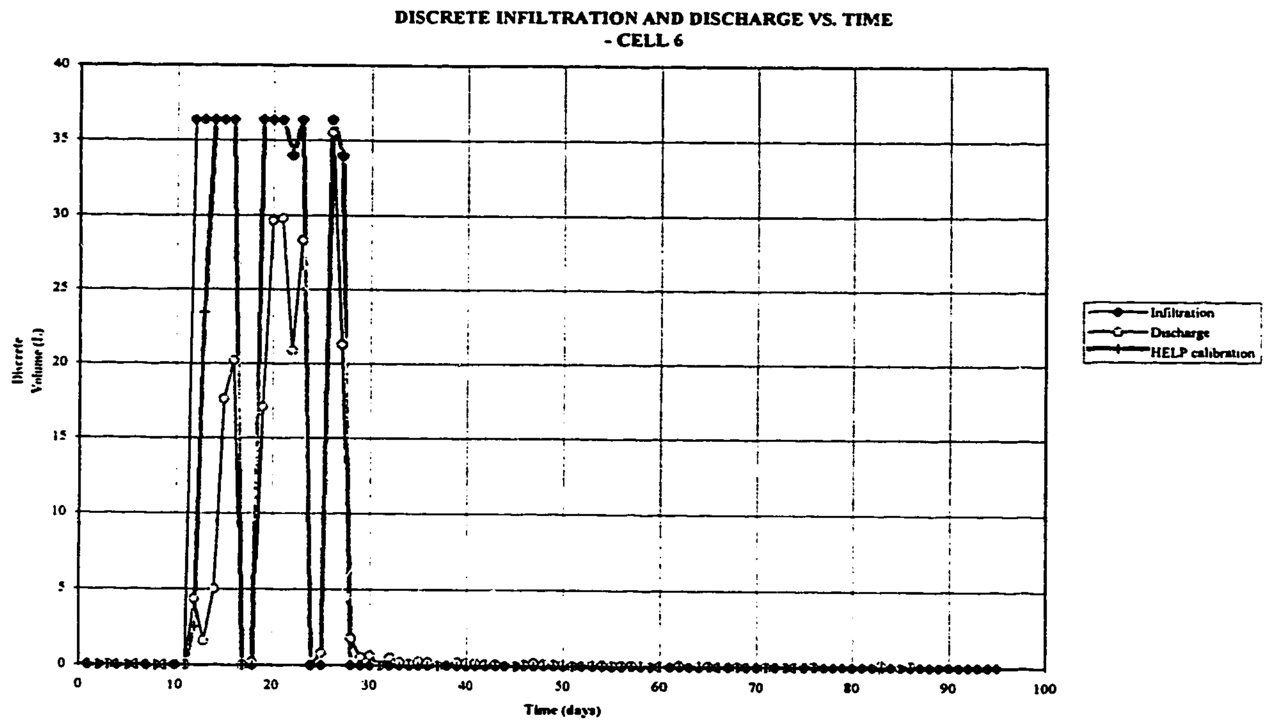


Figure 4.33: Discrete Leachate Volume Predicted From Calibrated HELP Simulations for High Infiltration Intensity, High Compaction Cells (Cells 6 and 8)



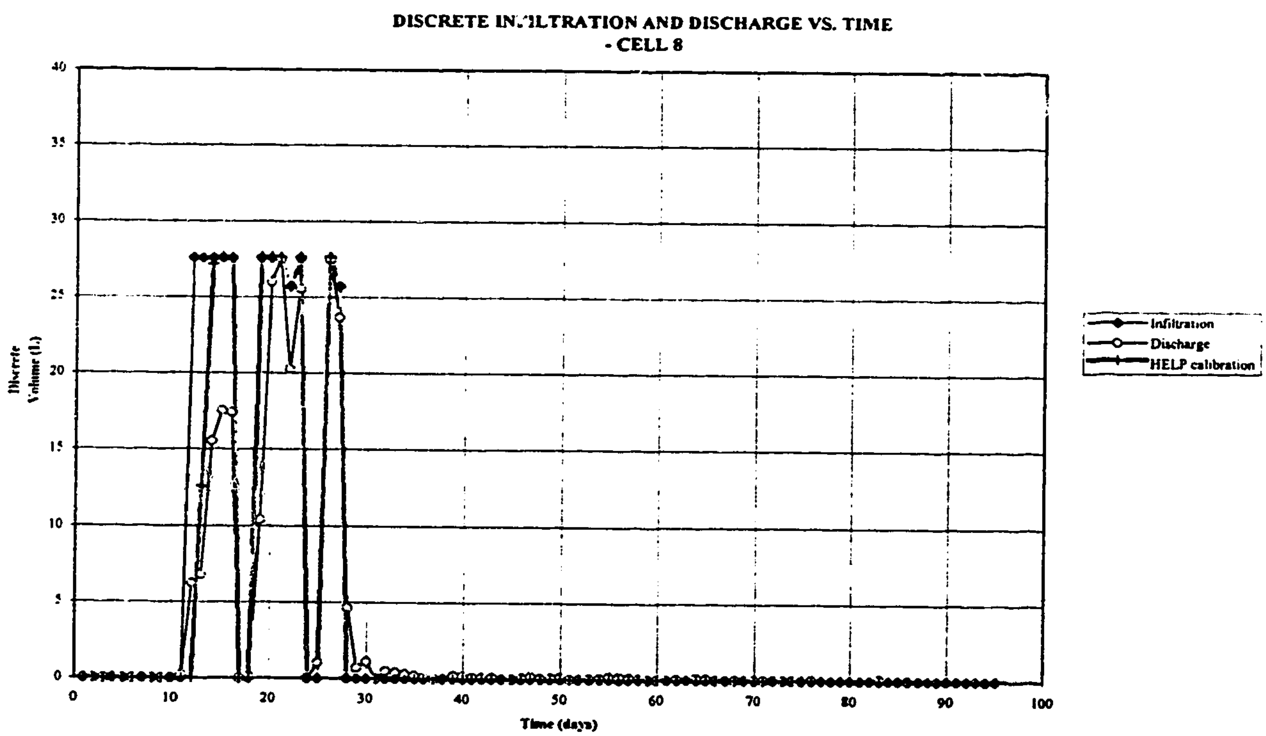
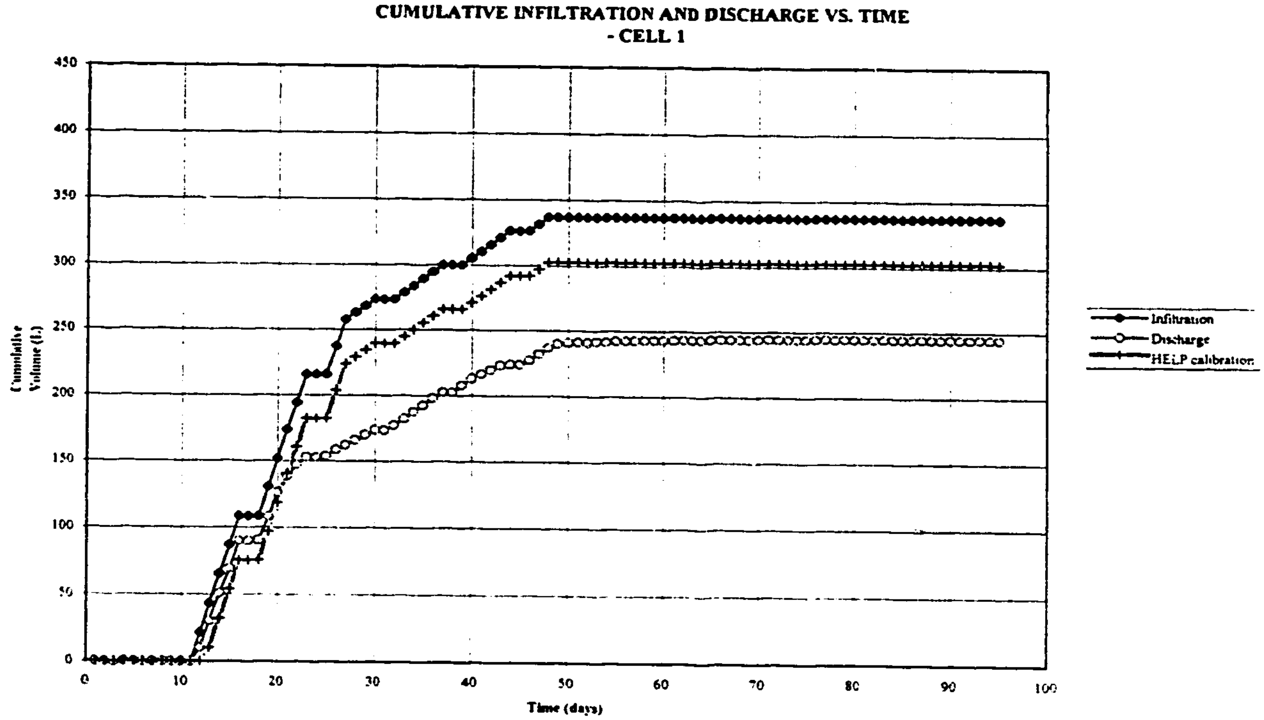


Figure 4.34: Cumulative Leachate Volume Predicted From Calibrated HELP Simulations for Low Infiltration Intensity, Low Compaction Cells (Cells 1 and 3)



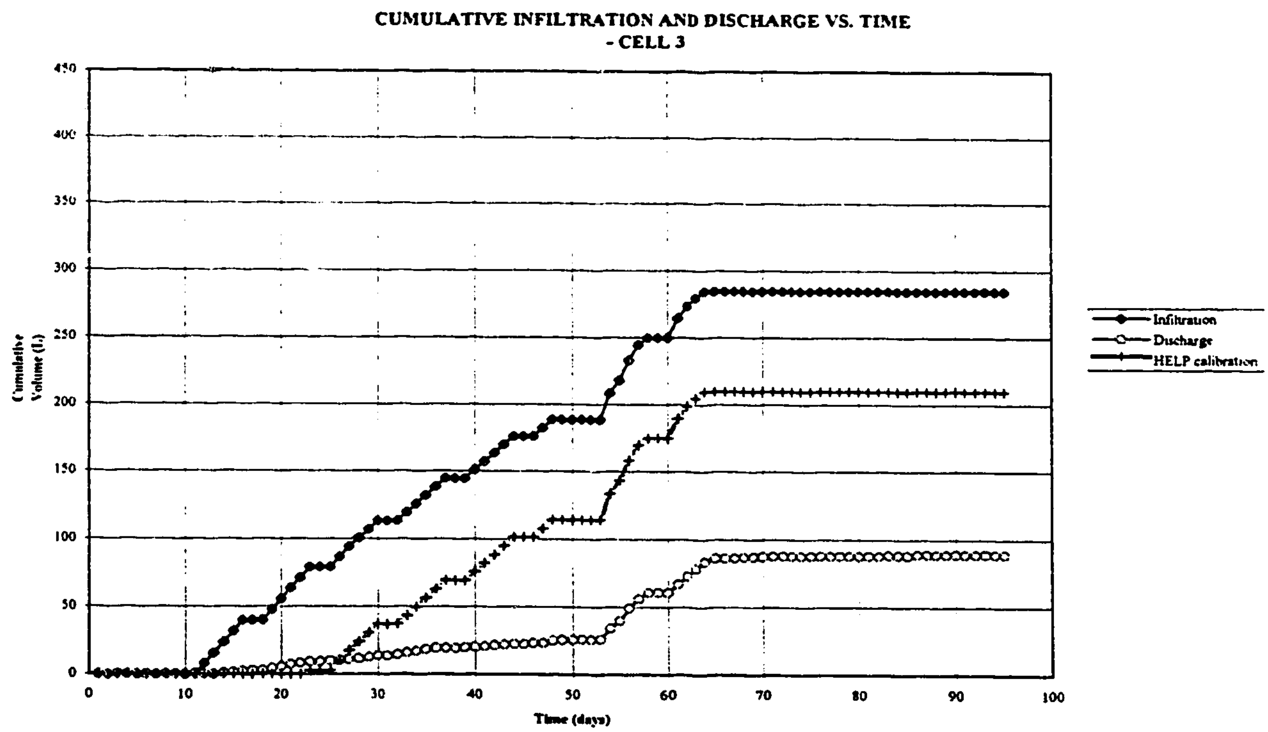
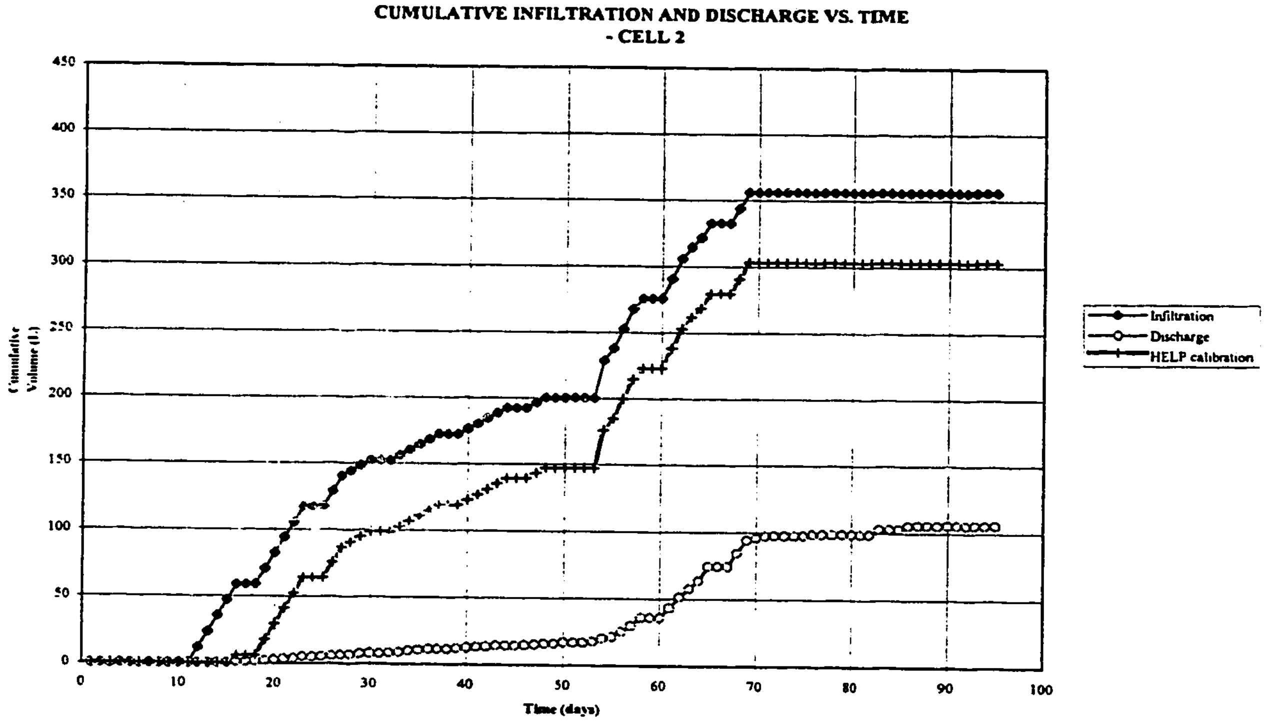


Figure 4.35: Cumulative Leachate Volume Predicted From Calibrated HELP Simulations for Low Infiltration Intensity, High Compaction Cells (Cells 2 and 4)



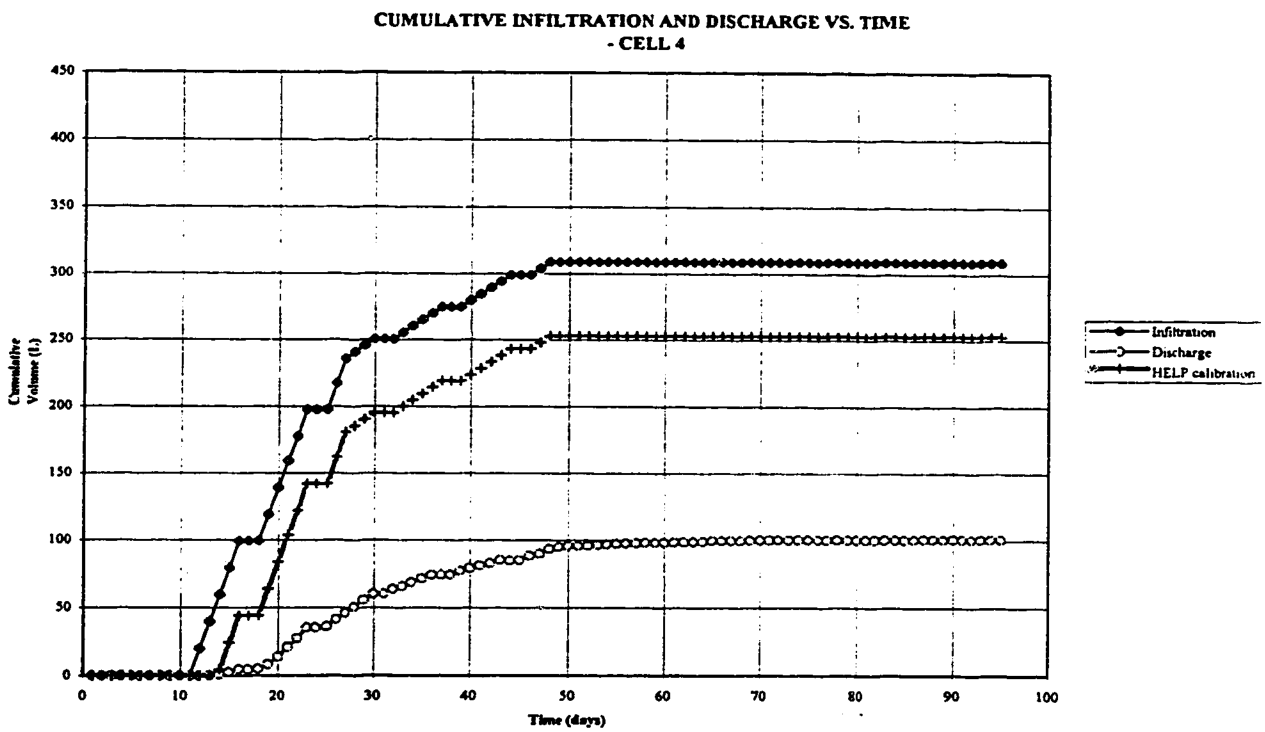
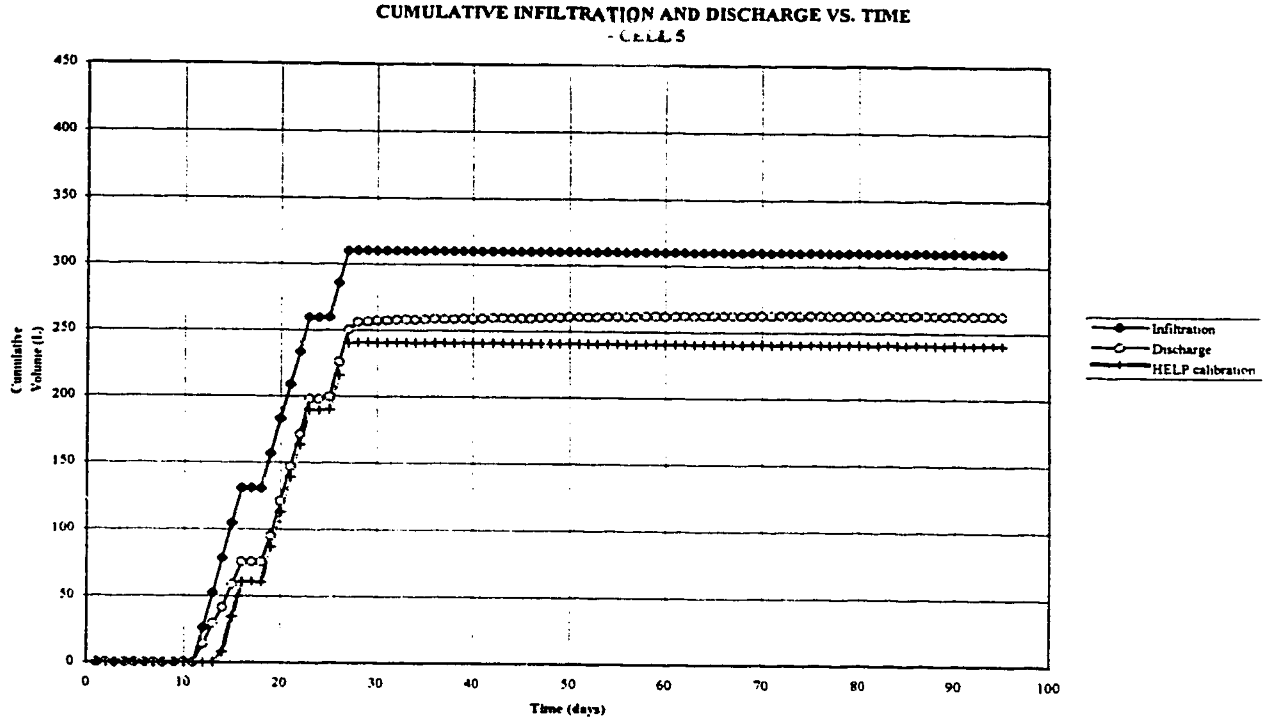


Figure 4.36: Cumulative Leachate Volume Predicted From Calibrated HELP Simulations for High Infiltration Intensity, Low Compaction Cells (Cells 5 and 7)



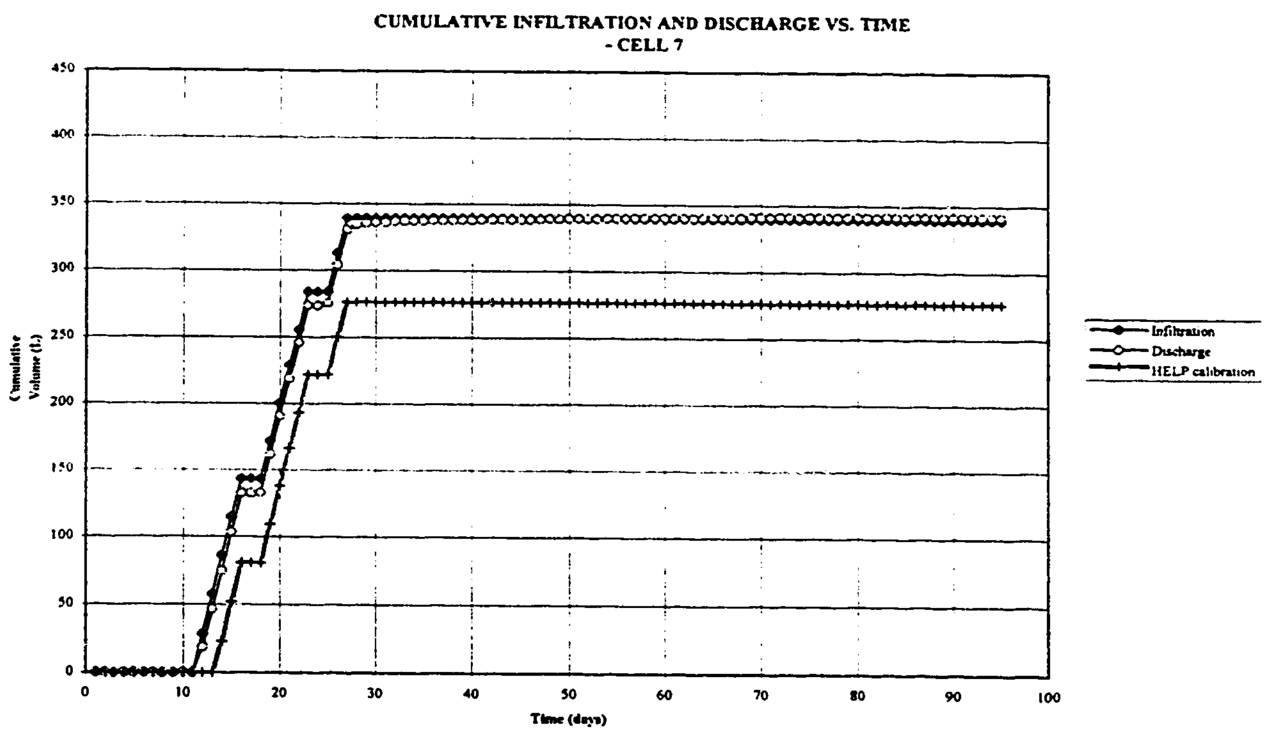
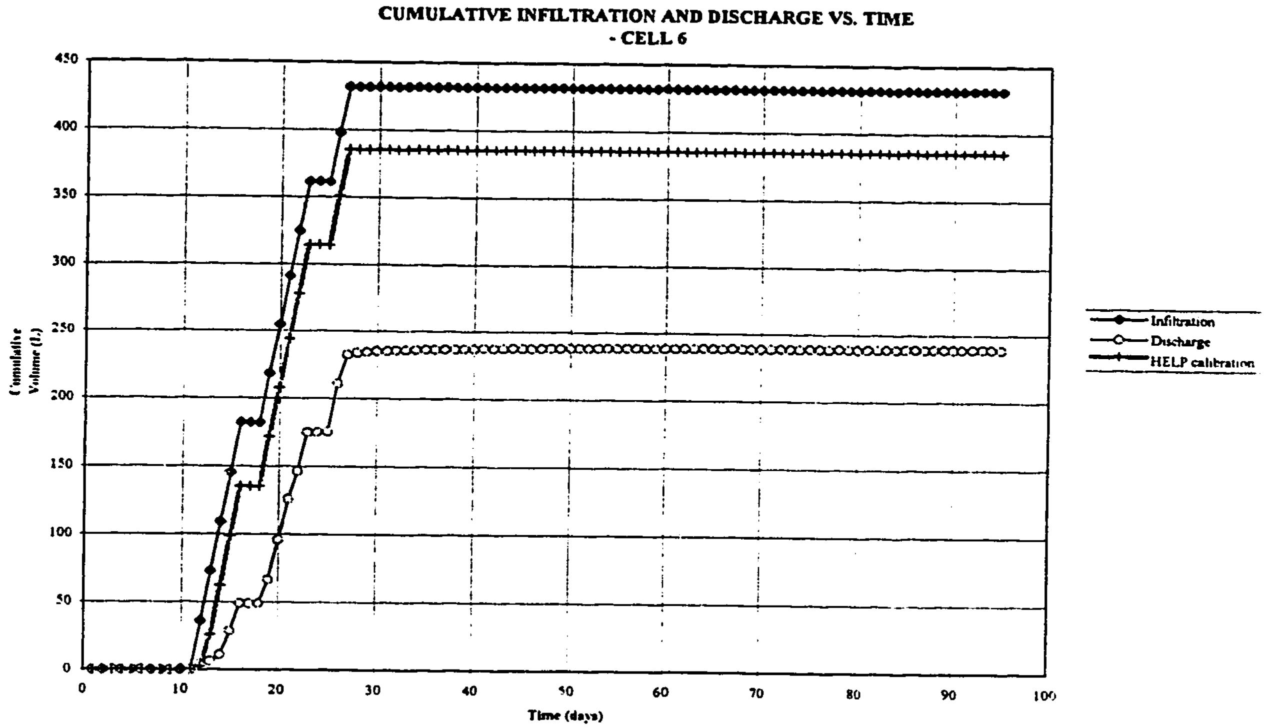
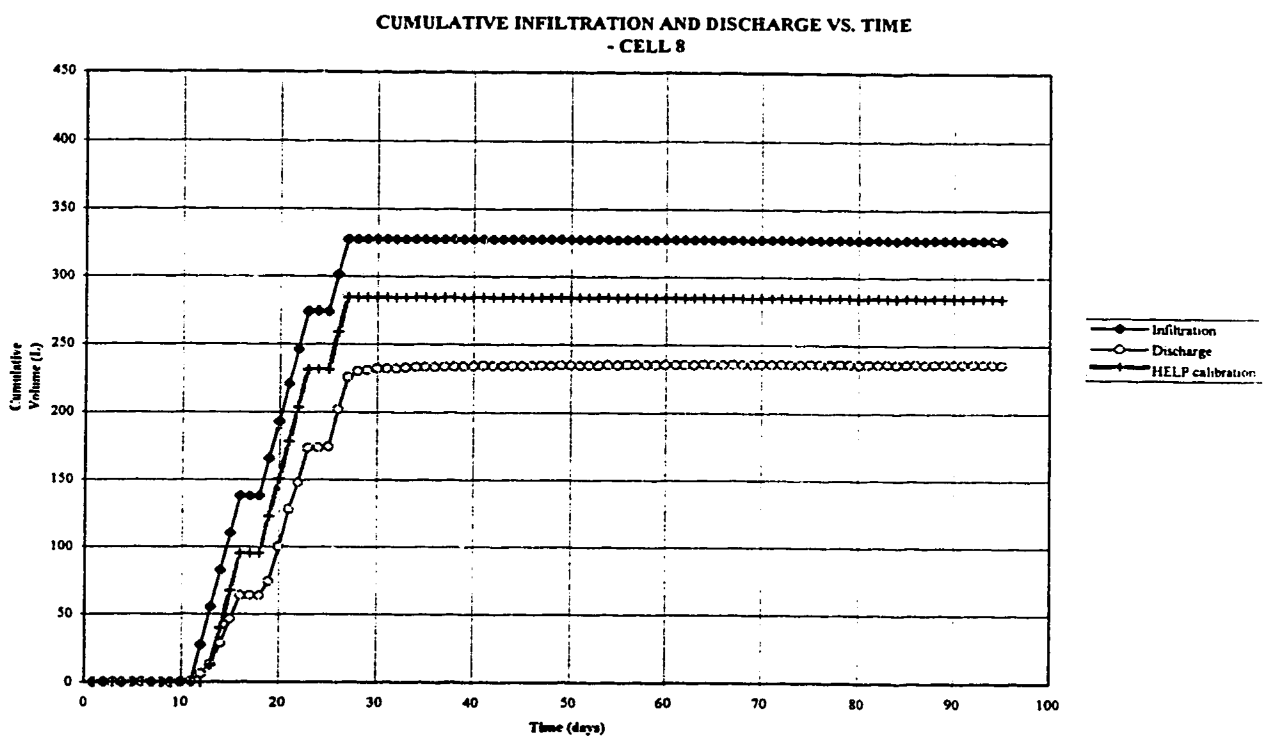


Figure 4.37: Cumulative Leachate Volume Predicted From Calibrated HELP Simulations for High Infiltration Intensity, High Compaction Cells (Cells 6 and 8)





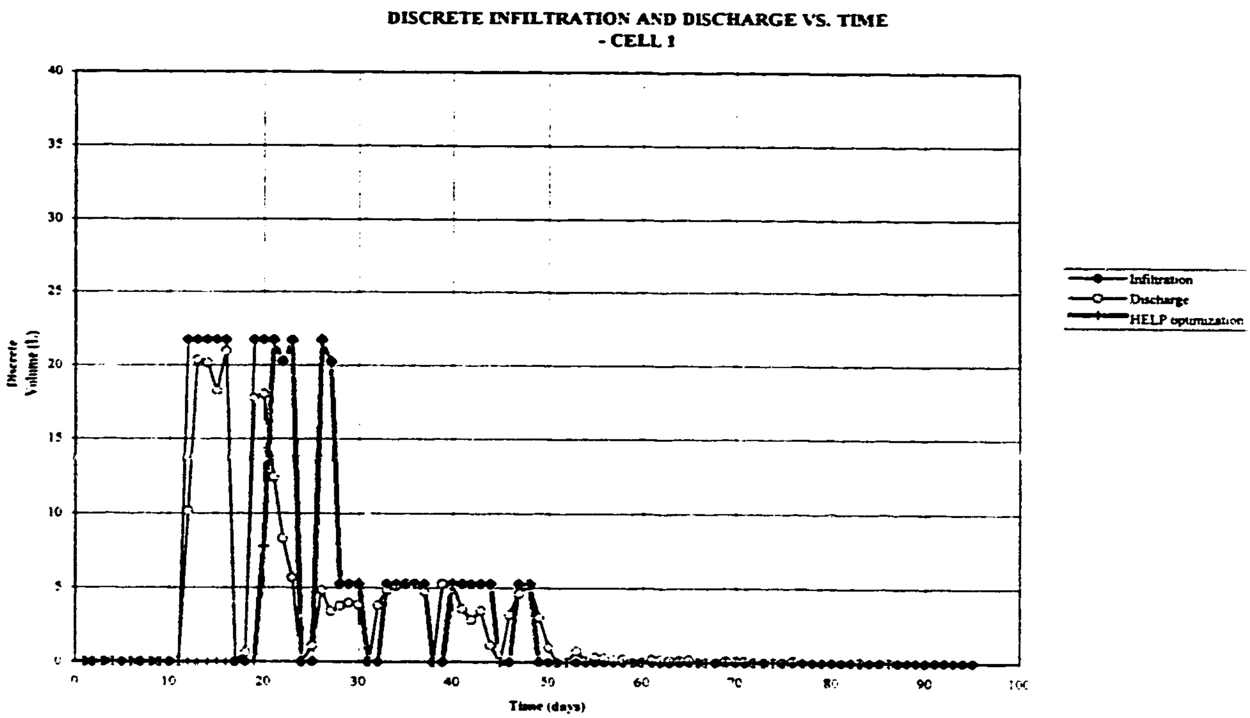
From the results of the simulations with experimental input parameters it is evident that some parameters should be adjusted to better predict measured leachate discharge. In order to determine how much adjustment of a parameter was necessary a sensitivity analysis was performed. This analysis tested the effects of the input parameters porosity, field capacity, wilting point, initial moisture content, saturated hydraulic conductivity, and waste layer depth, on leachate discharge. Specifically, the effects of the above input parameters on six dependent variables characterizing leachate generation were examined. These variables were breakthrough time, time to steady state, peak leachate volume, time to reach peak, total leachate volume, and duration of the leachate event.

The results of the analysis showed that only breakthrough time and time to reach peak leachate discharge were significantly affected by a change in the above input parameters. Breakthrough time is sensitive to porosity, saturated hydraulic conductivity, and initial moisture content. Time to peak is also sensitive to porosity, hydraulic conductivity, and initial moisture content. An increase in porosity, or a decrease in hydraulic conductivity or initial moisture content results in an increase in both breakthrough time and time to peak. Also, though not shown in the sensitivity analysis, field capacity also has an effect on moisture movement. This is due to the drainage calculation used in the model. Drainage does not proceed until the layer has reached field capacity. The greater the field capacity moisture content, the more water is needed, and thus more time is taken before leachate is first discharged. Since the initial moisture content of the waste in each cell is used to more closely represent the experimental conditions, this parameter was not changed. However, porosity, field capacity and saturated hydraulic conductivity were varied to optimize the predictive ability of the model.

As discussed, the results of the simulations with experimentally derived input variables could be optimized because breakthrough time and volume of leachate generated were not predicted as well as the other parameters. Unfortunately, due to the nature of the model, which does not accurately represent the physical system, it is difficult to decrease the breakthrough time as well as decreasing the volume discharged while still having the leachate generation follow the precipitation event (and the measured leachate discharge). The greatest over estimation of discharge was in cells 2 and 3. Though these cells discharged shortly after moisture was first added, very little discharge was collected until the loading rate increased (day 54). In order to optimize the simulation results for these cells the field capacity was increased as was the porosity and saturated hydraulic conductivity. This increases the storage capacity of the waste and therefore, delays leachate discharge. However, with an increase in hydraulic conductivity, the leachate discharge will closely follow the changes in moisture loading, and, measured leachate discharge. For all cells except 5 and 7 the field capacity was increased 50%, and the saturated hydraulic conductivity (K_s') was doubled. For the high infiltration intensity, low compaction cells 5 and 7, the filed capacity was decreased 15% in order to decrease the breakthrough time of the simulation, and therefore, increase the total amount of leachate discharged. As with the other cells K_s' was doubled to ensure a rapid response time. This adjustment was derived from the sensitivity analysis, where the effects of these input parameters on breakthrough time and total leachate discharge was tested.

The simulation results of optimized input data are presented in Figures 4.38 to 4.45, and Tables 4.12 to 4.15. An improvement in the prediction of leachate discharge is evident from these figures. Though for the low intensity cells breakthrough time is increased, the simulated discharge matches the measured discharge quite well, as does the total volume of leachate discharged. Though the HELP model with optimized parameters, can quite accurately simulate measured leachate generation the drainage calculations still limit its accuracy (summary data is presented in Table 4.12 through 4.15). For example, because field capacity must be reached before drainage can commence a lag in breakthrough time is noted. Also, if field capacity is decreased, breakthrough time may decrease but a large volume will drain shortly after breakthrough and will continue until moisture loading is stopped. In the experimental cells, particularly, the low intensity cells, leachate broke through immediately, however, most of the leachate volume was discharged later. This suggests that small amounts of leachate may move quickly through the waste, being conveyed by channels, but the main leachate flow occurs when the waste becomes wetter and conveys more flow (e.g., micropore flow). The use of PREFLO, a two-domain model which explicitly accounts for channeled flow, may result in better leachate discharge predictions than using the HELP model. The results and analysis of the PREFLO simulations is discussed in the following section.

Figure 4.38: Discrete Leachate Volume Predicted From Optimized HELP Simulations for Low Infiltration Intensity, Low Compaction Cells (Cells 1 and 3)



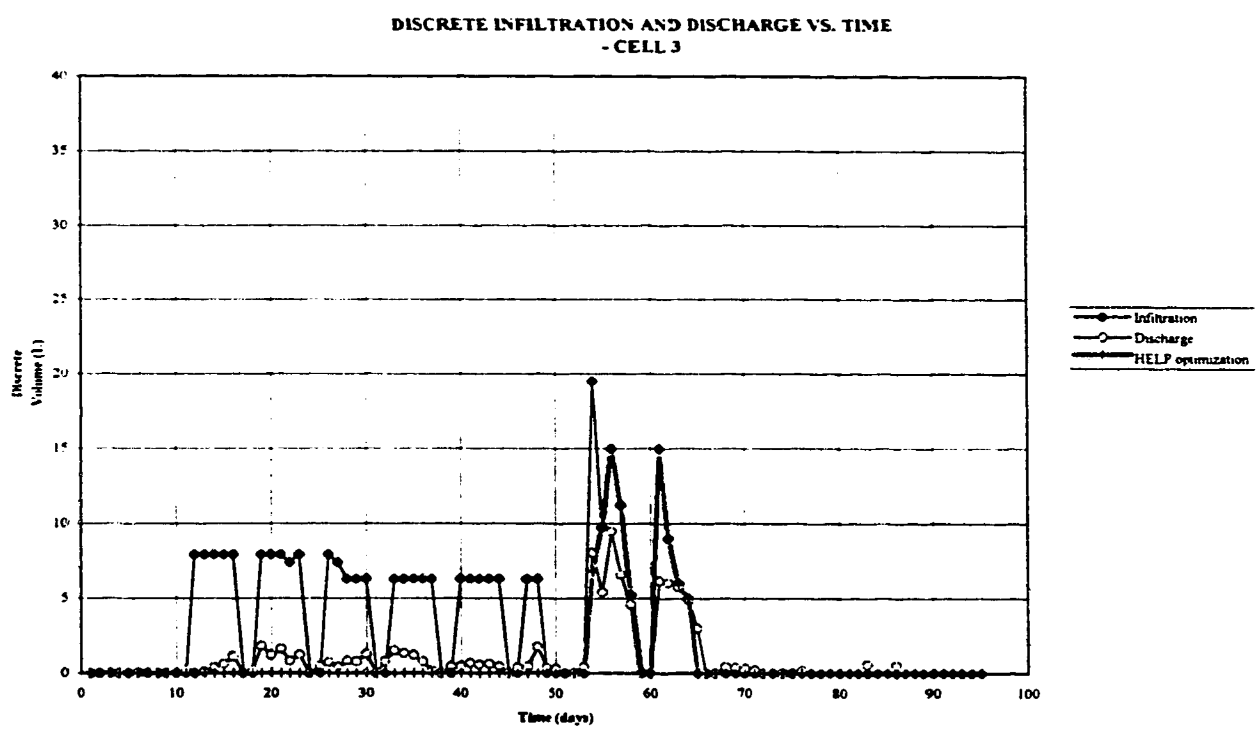
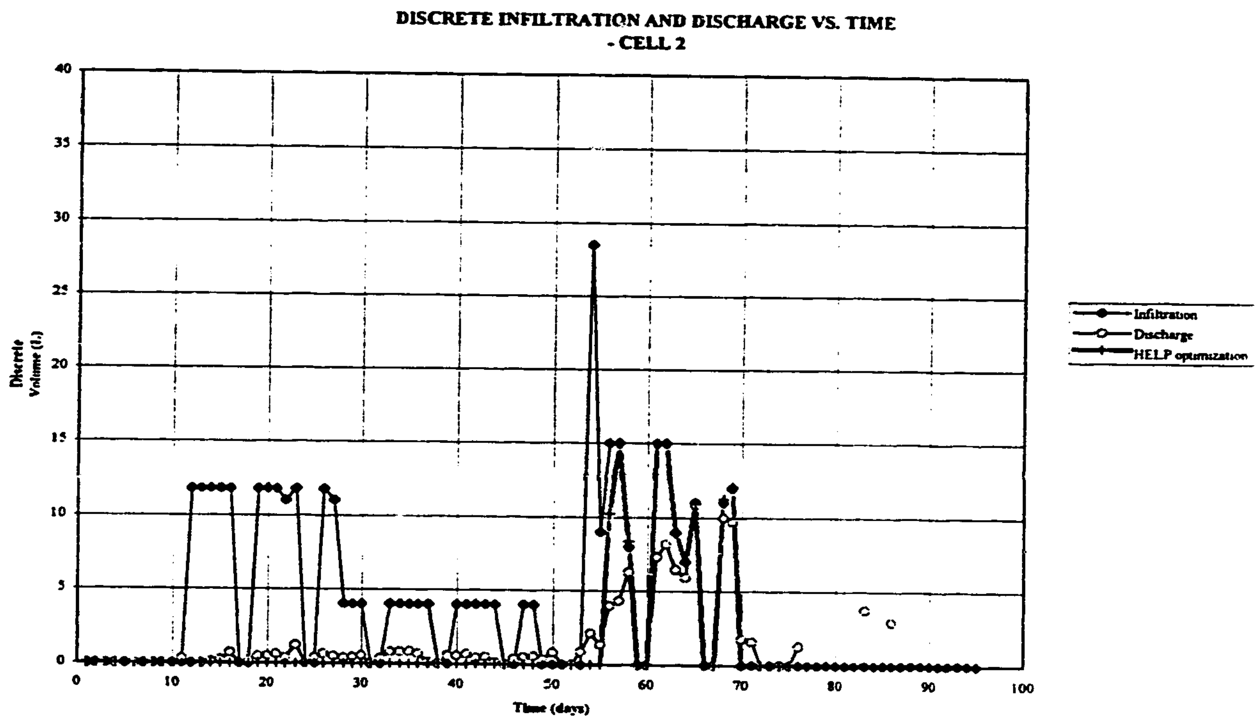


Figure 4.39: Discrete Leachate Volume Predicted From Optimized HELP Simulations for Low Infiltration Intensity, High Compaction Cells (Cells 2 and 4)



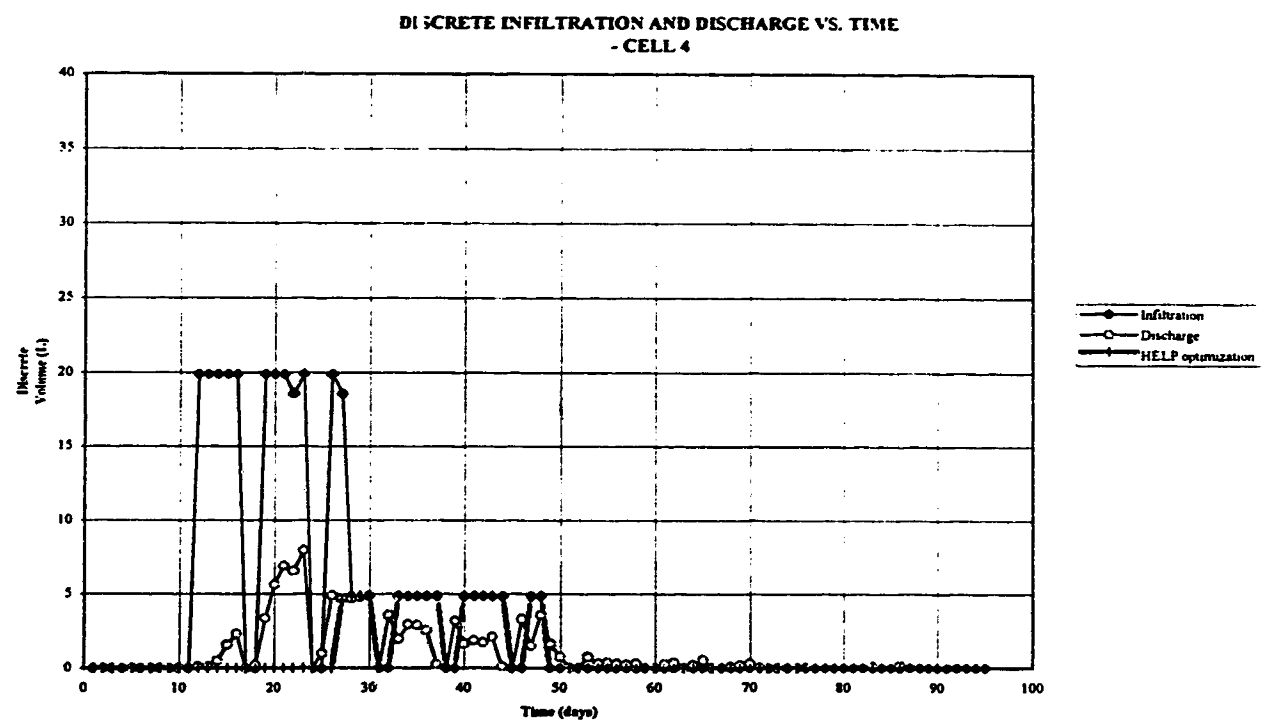
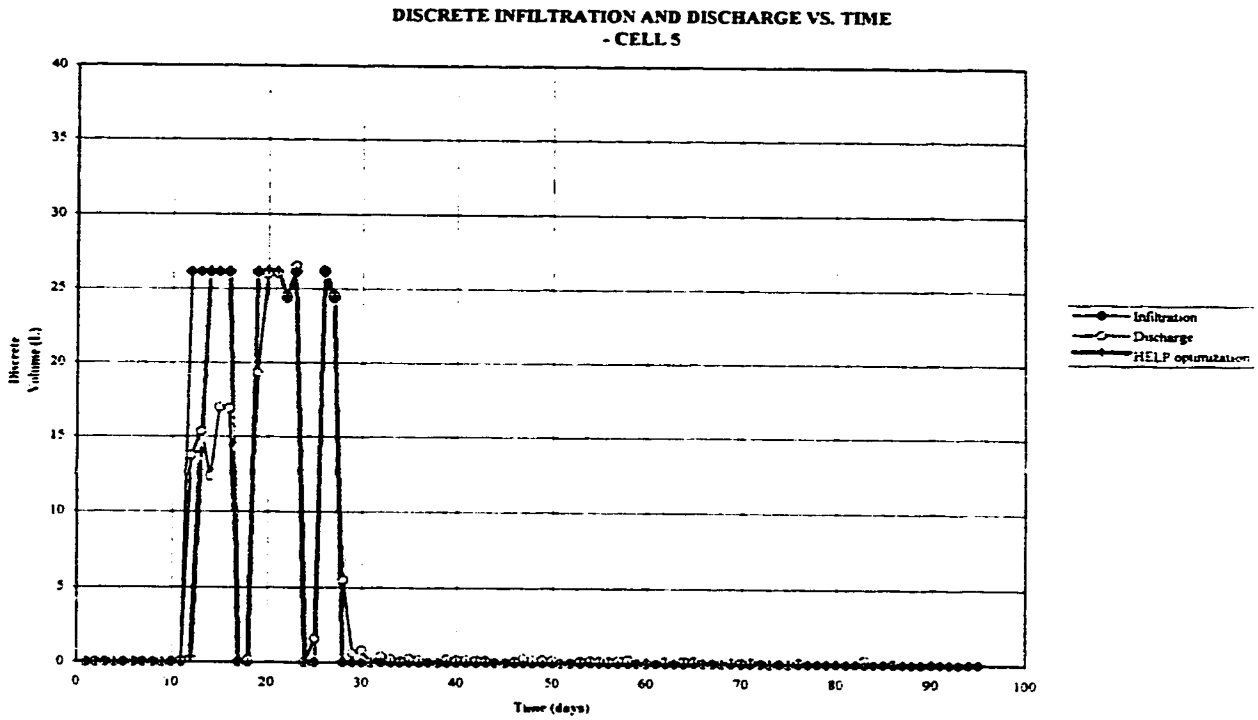


Figure 4.40: Discrete Leachate Volume Predicted From Optimized HELP Simulations for High Infiltration Intensity, Low Compaction Cells (Cells 5 and 7)



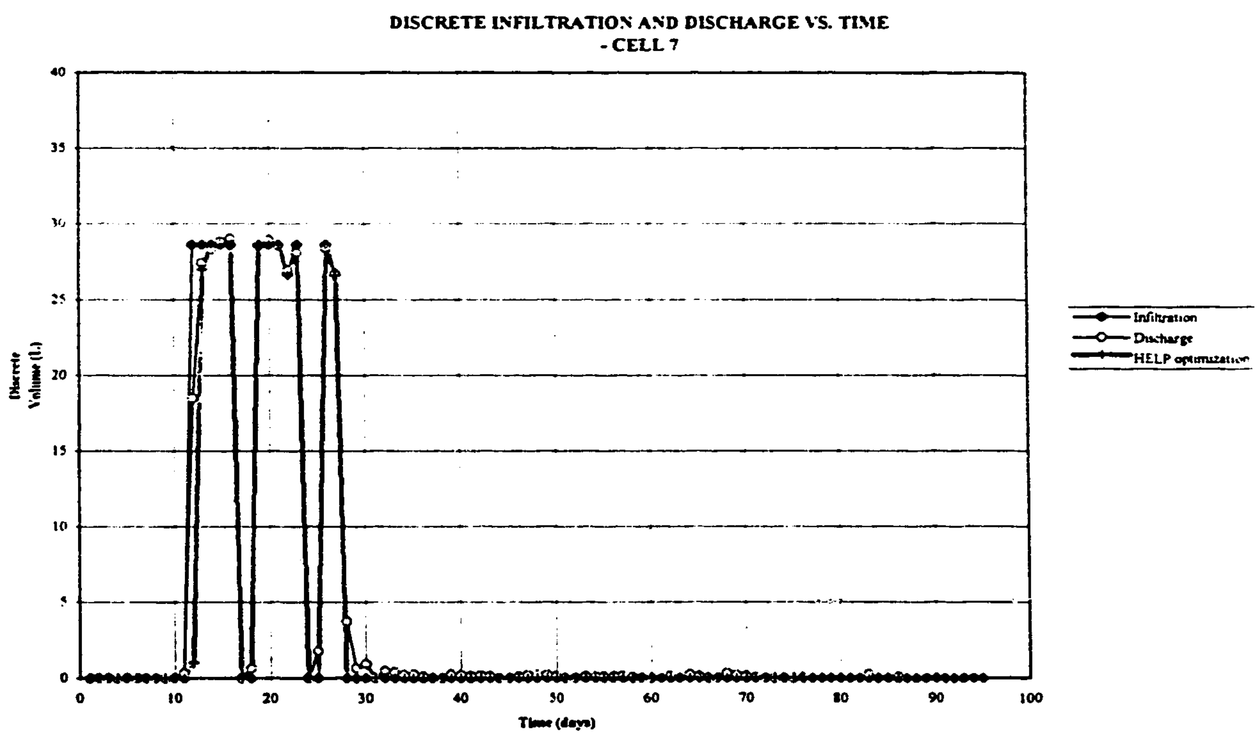
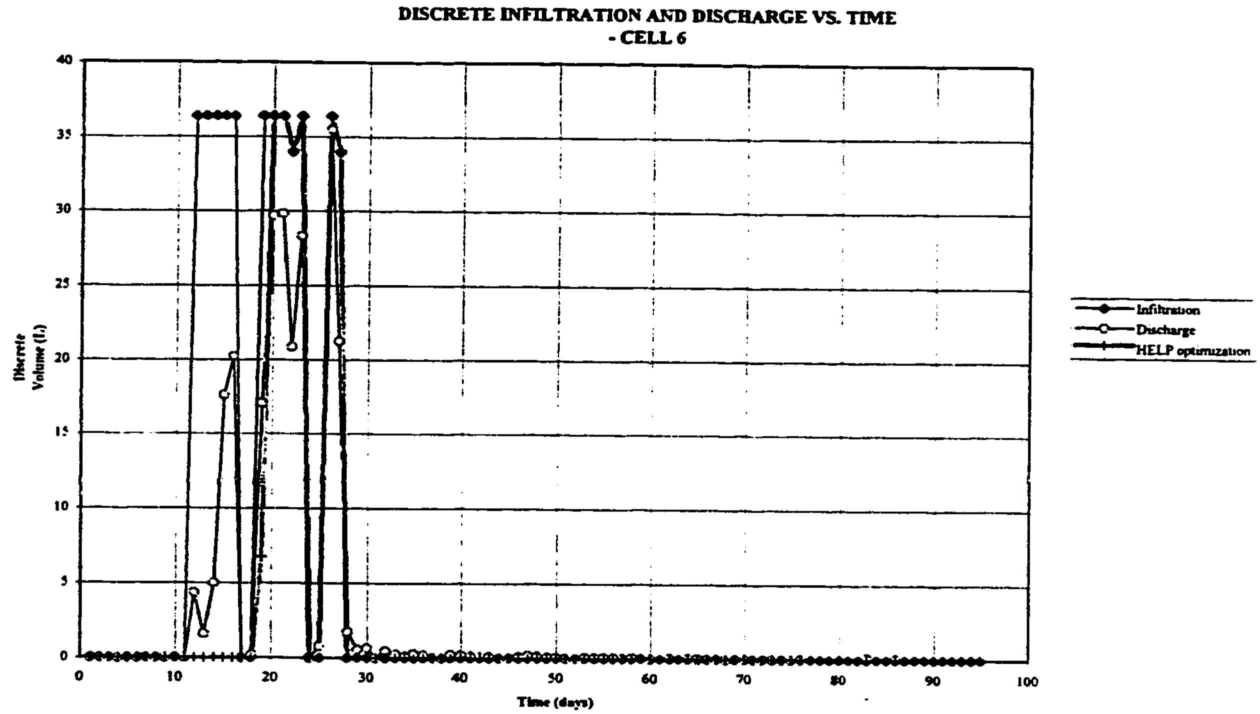


Figure 4.41: Discrete Leachate Volume Predicted From Optimized HELP Simulations for High Infiltration Intensity, High Compaction Cells (Cells 6 and 8)



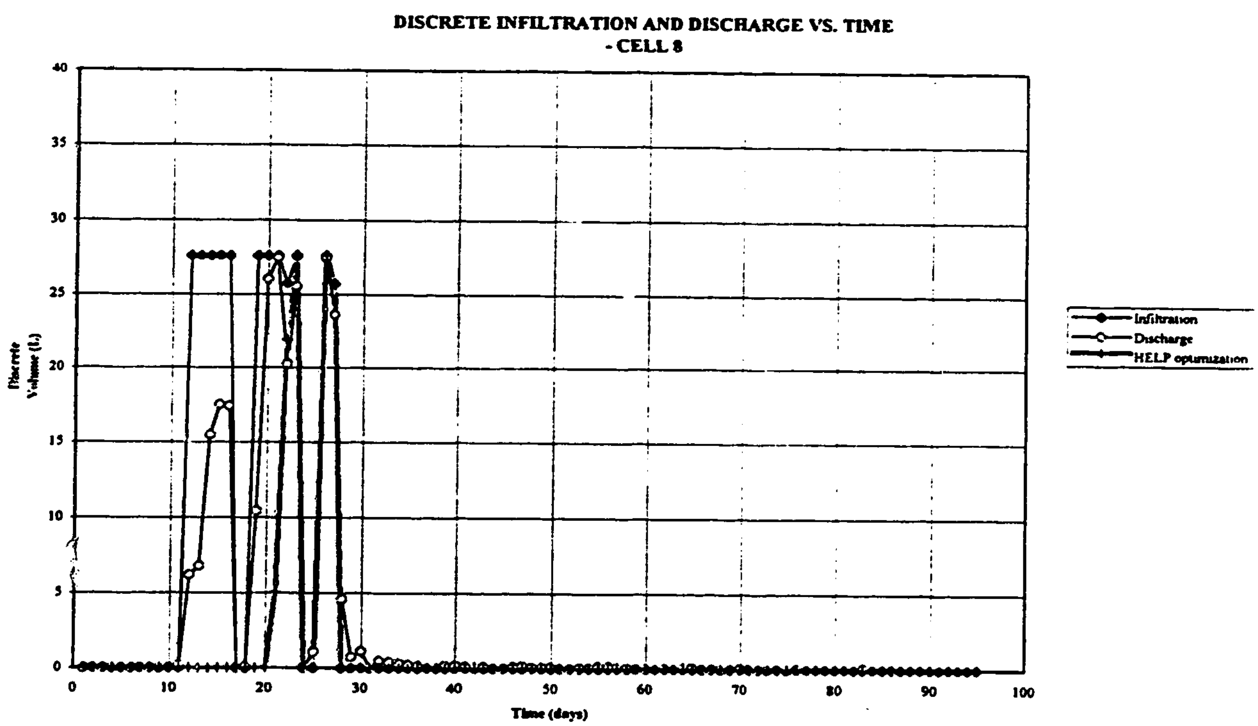
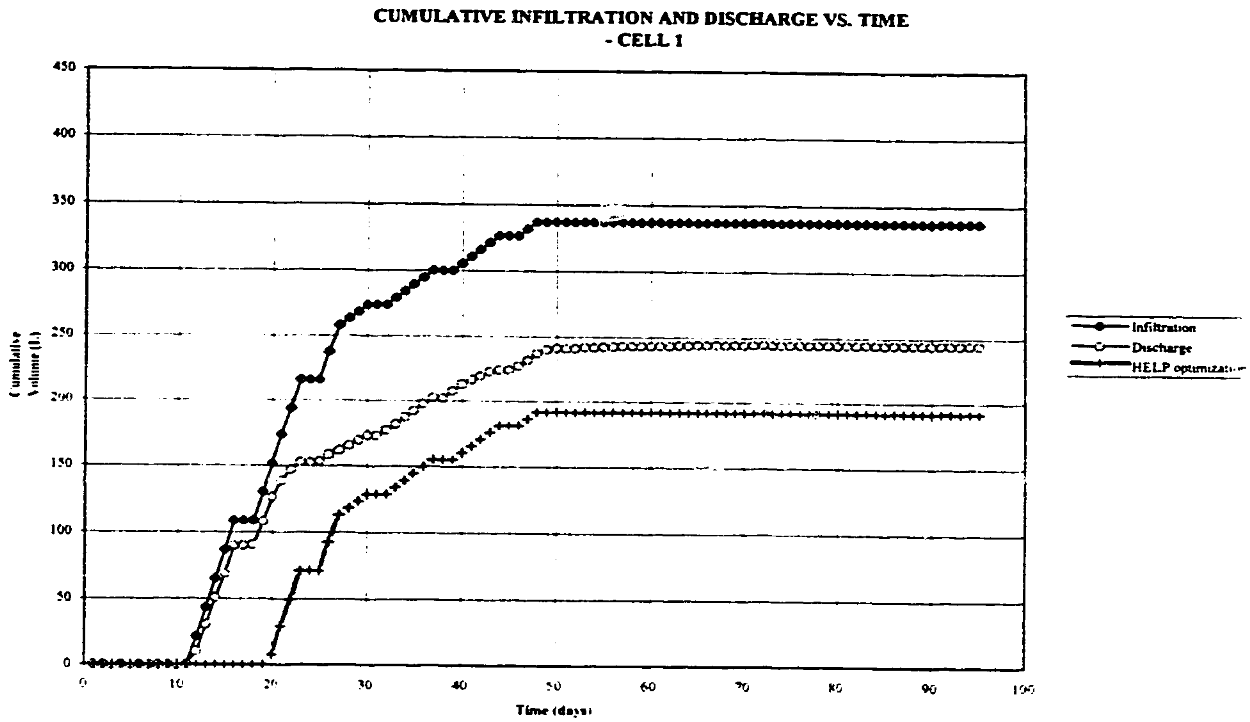


Figure 4.42: Cumulative Leachate Volume Predicted From Optimized HELP Simulations for Low Infiltration Intensity, Low Compaction Cells (Cells 1 and 3)



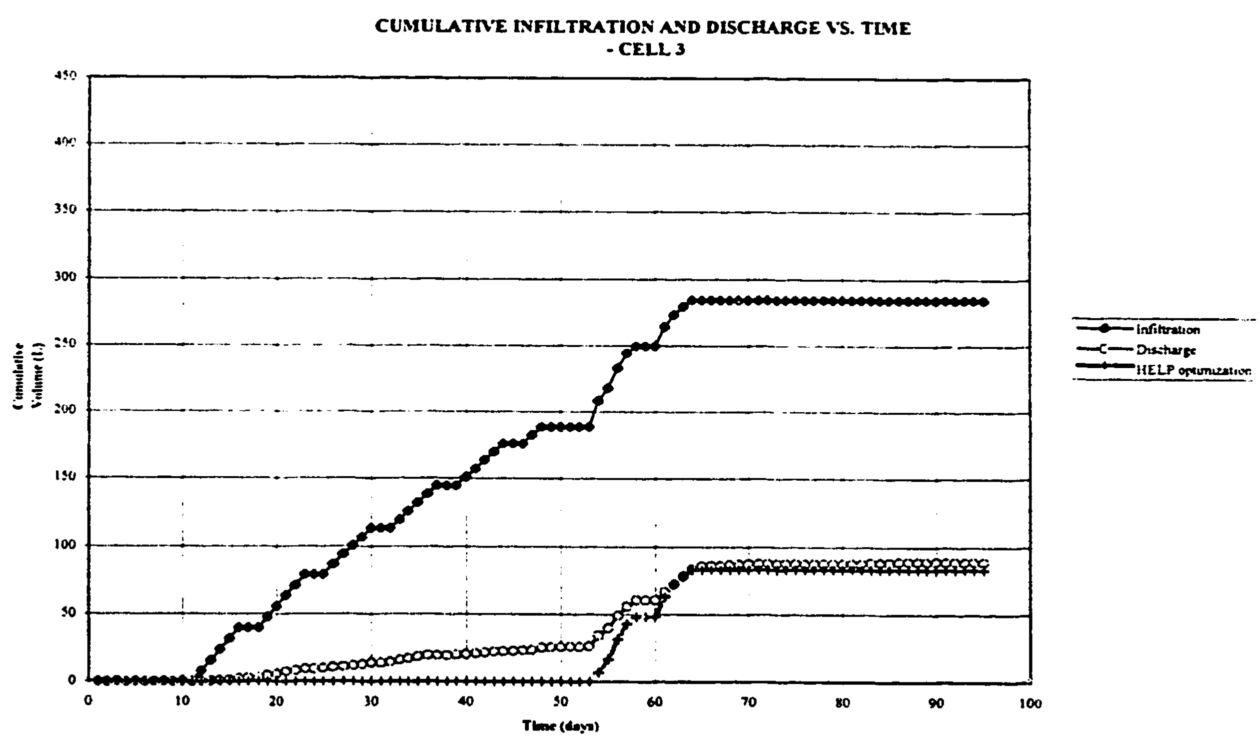
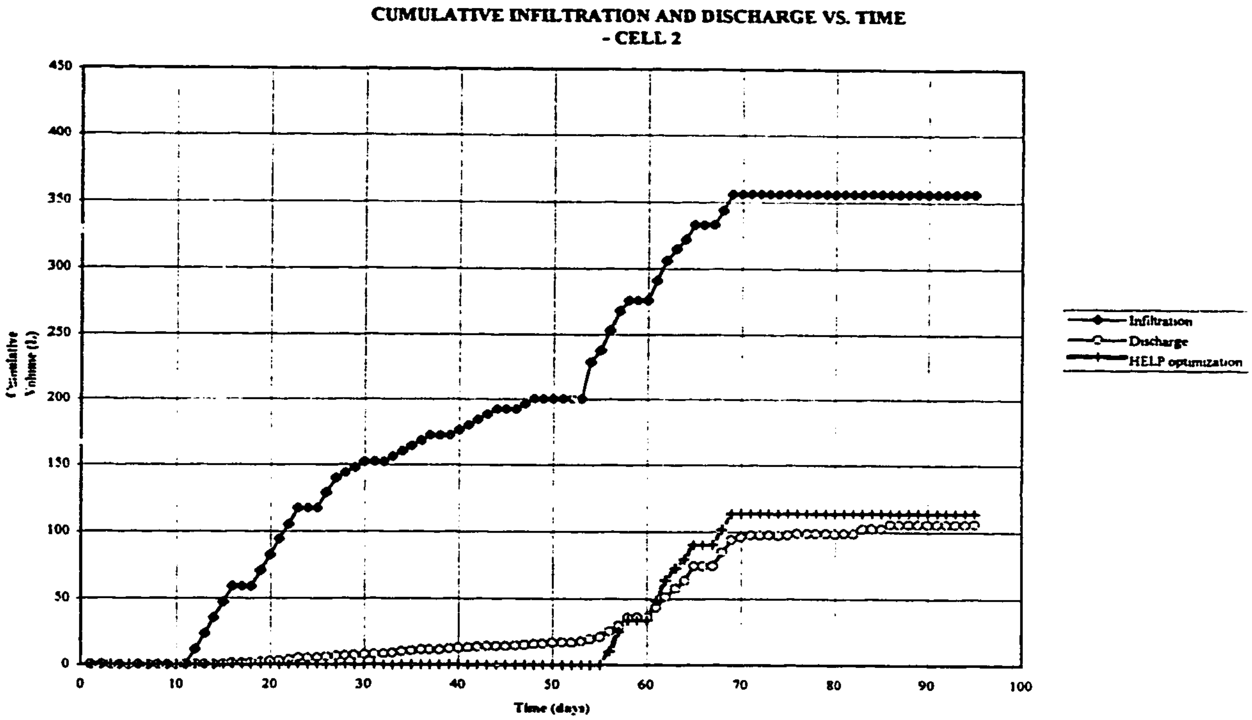


Figure 4.43: Cumulative Leachate Volume Predicted From Optimized HELP Simulations for Low Infiltration Intensity, High Compaction Cells (Cells 2 and 4)



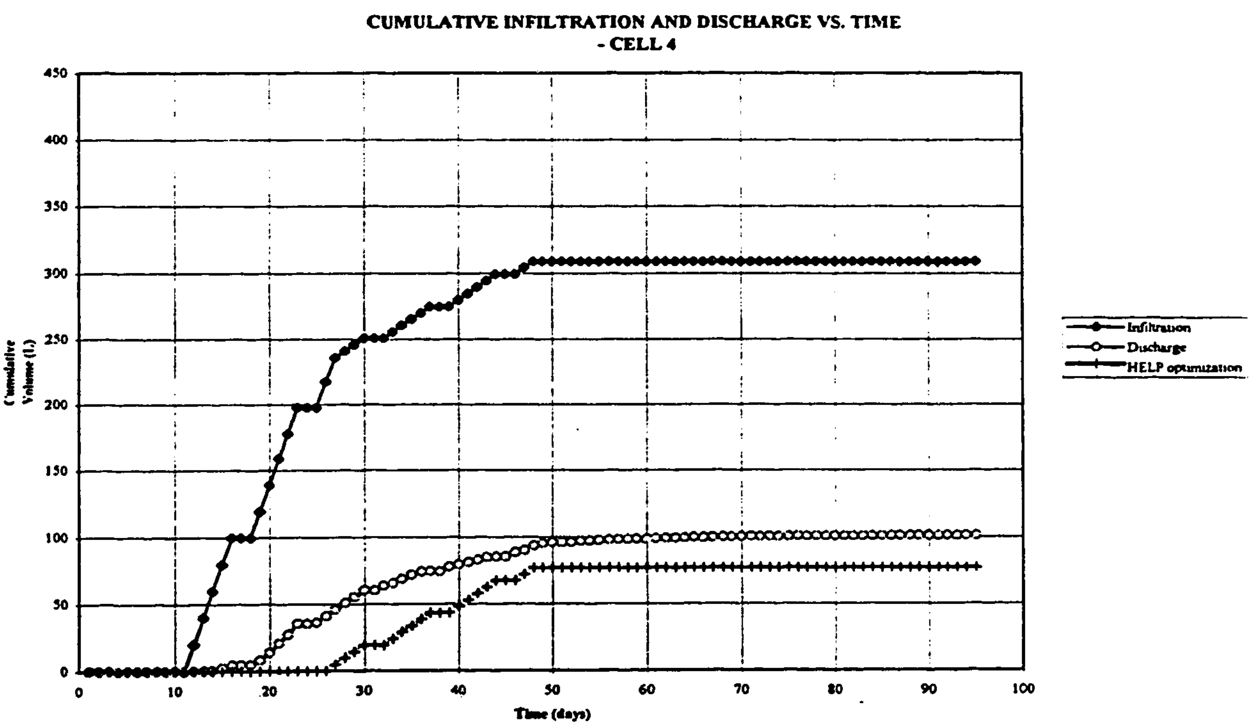
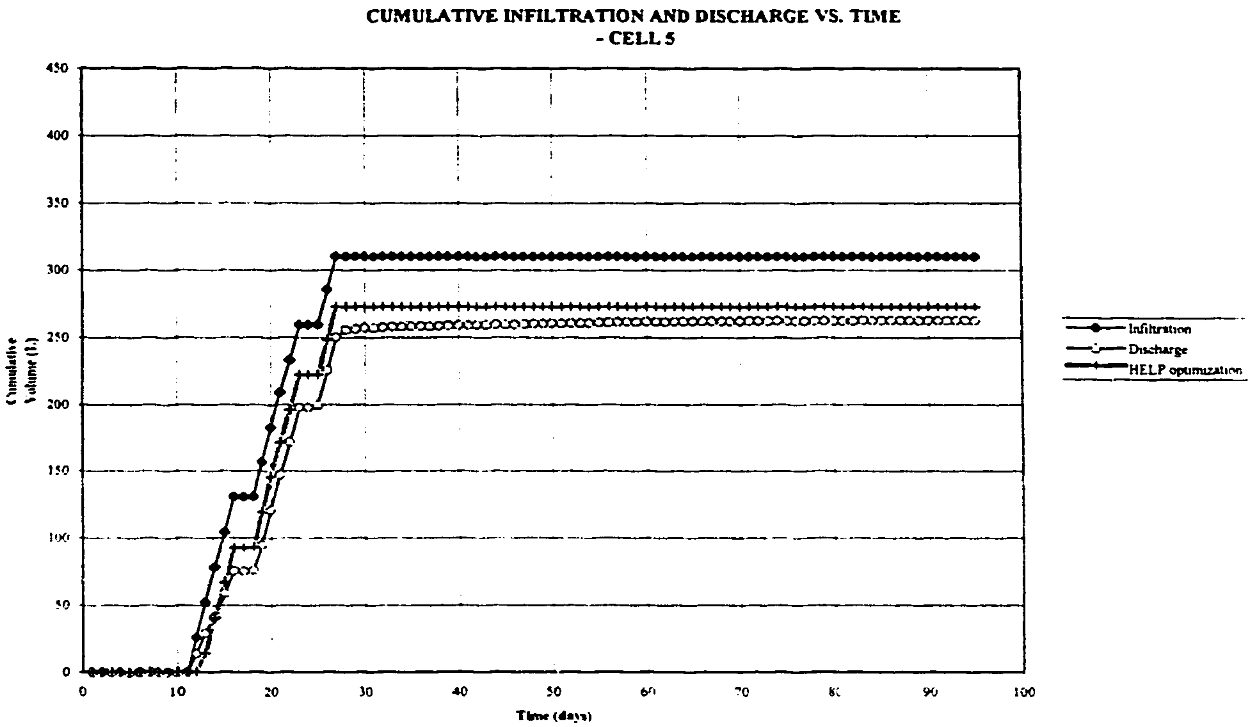


Figure 4.44: Cumulative Leachate Volume Predicted From Optimized HELP Simulations for High Infiltration Intensity, Low Compaction Cells (Cells 5 and 7)



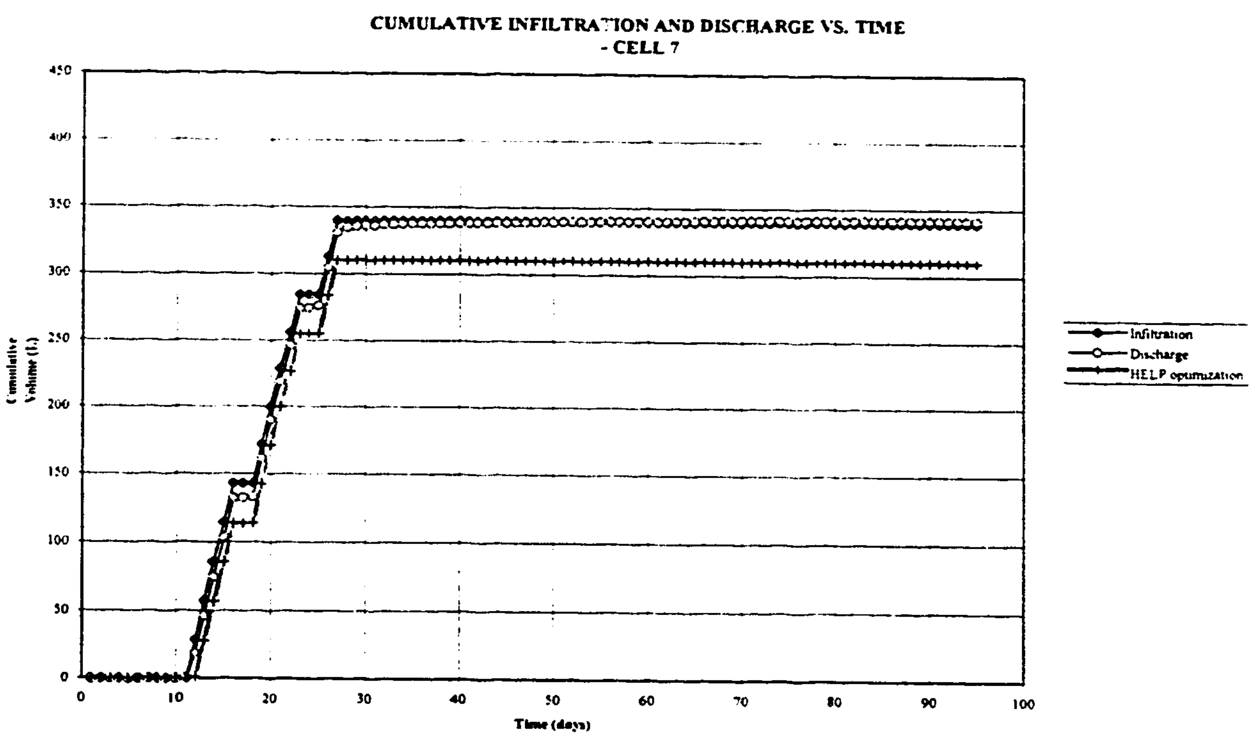
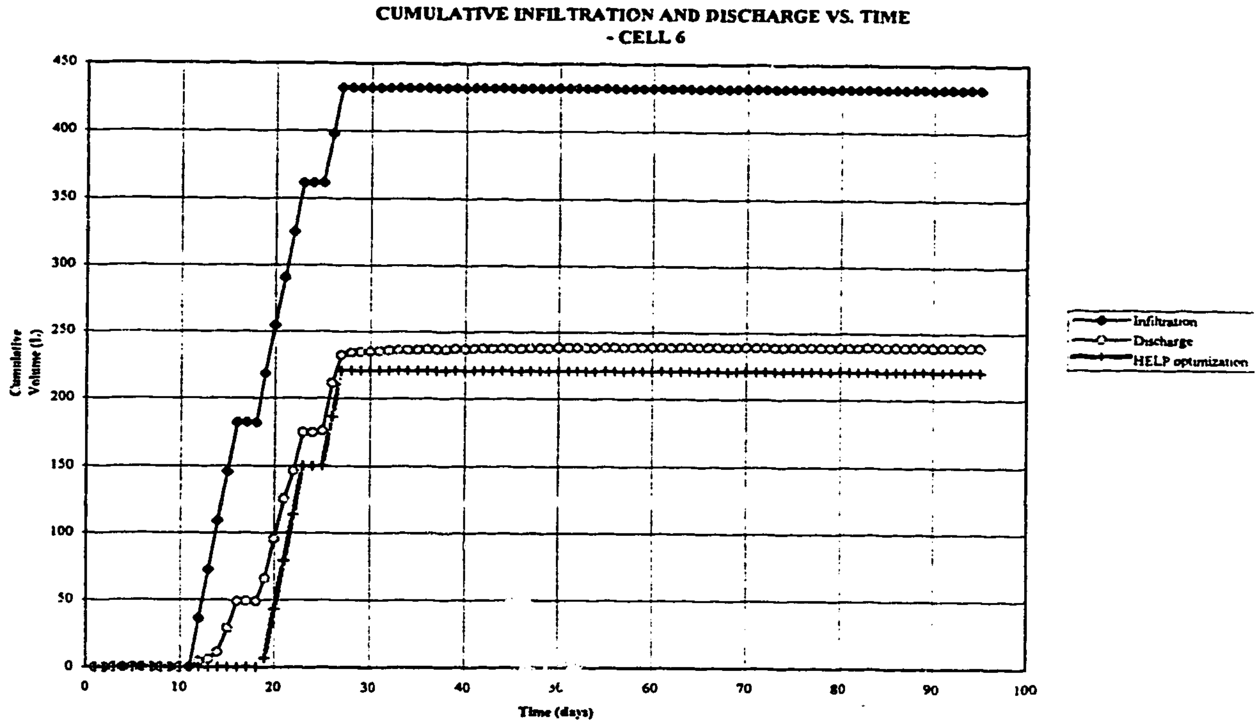


Figure 4.45: Cumulative Leachate Volume Predicted From Optimized HELP Simulations for High Infiltration Intensity, High Compaction Cells (Cells 6 and 8)



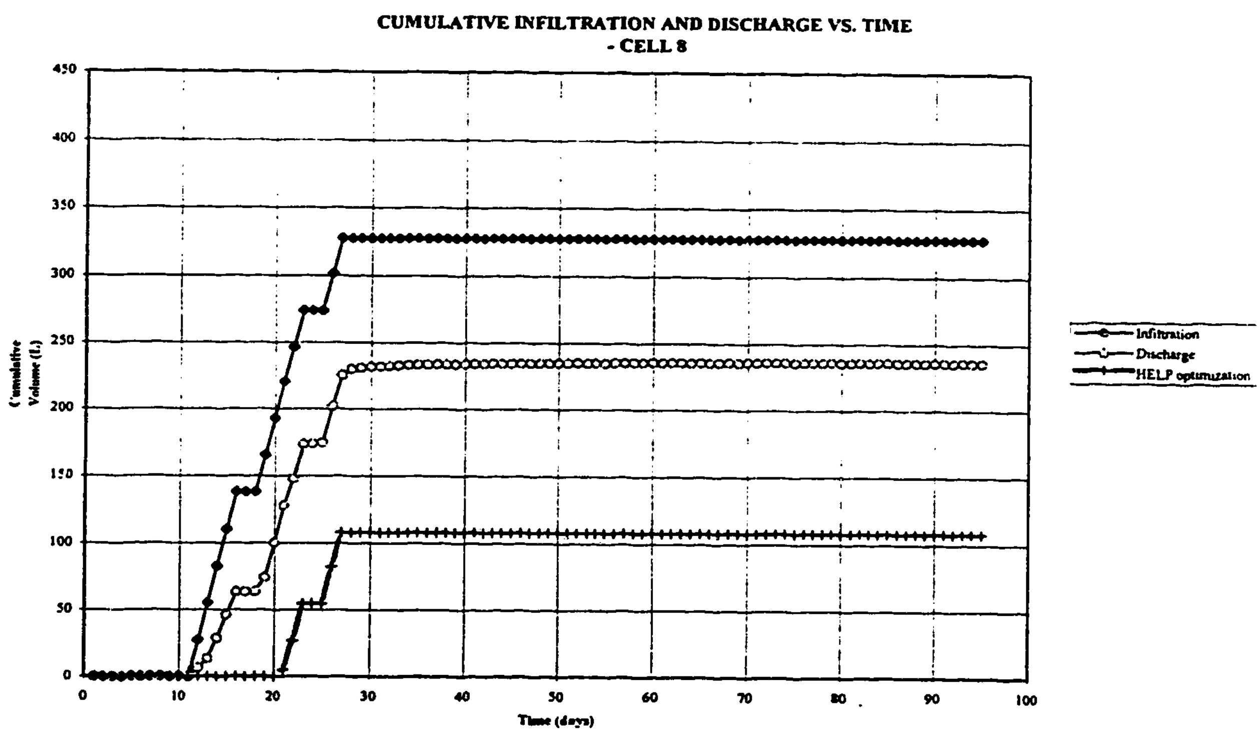


Table 4.12: Summary Table of Measured, HELP, and PREFLO Results for Low Infiltration Intensity, Low Compaction Cells 1 and 3

CELL 1	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	1	8 (800%)	4 (400%)
Time to Effective Storage (days)	23	9 (39%)	20 (87%)
Peak Volume (L)	20.9	21.6 (103%)	18.5 (89%)
Time to Peak Volume (days)	5	9 (180%)	5 (100%)
Total Volume (L)	244	192 (79%)	289 (118%)
Duration of Event (days)	39	28 (72%)	79 (203%)
CELL 3	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	2	42 (1400%)	1 (50%)
Time to Effective Storage (days)	50	43 (86%)	28 (56%)
Peak Volume (L)	9.5	15.0 (158%)	12.9 (136%)
Time to Peak Volume (days)	45	43 (96%)	45 (100%)
Total Volume (L)	89	83 (93%)	283 (318%)
Duration of Event (days)	55	11 (20%)	81 (147%)

Table 4.13: Summary Table of Measured, HELP, and PREFLO Results for Low Infiltration Intensity, High Compaction Cells 2 and 4

CELL 2	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	3	45 (1500%)	2 (67%)
Time to Effective Storage (days)	51	46 (90%)	16 (31%)
Peak Volume (L)	10.9	15.0 (138%)	12.7 (117%)
Time to Peak Volume (days)	57	46 (81%)	40 (70%)
Total Volume (L)	106	113 (107%)	350 (330%)
Duration of Event (days)	75	14 (19%)	80 (107%)
CELL 4	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	1	15 (1500%)	4 (400%)
Time to Effective Storage (days)	17	16 (94%)	13 (76%)
Peak Volume (L)	7.9	4.8 (61%)	17.8 (225%)
Time to Peak Volume (days)	13	16 (123%)	2 (15%)
Total Volume (L)	101	77 (76%)	278 (275%)
Duration of Event (days)	39	21 (54%)	77 (197%)

Table 4.14: Summary Table of Measured, HELP, and PREFLO Results for High Infiltration Intensity, Low Compaction Cells 5 and 7

CELL 5	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	1	1 (100%)	3 (300%)
Time to Effective Storage (days)	9	3 (33%)	effective storage not reached
Peak Volume (L)	26.2	26.2 (100%)	20.2 (89%)
Time to Peak Volume (days)	9	3 (33%)	10 (111%)
Total Volume (L)	260	273 (105%)	233 (95%)
Duration of Event (days)	17	15 (88%)	68 (447%)
CELL 7	**Measured**	**HELP (% of measured)**	**PREFLO (% of measured)**
Breakthrough Time (days)	1	1 (100%)	-3 (-300%)
Time to Effective Storage (days)	3	3 (100%)	effective storage not reached
Peak Volume (L)	29.0	28.6 (99%)	19.0 (66%)
Time to Peak Volume (days)	4	3 (75%)	3 (75%)
Total Volume (L)	339	310 (91%)	254 (75%)
Duration of Event (days)	17	15 (88%)	65 (394%)

Table 4.15: Summary Table of Measured, HELP, and PREFLO Results for High Infiltration Intensity, High Compaction Cells 6 and 8

CELL 6	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	1	7 (700%)	-12 (-1200%)
Time to Effective Storage (days)	15	8 (53%)	effective storage not reached
Peak Volume (L)	36.4	34.0 (93%)	23.0 (63%)
Time to Peak Volume (days)	15	10 (67%)	10 (80%)
Total Volume (L)	243	220 (91%)	315 (130%)
Duration of Event (days)	17	9 (53%)	97 (571%)
CELL 8	Measured	HELP (% of measured)	PREFLO (% of measured)
Breakthrough Time (days)	1	9 (900%)	-5 (-500%)
Time to Effective Storage (days)	15	11 (73%)	effective storage not reached
Peak Volume (L)	27.6	27.6 (100%)	23.0 (83%)
Time to Peak Volume (days)	15	11 (73%)	5 (33%)
Total Volume (L)	234	108 (46%)	296 (126%)
Duration of Event (days)	17	7 (41%)	99 (582%)

4.2.2 PREFLO Model Results

The second modeling hypothesis states that simulating channeling as a two-domain process results in better prediction of moisture movement than accounting for channeling by adjusting the parameters of a one-domain Darcian flow model. The test of this hypothesis requires that modeling results of the PREFLO model be compared with measured and HELP model results to determine which model better predicts moisture movement. Unlike the HELP model, the PREFLO model was developed for soils, and therefore, no default input values for modeling moisture flow through MSW exist. Three sets of simulations are performed. The first set of simulations use default HELP data, but include experimentally derived percentage pore area data (section 3.3). The second set of simulations used the calibration data with the same pore data used in the first set of runs (see Table 4.16). The final simulations use input data optimized through a sensitivity analysis (Table 4.16)

PREFLO simulations for both default and calibration HELP input parameters predicted no leachate was generated (see sample graphs, Figures 4.46 and 4.47). These results can be explained by reviewing how moisture movement is modeled in PREFLO. Channeled flow can only occur if the infiltration intensity is greater than the saturated hydraulic conductivity of the matrix. In both default and calibration cases the saturated hydraulic conductivity is greater than the highest infiltration intensity experienced in any simulation (3.9E-5 cm/s for cell 2). Therefore, no channel flow occurred. However, water did infiltrate the waste, and was conveyed through the matrix. This routing is modeled using the Richards equation. Originally, the drainage determined by the Richards equation was added to a water table at the base of the profile. The model was modified to simulate free drainage conditions and, therefore, drainage, only occurs when the pressure at the bottom of the profile is atmospheric. The program was also modified so that instead of an initial "drained-to-equilibrium" capillary pressure profile the capillary pressure throughout the profile was set to a single value corresponding to the initial moisture content of the waste. Again, the moisture content - capillary pressure relationship was determined using the Brooks-Corey equation with the parameters shown in Table 4.14. Drainage did not occur in both sets of simulations because the amount of water added through infiltration combined with the initial moisture content of the waste, which corresponded to an extremely high capillary pressure, was not enough to saturate the bottom node of the waste layer. Thus the amount of water added was not sufficient to raise the pressure to zero, and drainage did not occur. The initial capillary pressures of the calibration runs were higher than the default runs, however, the porosity was still fairly large (0.52 v/v) compared with the initial moisture contents of the waste. Again, the quantity of water added was not sufficient to raise the moisture content of the bottom node to 0.52 and thus allow drainage.

Table 4.16: Input Parameters for PREFLO Simulations

Input Parameter	Low Infiltration Intensity				High Infiltration Intensity			
	Low Compaction		High Compaction		Low Compaction		High Compaction	
	INPUT PARAMETERS COMMON TO ALL PREFLO SIMULATIONS							
	Cell 1	Cell 3	Cell 2	Cell 4	Cell 5	Cell 7	Cell 6	Cell 8
Layer Thickness (cm)	84	82	99	94	81	77	92	92
Initial Moisture Content (v/v)	0.077	0.091	0.114	0.111	0.083	0.077	0.108	0.117
	INPUT PARAMETERS CORRESPONDING TO DEFAULT VALUES*							
Porosity (v/v)	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
Pore Size Dist. Index (-)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Percent Pore Area (%)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Saturated Hydraulic Conductivity K_s' (cm/s)	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3
	INPUT PARAMETERS CORRESPONDING TO CALIBRATION VALUES**							
Porosity (v/v)	0.52	0.52	0.52	0.52	0.52	0.52	0.52	0.52
Pore Size Dist. Index (-)	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Percent Pore Area (%)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Saturated Hydraulic Conductivity K_s' (cm/s)	5.2E+3	4.1E+1	2.2E+1	2.1E+2	1.0E+3	2.0E+3	4.2E+2	2.3E+2
	INPUT PARAMETERS OPTIMIZED THROUGH SENSITIVITY ANALYSIS							
Porosity (v/v)	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Pore Size Dist. Index (-)	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Percent Pore Area (%)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Saturated Hydraulic Conductivity K_s' (cm/s)	1.0E-5	1.0E-5	1.0E-5	1.0E-5	1.0E-5	1.0E-5	1.0E-5	1.0E-5

* These values correspond to the HELP default parameters (Table 4.11)

** These values correspond to the HELP calibration parameters (Table 4.11)

Figure 4.46: Sample of Discrete and Cumulative Leachate Volume Predicted From Default PREFLO Simulations - Cell 1

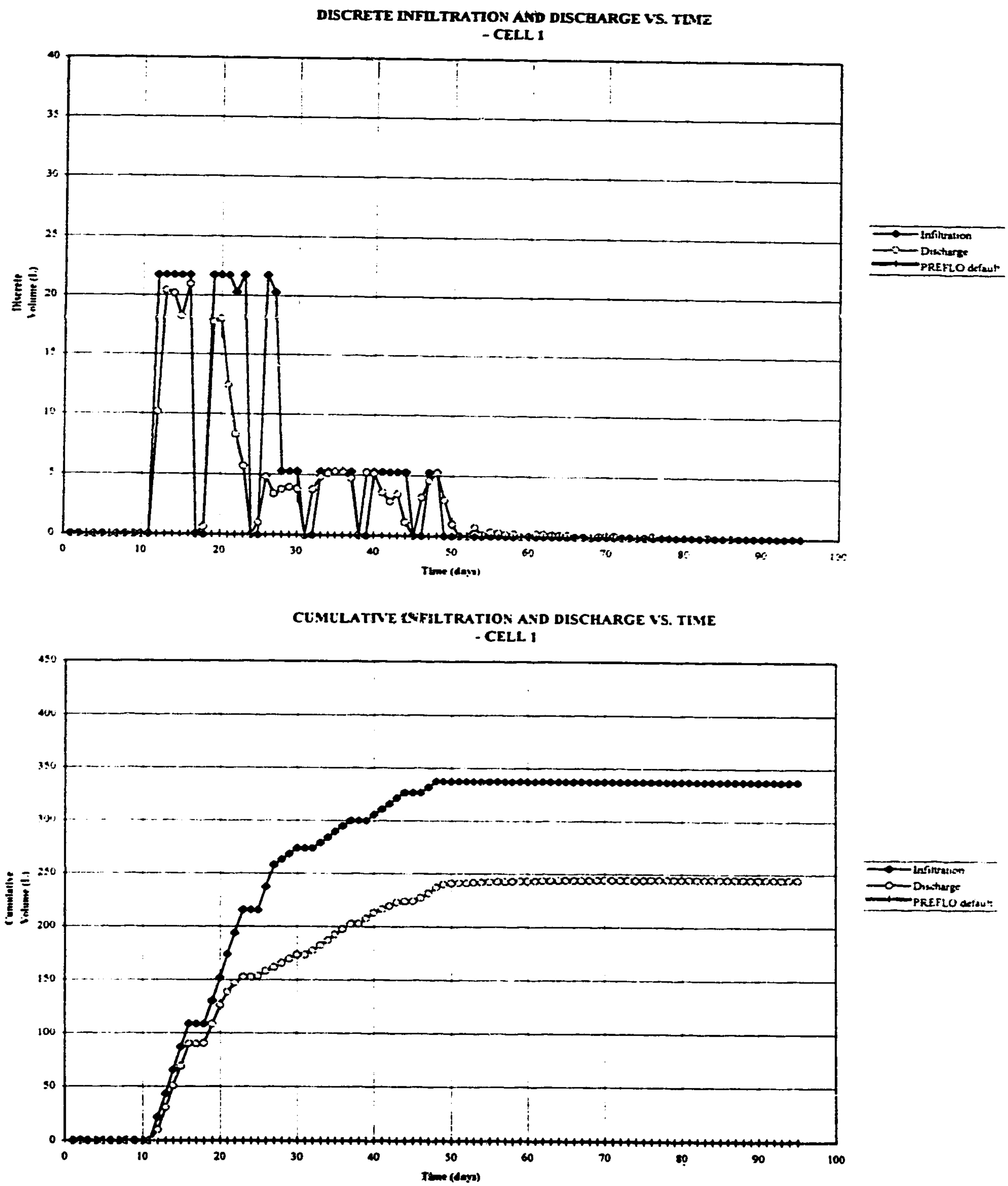
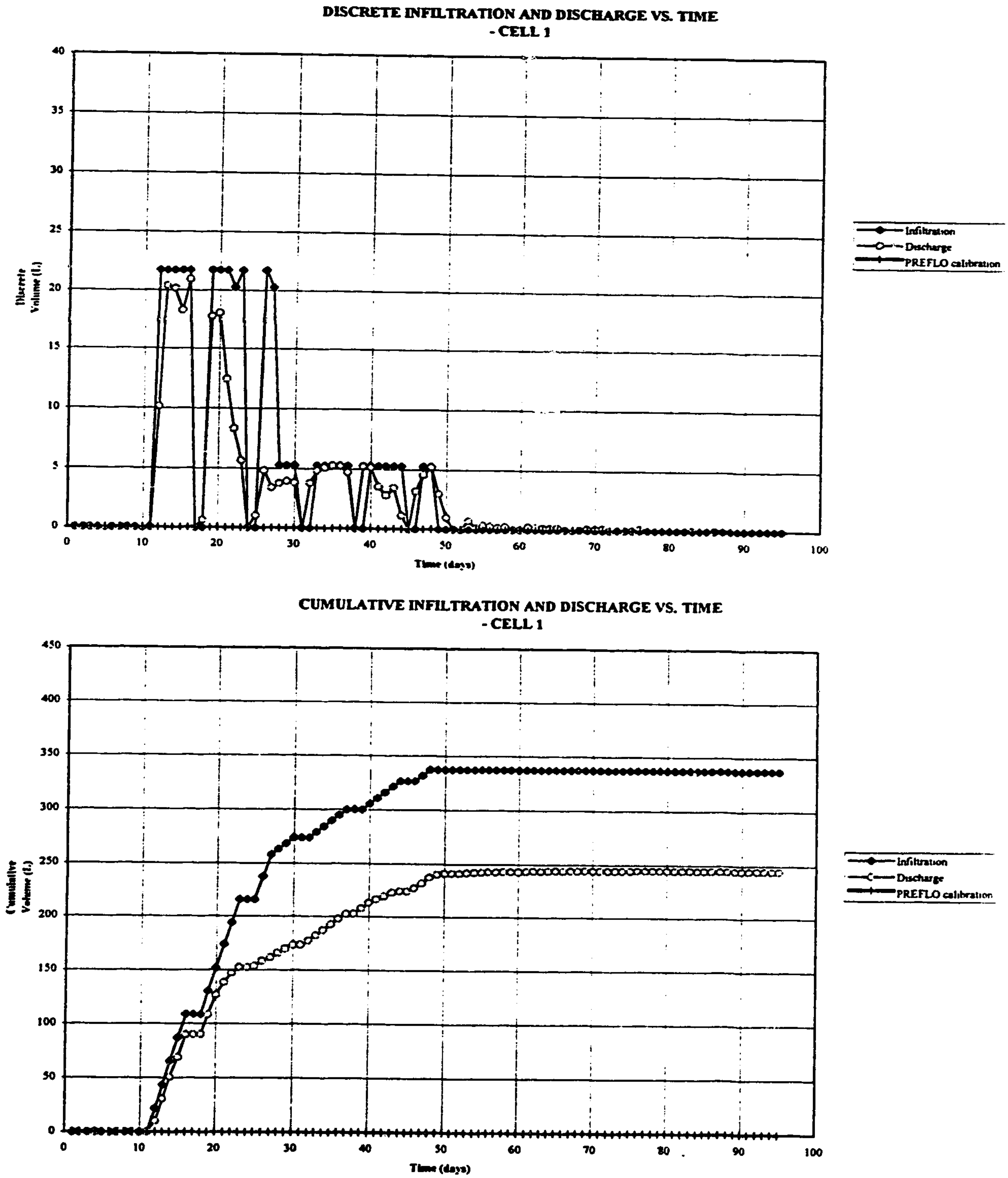


Figure 4.47: Sample of Discrete and Cumulative Leachate Volume Predicted From Calibrated PREFLO Simulations - Cell 1

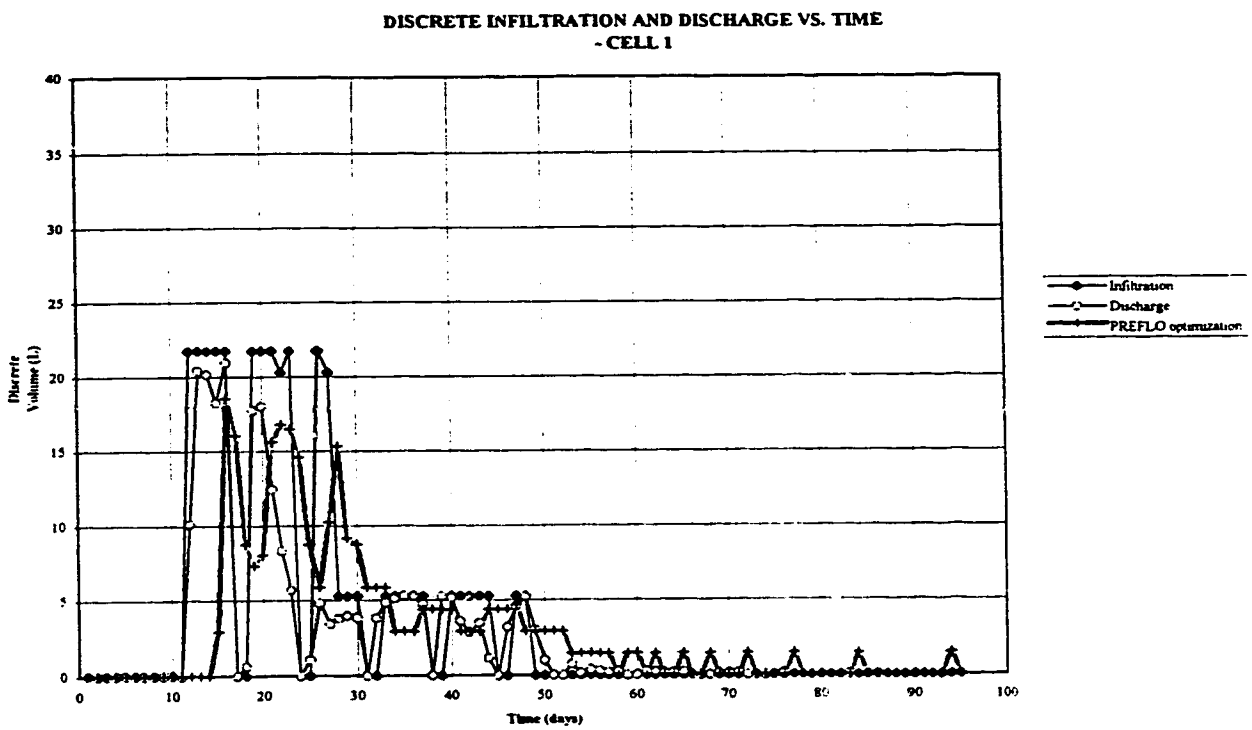


A sensitivity analysis was performed to determine the impact of the input variables on the model results. The results of the sensitivity analysis were used to optimize the input parameters and allow better prediction of leachate discharge by PREFLO. Porosity, initial moisture content, saturated hydraulic conductivity, pore area and waste layer depth on leachate discharge were examined. Similar to the sensitivity analysis performed on the HELP model, the dependent variables used to characterize leachate discharge were breakthrough time, time to steady state, peak leachate volume, time to peak, total leachate volume, and duration of the leachate event.

The analysis showed that breakthrough time, total leachate volume, and duration of the event, were the only parameters sensitive to the parameters tested. Breakthrough time is sensitive to porosity, with an increase in porosity resulting in an increase in breakthrough time. Total leachate volume is sensitive to porosity, waste layer depth, and initial moisture content. An increase in porosity or waste layer depth result in a decrease in the total volume of leachate discharged, while an increase in initial moisture content causes an increase in the total discharge. Finally, the duration of the leachate event is sensitive to porosity, waste layer depth, initial moisture content and saturated hydraulic conductivity. An increase in porosity, layer depth, and saturated hydraulic conductivity decrease the duration of the event, while an increase in initial moisture content lengthens the event. Since waste layer depth and initial moisture content are cell specific, experimentally determined parameters, and are used to more closely represent experimental conditions, these parameters were not varied. However, porosity and saturated hydraulic conductivity were adjusted for the optimization runs. Also, though not tested in the sensitivity analysis the pore size distribution index, λ, used to determine the moisture content - capillary pressure relationship was also varied in the optimization runs. This parameter, which is the slope of a log effective saturation - log capillary pressure graph, affects moisture contents and hydraulic conductivity values at given capillary pressures. A small value of the pore size distribution index, corresponding to a flatter slope, results in less change in moisture content over a range of capillary pressure. The pore size distribution index influences the leachate discharge predicted by PREFLO because a range of capillary pressures and corresponding moisture contents are used as input into the model. The capillary pressures are not varied between runs, however, the moisture contents, determined using the Brooks-Corey equation vary according to the value of λ.

Porosity was lowered significantly in order to increase the volume of leachate and the duration of the leachate event. The value chosen is lower than any of the values shown in the literature for solid waste and is more in the range of sandstone (Price, 1985). However, in supplementary PREFLO trials these values ensured leachate generation, with the hydraulic conductivity and the pore size distribution index listed in Table 4.14. The saturated hydraulic conductivity was reduced to one half the value of the lowest infiltration intensity experienced in the experiment to ensure that channeling would occur. Again, this parameter is used to force PREFLO to route water through the channels, and it is not based on the actual physical properties of the waste (it is therefore also denoted K_s'). The pore size distribution index was reduced so the initial moisture contents for all simulations would be within a small range of capillary pressures. This is consistent with experimental results as the initial tensiometer readings for all cells are limited to a 20 centibar range (see Figures 4.5 to 4.12). The initial moisture contents used in the simulations varied over a 14 centibar range with the pore size distribution index used. This value of lambda, 0.21, is the same as the default value of version 2 of the HELP model (Schroeder et. al., 1988). Therefore, this value is consistent with literature values, however, like K_s' it is a fitting parameter used to allow better prediction of experimental results. Figures 4.48 through 4.55 show the results of the "optimized" PREFLO simulations.

Figure 4.48: Discrete Leachate Volume Predicted From Optimized PREFLO Simulations for Low Infiltration Intensity, Low Compaction Cells (Cells 1 and 3)



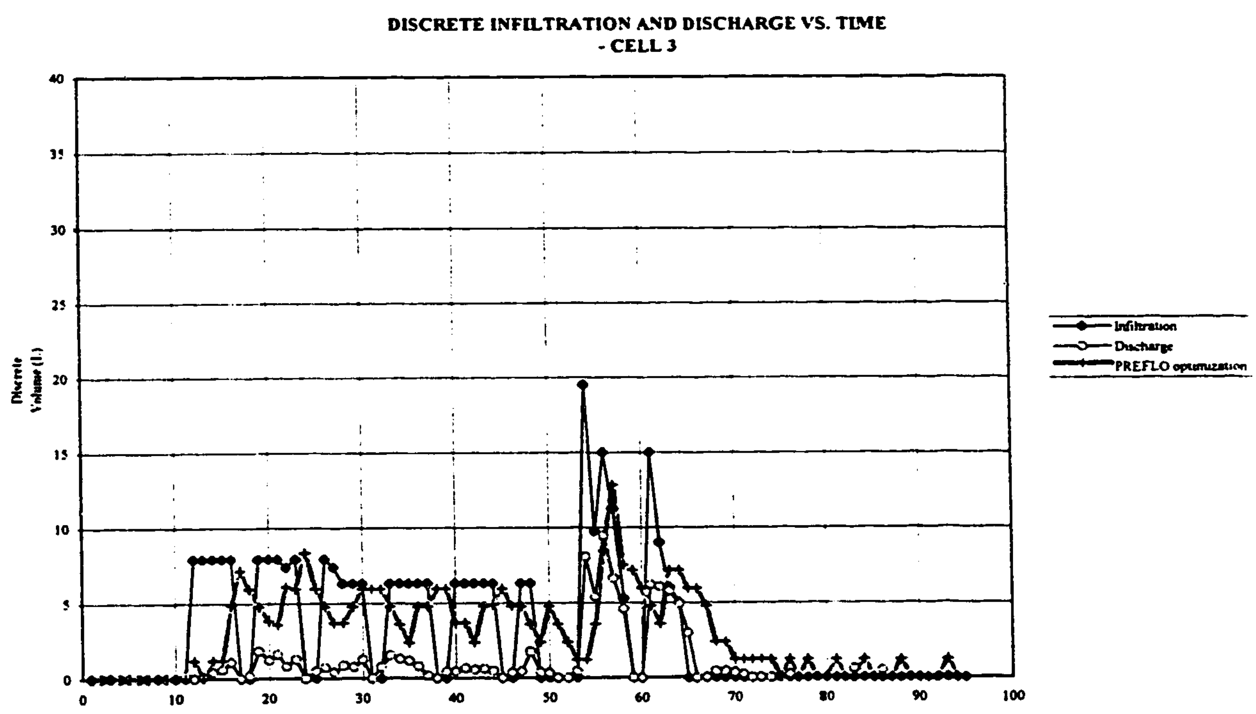
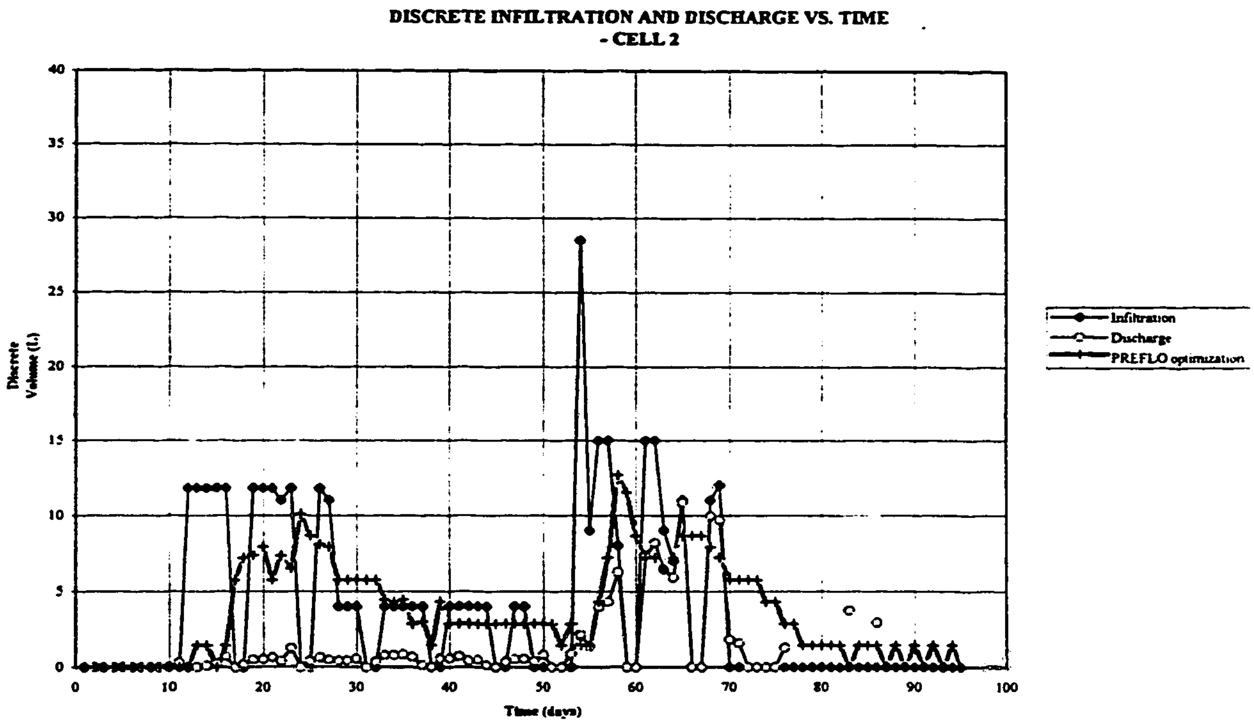


Figure 4.49: Discrete Leachate Volume Predicted From Optimized PREFLO Simulations for Low Infiltration Intensity, High Compaction Cells (Cells 2 and 4)



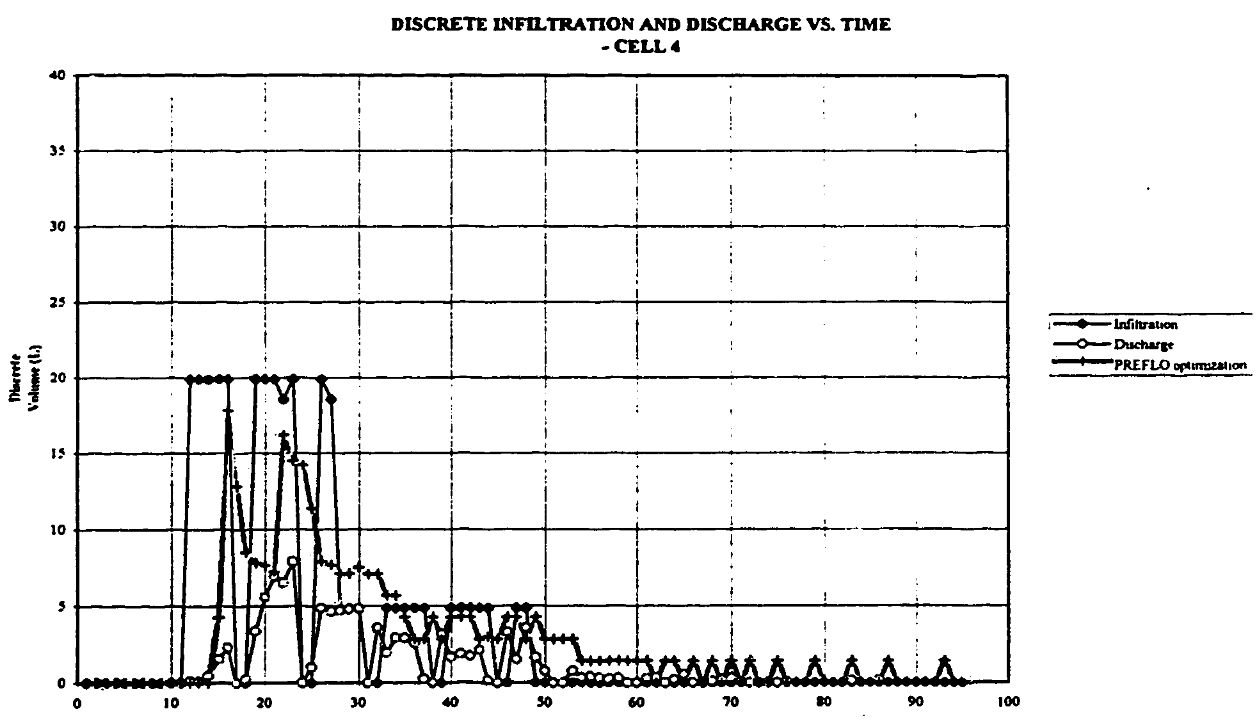
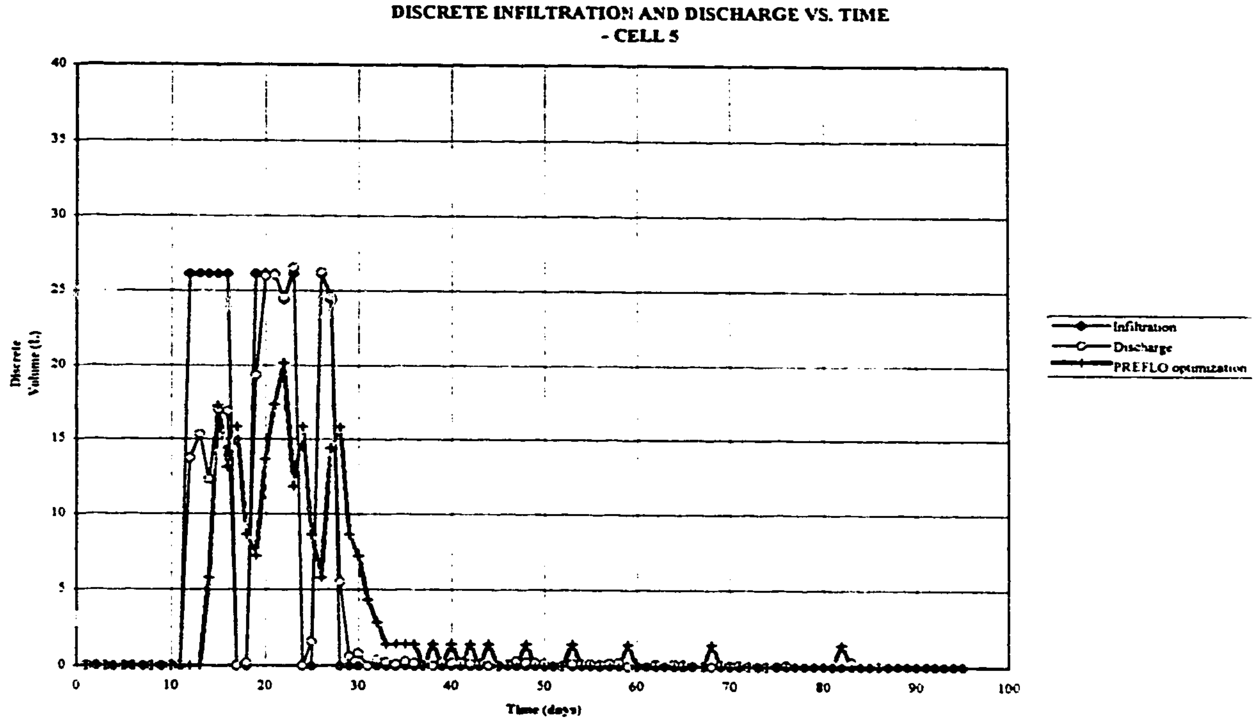


Figure 4.50: Discrete Leachate Volume Predicted From Optimized PREFLO Simulations for High Infiltration Intensity, Low Compaction Cells (Cells 5 and 7)



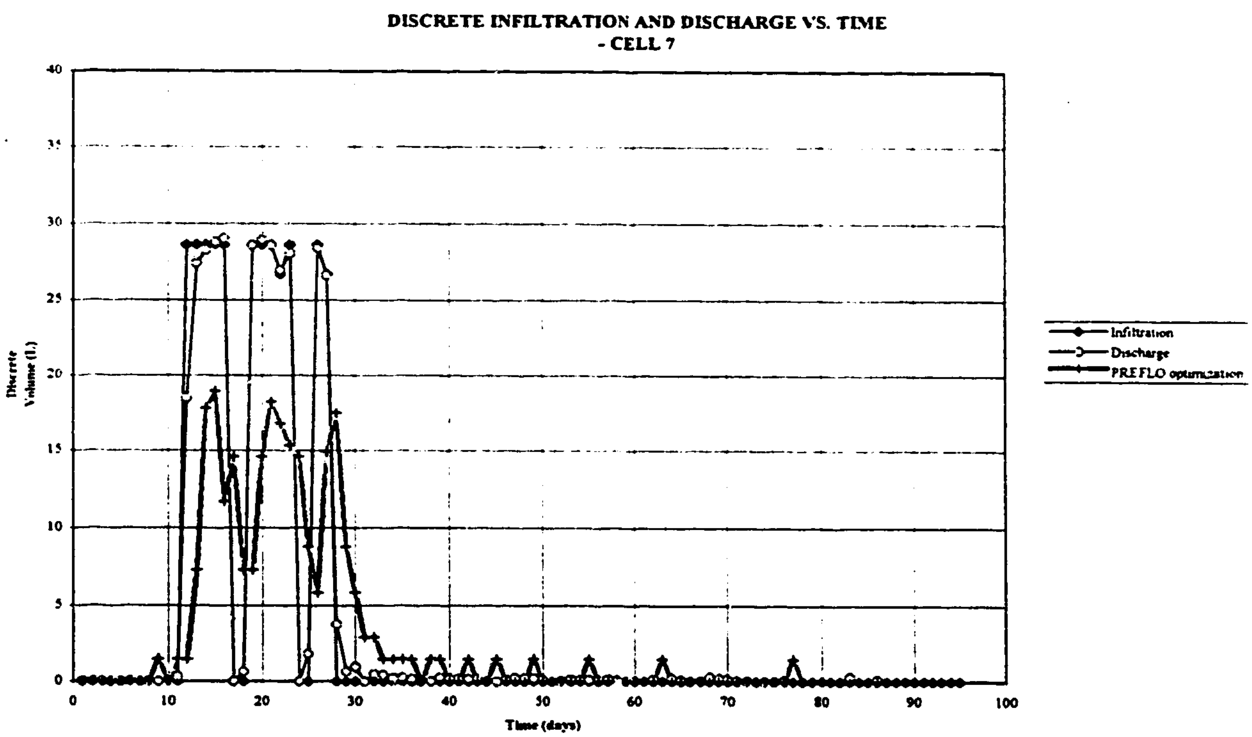
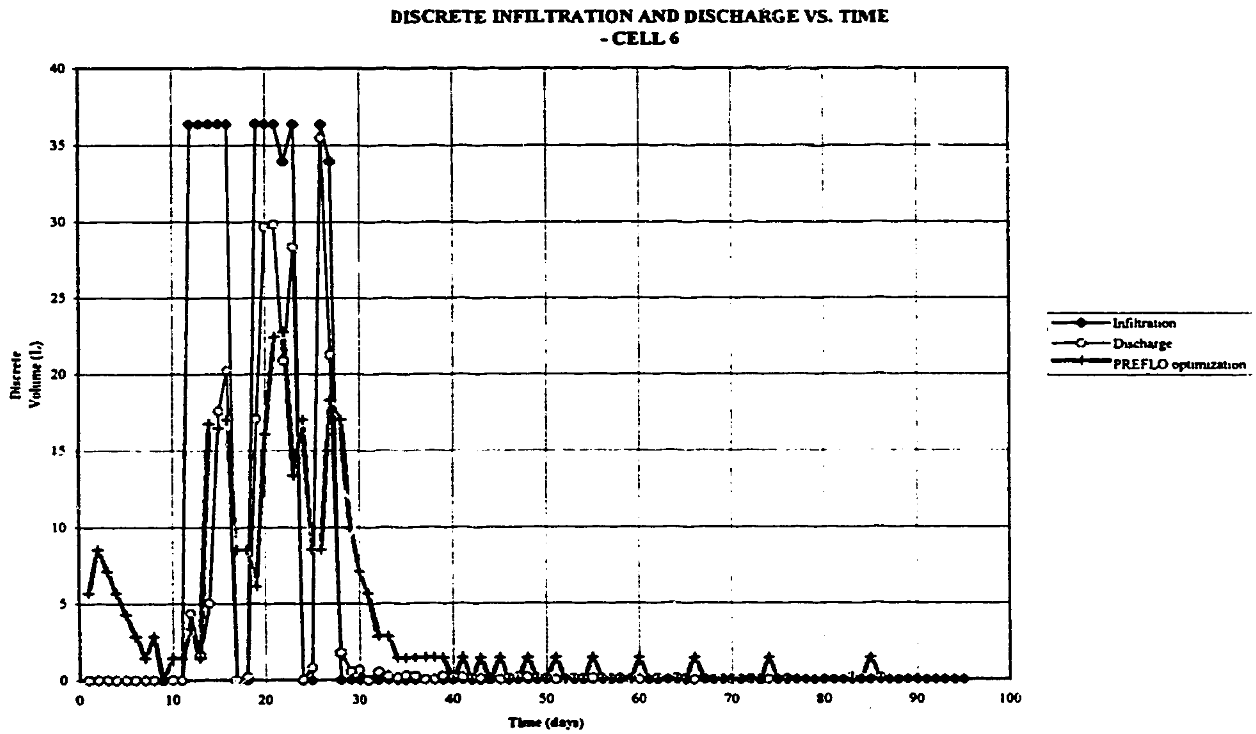


Figure 4.51: Discrete Leachate Volume Predicted From Optimized PREFLO Simulations for High Infiltration Intensity, High Compaction Cells (Cells 6 and 8)



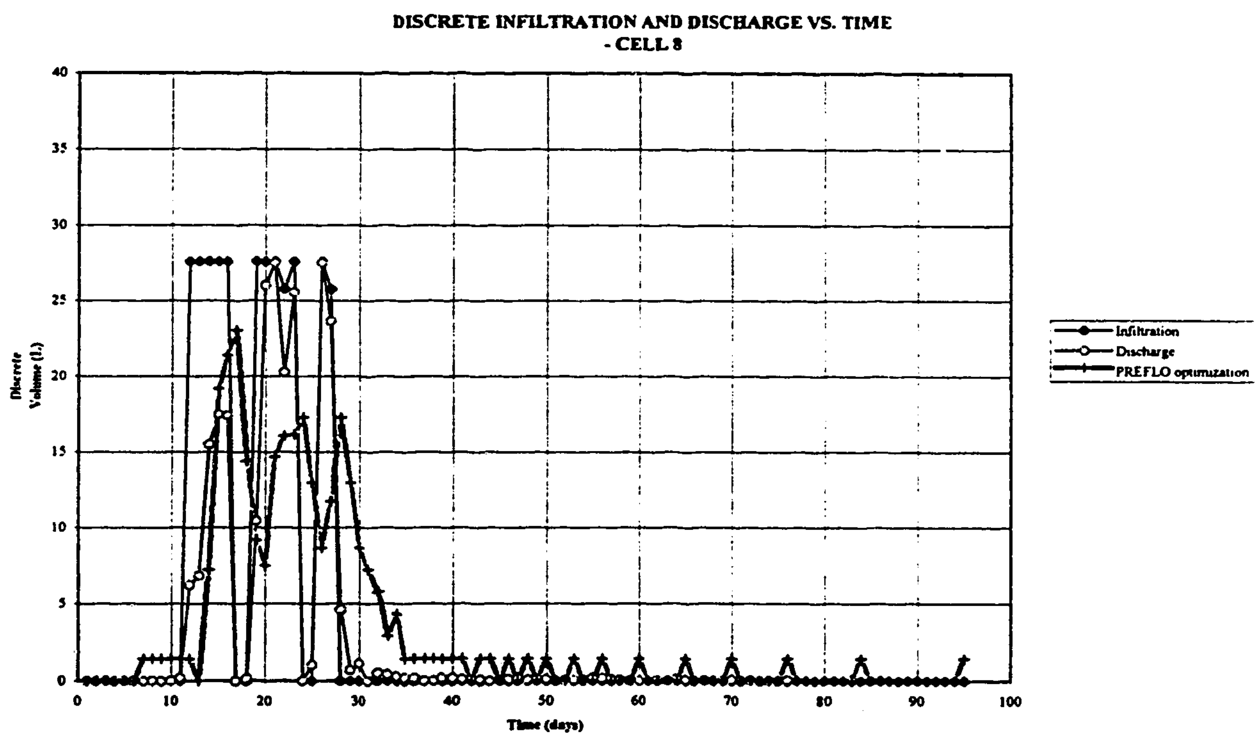
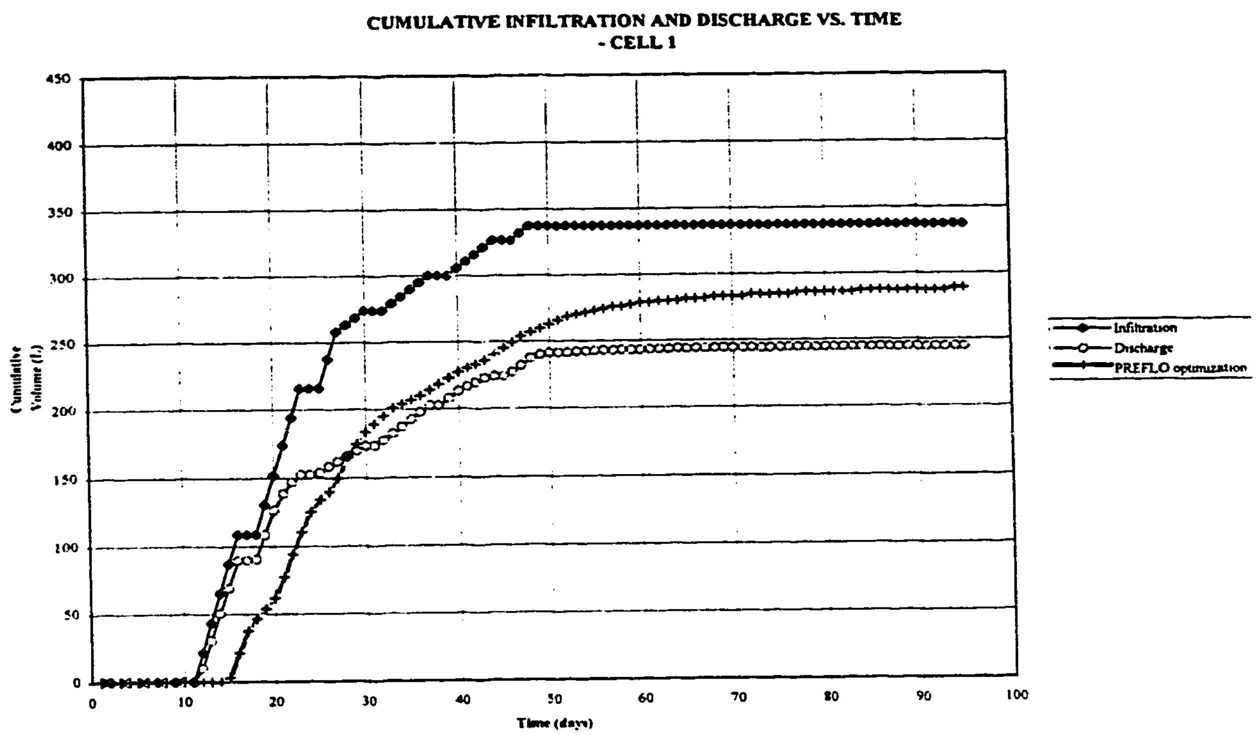


Figure 4.52: Cumulative Leachate Volume Predicted From Optimized PREFLO Simulations for Low Infiltration Intensity, Low Compaction Cells (Cells 1 and 3)



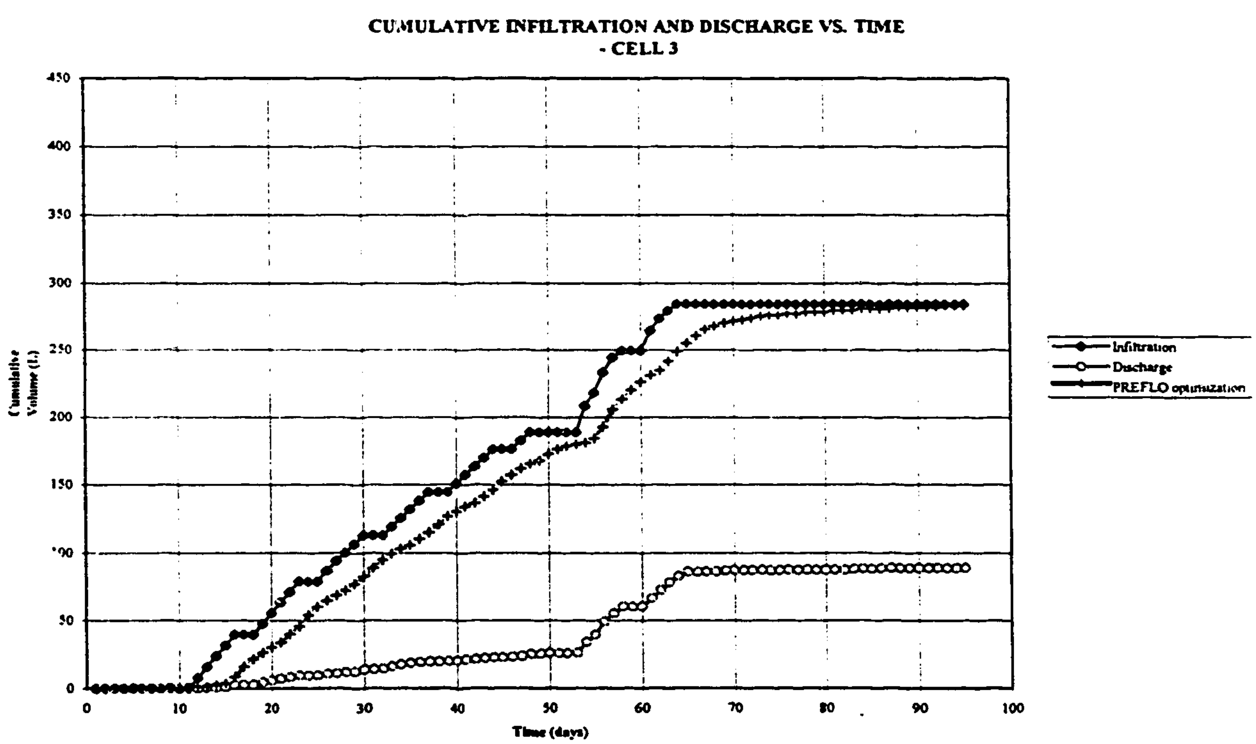
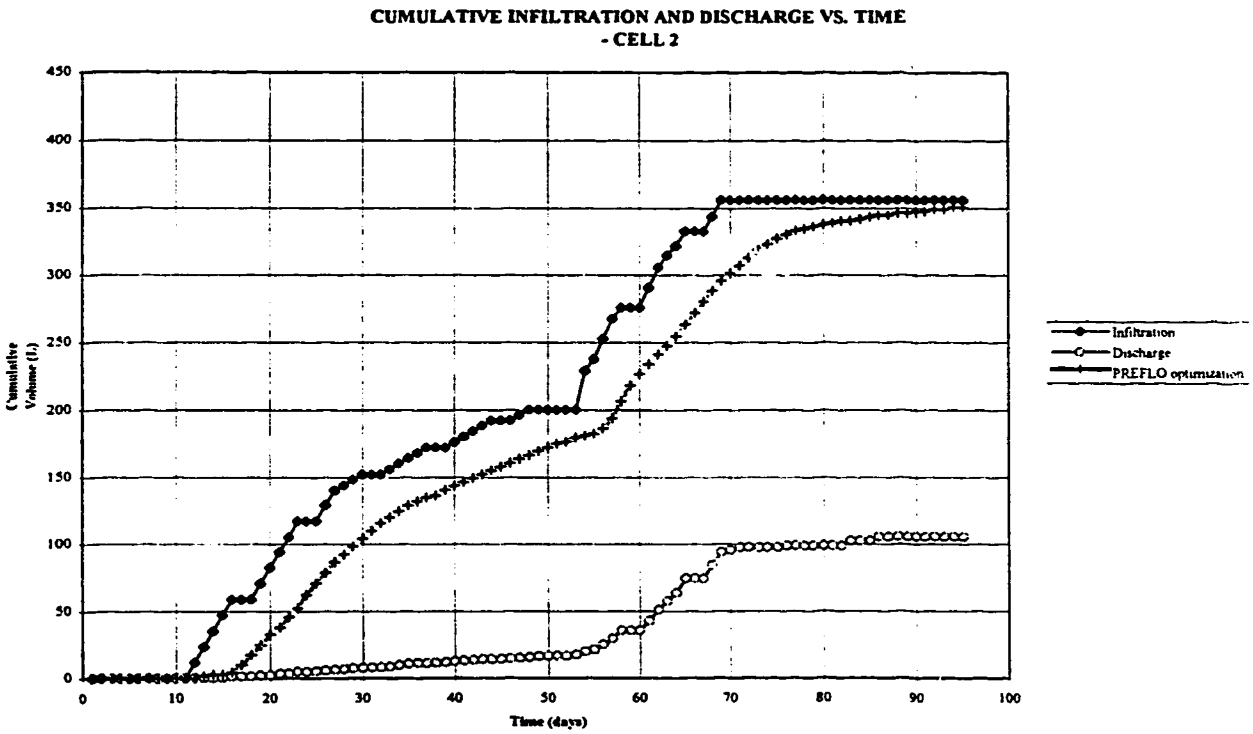


Figure 4.53: Cumulative Leachate Volume Predicted From Optimized PREFLO Simulations for Low Infiltration Intensity, High Compaction Cells (Cells 2 and 4)



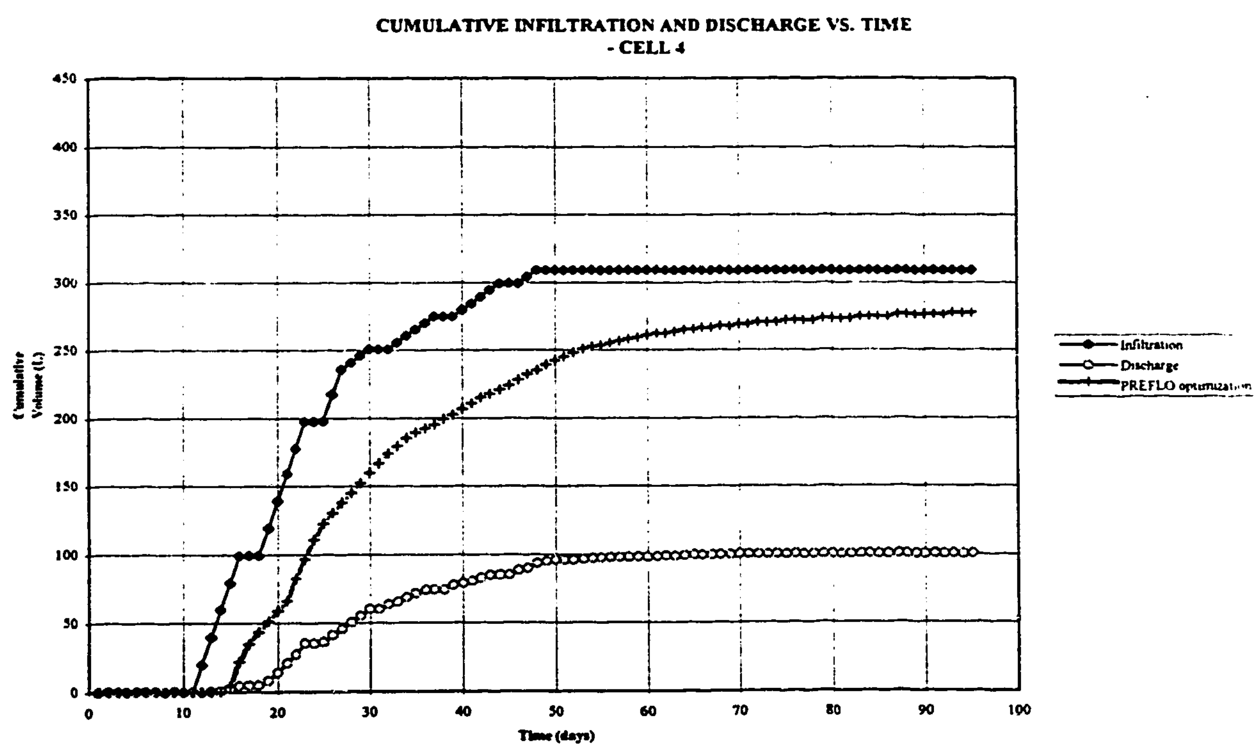
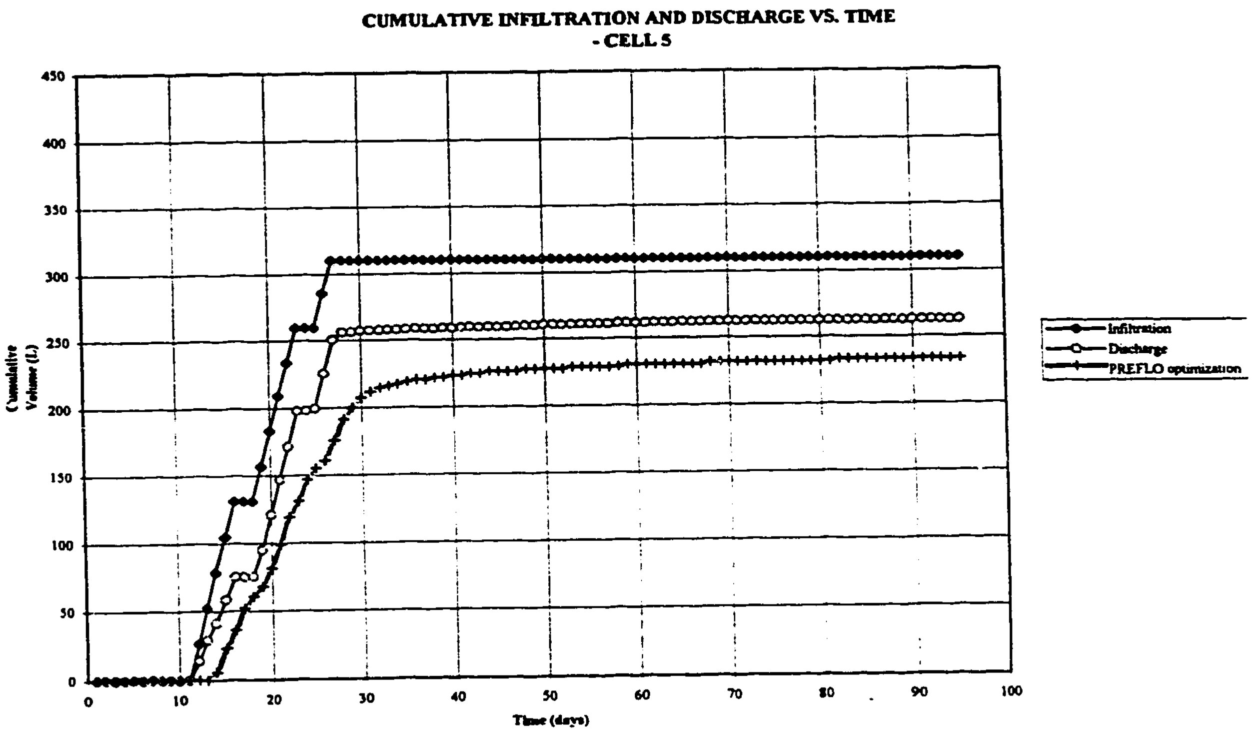


Figure 4.54: Cumulative Leachate Volume Predicted From Optimized PREFLO Simulations for High Infiltration Intensity, Low Compaction Cells (Cells 5 and 7)



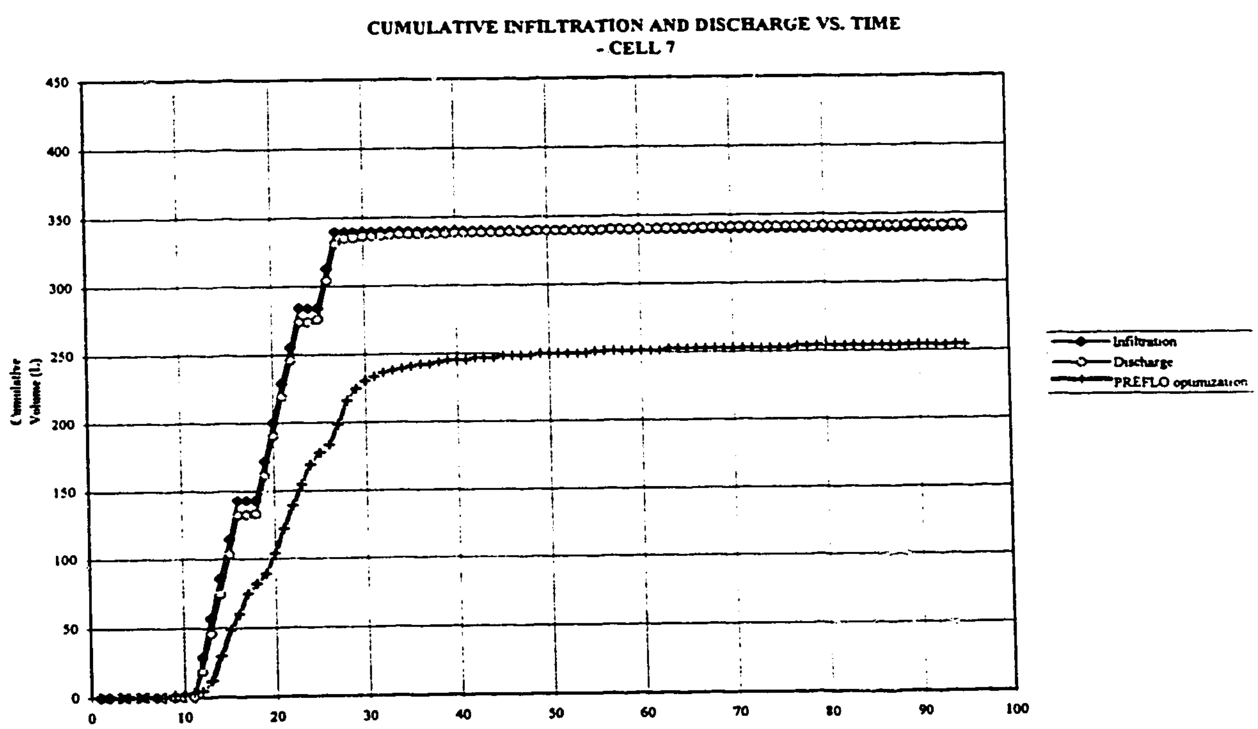
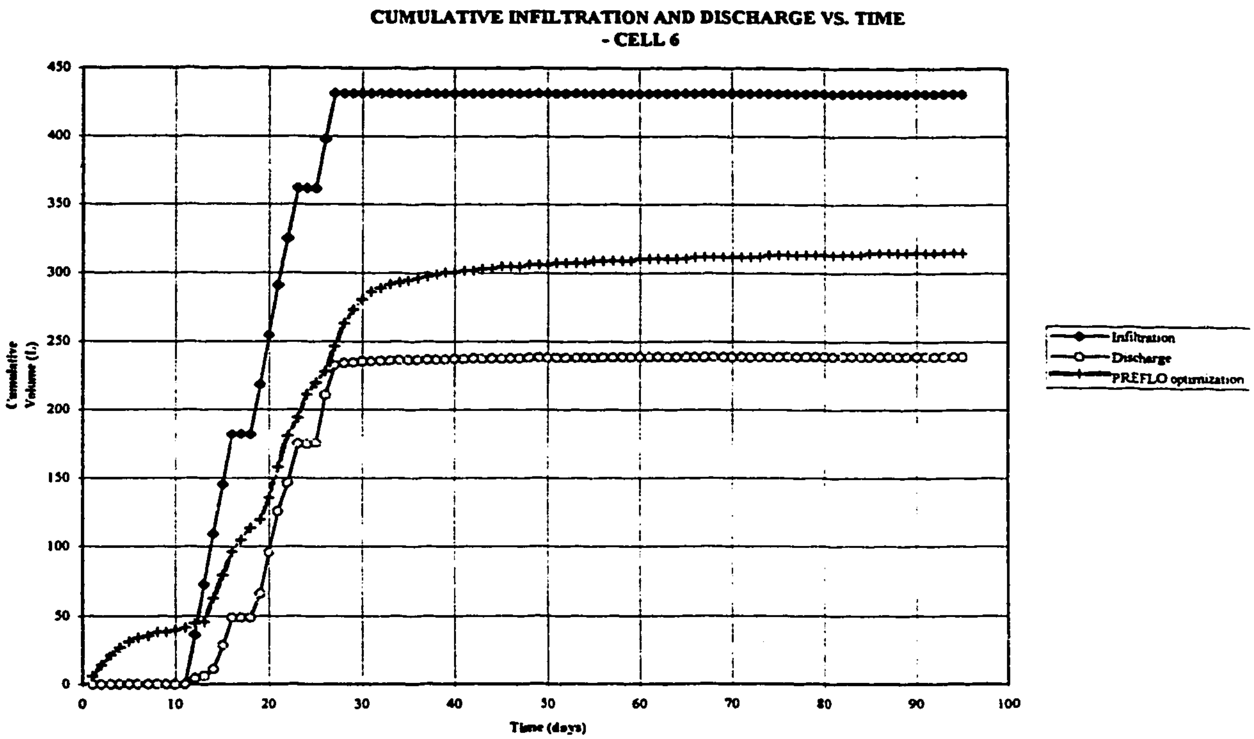
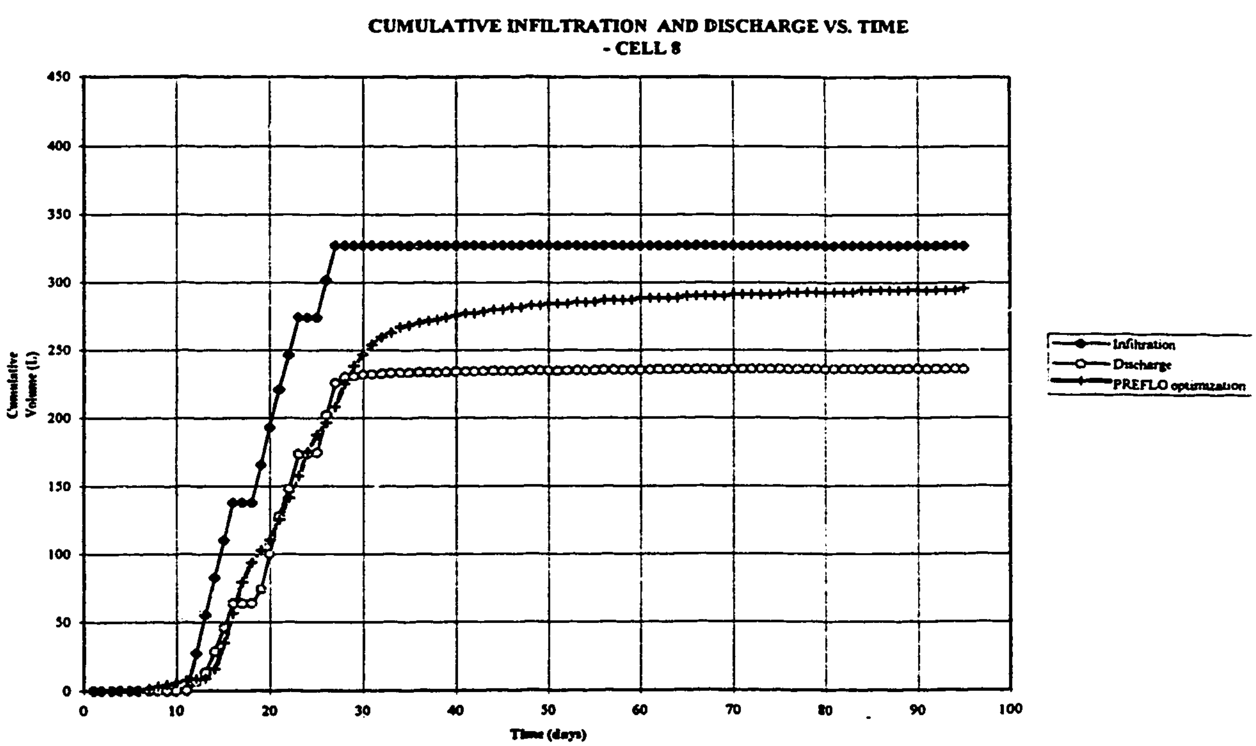


Figure 4.55: Discrete Leachate Volume Predicted From Optimized PREFLO Simulations for High Infiltration Intensity, High Compaction Cells (Cells 6 and 8)





Unlike the HELP model, the PREFLO model responds immediately to moisture addition, which is consistent with the experimental results, specifically for low infiltration intensity simulations (cells 1 and 4). This is due to the explicit simulation of channeling. The HELP model does not accurately predict breakthrough time because channeling is not considered as a separate flow mechanism. Breakthrough time is underestimated for all the high infiltration intensity simulations, except cell 5 (Figure 4.50). This results from the initial settings of PREFLO, as the initial moisture content was high enough to promote drainage before precipitation began. The model begins to route moisture through the matrix at the start of the simulation using the Richards equation. If the initial moisture content and hydraulic conductivity of the profile is great enough water may saturate the bottom node and drainage will occur. This is the case with the simulations of cell 6, 7, and 8. Though breakthrough time is modeled more accurately by PREFLO for low intensity cases, the model overestimates the total leachate volume discharged for these cells (Figures 4.51 and 4.52). This overestimation is less pronounced in cell 1 because of the high discharge of this cell during the early stage of the experiment. The discharge of cells 2, 3, and 4, however, is grossly overestimated during the early stages of the test. The simulated discharge agrees better with experimental results of these cells from about day 50 until the end of the test. Leachate is also discharged throughout the later stages of the test. This is due to the continuous drainage of the profile after water addition. PREFLO continues to route water through the matrix after moisture loading has stopped, but because drainage out of the profile occurs only when the bottom node is saturated, discrete drainage events occur when the water routed through to the bottom node can drain. These drainage events are less frequent with time as less water exists in the profile, so higher capillary pressures, lower moisture contents and lower hydraulic conductivities are experienced at each node. Therefore, the routing process is slower and the time between events is lengthened. This phenomena is evident in simulations of both high and low infiltration intensity cells. The simulation results for the high infiltration intensity cells are more accurate than for the low intensity cells with respect to volume of leachate generated. Also, the discrete discharge predicted by the model is always lower than the experimental discharge, and the model never reaches steady state. The maximum leachate volume which can be discharged in a time step by the model is equal to the volume of water in the channels plus the hydraulic conductivity of the matrix. The hydraulic conductivity or the pore area must therefore be increased in order to increase the volume of leachate discharged. However, the value of hydraulic conductivity was chosen so channeling would occur, and the pore area, determined experimentally, should provide a clear representation of the experimental system. It is difficult to adjust these parameters to increase the volume discharged while ensuring channeling occurs and the physical system is represented. Also, the model overestimates the discrete volumes of leachate discharged from low intensity cells so any adjustment to better model high infiltration intensity cells may worsen the predictive ability of the model with respect to low moisture loading intensity.

The HELP and PREFLO models can be directly compared by examining their ability to predict breakthrough time, time to effective storage, peak volume, time to peak volume, total volume, and duration of the leachate event. Table 4.12 through 4.15 show the six output variables characterizing leachate discharge for the optimization runs for both models as well as the experimental results. Table 4.17 shows a direct comparison of the six variables characterizing leachate discharge for the HELP and PREFLO models. These results clearly show that with respect to breakthrough time the PREFLO model results are closer to the measured results for low infiltration intensity cases, however, this model overestimates breakthrough time for the high intensity cases. As mentioned, this is due to the initial variable settings of the simulation. Based on the overall average, however, PREFLO predicts breakthrough time more accurately that the HELP model.

Time to effective storage is underestimated by both models. The HELP model predicts time to effective storage better for low intensity and high compaction, while PREFLO predicts this parameter best in low intensity, low compaction cases. Effective storage is not reached in all PREFLO high infiltration intensity simulations. As mentioned, this may be due to the drainage condition, which limits the maximum drainage of the profile to the saturated hydraulic conductivity. Generally, the HELP model predicts this parameter more accurately than PREFLO.

The prediction of the peak volume discharged is similar for both models. The HELP model predicts the measured peak volume better in all cases except low infiltration intensity, low compaction cells. In these cells HELP overestimates the peak volume by an average of 130%. PREFLO overestimates the average peak volume in low intensity and high compaction cases, and the range of peak volumes predicted by the model is larger than HELP. PREFLO overestimates the average peak volumes only in low intensity, high compaction simulations. When all simulations are considered, HELP predicts this parameter better.

Time to reach peak volume was overestimated by the HELP model for low intensity cases. However, PREFLO correctly predicts this variable for low intensity, low compaction cases while underestimating all other conditions. Generally, both models underestimate the time to reach peak volume, with the HELP model more closely predicting this parameter with respect to the overall average.

The total amount of leachate discharged from the waste is predicted quite differently by the HELP and PREFLO models. The HELP model under predicts the total volume in all cases (considering replicate averages). However, with the exception of high intensity, high compaction cells, specifically Cell 8 (Figure 4.47), HELP closely predicts the measured total volume discharged. The PREFLO model overestimates the total volume in all cases except high intensity, low compaction cells. However, when the results of all simulations are averaged PREFLO overestimates the total volume discharged (183% of measured). These results clearly show that the HELP model predicts the total volume of leachate better than PREFLO.

Table 4.17: Summary Table of Predictive Ability of HELP and PREFLO to Model Moisture Movement Through MSW

Predicted Moisture Movement Values From HELP and PREFLO, expressed as Percent of Actual

PARAMETER	Breakthrough Time (% of actual)		Time to Effective Storage (% of actual)		Peak Volume (% of actual)		Time to Reach Peak Volume (% of actual)		Total Volume (% of actual)		Duration of Leachate Event (% of actual)	
	HELP	PREFLO	HELP	PREFLO	HELP	PREFLO	HELP	PREFLO	HELP	PREFLO	HELP	PREFLO
Low Infiltration Intensity, Low Compaction												
Average	1450	225	63	72	131	113	138	100	86	218	46	175
Range	800 - 2100	50 - 400	39 - 86	56 - 87	103 - 158	89 - 136	96 - 180	100 - 100	79 - 93	118 - 318	20 - 72	147 - 203
Low Infiltration Intensity, High Compaction												
Average	1500	234	92	54	99	171	102	43	92	303	37	152
Range	1500 - 1500	67 - 400	90 - 94	31 - 76	61 - 138	117 - 225	81 - 123	15 - 70	76 - 107	275 - 330	19 - 54	107 - 197
High Infiltration Intensity, Low Compaction												
Average	100	0	67	NA*	99	72	54	93	98	83	88	391
Range	100 - 100	-300 - 300	33 - 100	NA	98 - 100	66 - 77	33 - 75	75 - 111	91 - 105	75 - 90	88 - 88	382 - 400
High Infiltration Intensity, High Compaction												
Average	800	-850	63	NA*	96	73	70	50	69	128	47	577
Range	700 - 900	-1200 - -500	53 - 75	NA	93 - 100	63 - 83	67 - 73	33 - 67	46 - 91	126 - 130	41 - 53	571 - 582
Low Infiltration Intensity												
Average	1475	230	78	63	115	142	123	72	89	261	42	164
Range	800 - 2250	50 - 400	39 - 94	31 - 87	61 - 158	89 - 225	81 - 180	15 - 100	76 - 107	118 - 330	19 - 72	107 - 203
High Infiltration Intensity												
Average	450	-425	65	NA*	98	73	62	72	95	106	68	484
Range	100 - 900	-1200 - 300	33 - 100	NA	93 - 100	63 - 73	35 - 75	33 - 111	46 - 105	75 - 130	41 - 88	382 - 582
Low Compaction												
Average	775	50	65	72**	115	93	96	97	92	151	67	283
Range	100 - 1400	-300 - 400	33 - 100	56 - 87	99 - 158	66 - 136	33 - 180	75 - 111	79 - 105	75 - 318	20 - 88	147 - 400
High Compaction												
Average	1338	-308	78	54**	98	122	86	47	81	216	42	365
Range	700 - 2250	-1200 - 400	53 - 94	31 - 76	61 - 138	63 - 225	67 - 123	15 - 111	46 - 107	75 - 330	19 - 54	107 - 582
All Simulations												
Average	963	-98	71	63	107	83	91	72	86	183	55	324
Range	100 - 2100	-1200 - 400	33 - 100	31 - 87	61 - 158	63 - 225	33 - 180	15 - 111	46 - 107	75 - 330	19 - 88	197 - 582

* Effective Storage was not reached in these simulations

** only low infiltration intensity cases considered because effective storage was not reached in high infiltration intensity runs

Duration of the leachate event is predicted poorly by both models. The HELP model consistently underestimates the duration of the event, while the PREFLO model consistently overestimates this parameter. As mentioned, the HELP model quickly responds to precipitation after breakthrough. However, because breakthrough is delayed and drainage ceases immediately after precipitation ends, the duration of the event is underestimated. Water is continuously routed through the profile when the PREFLO model is used. Therefore, drainage will not stop until all water is drained from the profile, though the rate of drainage will decrease. This continuous drainage extends the duration of the event considerably. Examination of the results shows that the HELP model predicts the duration of the event better than PREFLO (55% of measured for HELP, 324% for PREFLO).

The choice of models to predict leachate discharge depends on which parameter is of interest. PREFLO predicts breakthrough time more accurately than the HELP model based on the overall average, while the HELP model predicts the five other parameters better than PREFLO. If an estimate of head on a landfill liner is needed, PREFLO should be used since it more accurately predicts the breakthrough time and should give a better estimate of the amount of water ponding on a liner. However, if, for example, the total volume of leachate generated is needed the HELP model should be used since it gives a more accurate prediction of this moisture movement parameter. Generally, HELP models moisture movement more accurately than PREFLO. However, both models require the use of fitting parameters such as K_s' to reasonably predict experimental results. Therefore, they do not accurately represent the physical system. As mentioned, HELP assumes Darcian flow through homogeneous porous media. The tensiometer and flow-cup results show that channeled flow also occurs, and the waste cannot be considered homogeneous. Also, though PREFLO explicitly accounts for channeling, channeled flow can only occur if infiltration intensity is greater than the saturated hydraulic conductivity of the media. As mentioned in section 2.1, previous studies, and the moisture movement experiment conducted here, have noted that channeling occurs at infiltration rates lower than the saturated hydraulic conductivity of MSW. Therefore, PREFLO, which was not developed for MSW, does not accurately represent the true flow mechanism. Also, a number of the parameters needed as input into the PREFLO model are not well known for MSW, such as the moisture content - capillary pressure relationship. Therefore, while HELP and PREFLO are perhaps the best available models, based on their development, and the information they provide (section 3.2) they do not adequately represent observed moisture movement through municipal solid waste.

5 SUMMARY, CONCLUSIONS, AND FURTHER RESEARCH

5.1 SUMMARY AND CONCLUSIONS

Moisture movement through municipal solid waste (MSW) has an effect on leachate quantity generated from landfills. Current modeling techniques represent this moisture movement as one-dimensional Darcian flow through homogeneous porous media. However, because previous research has shown that channeling is a significant flow mechanism, the representation of moisture movement should be adjusted to account for channeling. This should lead to better prediction of moisture movement, specifically leachate discharge, through municipal solid waste. Other methods of representing flow through MSW include the water balance method, fractured media models, and fractured - porous media models. Though the water balance method has been used to estimate moisture movement through MSW, fractured and fractured-porous media models have not yet been applied to the problem. The heterogeneity of the media adds to the difficulty of modeling moisture movement through MSW.

More accurate prediction of moisture movement is important because moisture influences biodegradation and methane generation in MSW landfills. If more is known about the mechanisms of moisture movement, operating conditions in landfills may be adjusted to optimize, for example, methane generation. Also, legislation such as the United States Resource Conservation and Recovery Act regulate landfill operation with respect to leachate generation. Therefore, to ensure compliance, an accurate estimation of moisture movement through MSW is critical for proper adjustment of landfill operations.

In order to solve the problem, research objectives were proposed and satisfied. The objectives required that the presence of channeling in pilot scale test cells be confirmed. Previous experimental work which concluded that channeling was a significant flow mechanism was conducted with bench-scale equipment. If channeling was shown to be significant in pilot-scale cells, it is likely that it would also occur in an actual landfill, and, therefore, its effect on moisture movement should be included in any model used to simulate flow through landfills. The presence of channeling was investigated in pilot scale cells with instrumentation which could determine channeled flow both directly and indirectly.

Also, because different environmental and operating conditions affect moisture movement, one research objective was to determine and quantify the effects of the most important factors on moisture movement through municipal solid waste. This was accomplished by using the same pilot-scale experiment used to determine the presence of channeling. The primary environmental and operating factors of concern were identified through a literature review. These factors were infiltration intensity, compaction and waste wet bulk density. Eight discrete variables, which had been used in previous studies to describe the effects of channeling on moisture movement, were used to test the effects of the factors on moisture movement. These variables were practical field capacity, effective storage, water added to reach practical field capacity, water added to reach effective storage, breakthrough time, time to reach effective storage, and initial and ultimate unsaturated hydraulic conductivity. The use of these parameters enabled the effects of infiltration intensity, compaction, and density on moisture movement to be determined.

The most commonly used model for representing moisture movement through MSW is the HELP model. As this model does not explicitly consider the channeling which has been shown to occur in MSW, one research objective stated that this model should be evaluated to determine its ability in predicting moisture movement. This was accomplished by using the model to predict the leachate discharge of the pilot-scale moisture movement experiment. The model results were compared to experimental results to determine the model accuracy. Again, because moisture movement (represented by leachate discharge) is a continuous process, discrete parameters were used so model results could be compared directly to experimental results. The parameters used to characterize moisture movement were breakthrough time, time to effective storage, peak volume of leachate discharged, time to reach peak volume, total volume of leachate discharged, and duration of leachate event. These parameters have been used in previous moisture movement studies and are similar to those used in hydrograph analysis. In addition to comparing HELP model simulations which neglected channeling to experimental results, HELP model simulations accounting for channeling were also used for comparison. As the HELP model can only implicitly account for channeling, one research objective was to test the predictive ability of a two-domain fractured - porous media model which could explicitly model channeled on moisture movement. A model which explicitly accounts for channeling, the PREFLO model, was also used to simulate experimental results. This model was chosen from a number of possible models identified in the literature, based on criteria developed to determine model applicability in representing moisture movement through MSW. The results of the PREFLO model were also compared to the HELP model to determine which model more accurately simulated observed moisture movement.

The research objectives were used to develop hypotheses which were tested with experimental data. The hypotheses along with the conclusions developed by testing them are given below.

Hypothesis 1 was developed to evaluate the presence of channeling. This hypothesis states that channeling occurs in pilot-scale cells. Tensiometer and flow-cup grid data were used to test this hypothesis. The analysis of tensiometer data showed that uniform flow does not occur in 63% of cases tested. Flow-cup data showed that at no time during water addition were all flow-cups discharging on the same day, for all cells. This shows that channeling occurs because if only micropore flow occurred the entire waste cross-section should contribute to flow, and, therefore, all flow-cups would discharge. The statistical analysis of the results also supported the channeling hypothesis. In seven of the eight experimental cells, moisture was shown to move non-uniformly through the waste. Also, it was shown that micropore flow is not the exclusive flow mechanism in the experimental cells (an average of 87% of all cases tested showed this result). Therefore, from the results it is concluded that channeling occurs in pilot-scale cells. Generally, the results showed that channeling is most prevalent in high infiltration intensity and low compaction cases, however, it also occurs in low infiltration intensity and high compaction cells.

Hypotheses 2, 3 and 4 were used to test if infiltration intensity, compaction, and waste density had a significant effect on moisture movement. Infiltration intensity was found to be the most important factor on moisture movement because it significantly affected six moisture movement variables. These variables were effective storage, water added to reach effective storage, breakthrough time, time to reach effective storage, and initial and ultimate unsaturated hydraulic conductivity. Waste density was also found to affect moisture movement as it had a significant effect on five variables including practical field capacity, effective storage, water added to reach practical field capacity and effective storage, and time to reach effective storage. The interaction of waste density with infiltration intensity also affected moisture movement. This interaction significantly affects effective storage, water added to reach practical field capacity and effective storage, as well as time to reach effective storage, and ultimate unsaturated hydraulic conductivity. The main effect of compaction, and the interaction of compaction and infiltration intensity on moisture movement was only significant with respect to water added to reach effective storage. In summary, hypotheses 2 and 4 are supported, while hypothesis 3 is not supported by the experimental results. Therefore it is concluded that infiltration intensity and waste density affect moisture movement through MSW, however, compaction does not (with respect to the variables examined).

Hypothesis 5 states that modeling moisture movement as a one-domain process accounting for channeling leads to better moisture movement prediction than modeling moisture movement as a one-domain process and neglecting channeling effects. This was tested by comparing the results of the HELP model simulations in which default input parameters were used to simulation results with optimized input parameters. Both sets of simulations were then compared to the results of the moisture movement experiment. The optimized input parameters were determined through the use of a sensitivity analysis. The comparison of the simulations shows that no leachate is predicted by HELP model runs neglecting channeling (default input parameters), however, leachate discharge is predicted when channeling is considered (optimized parameters), thus, hypothesis 5 is supported. Therefore, modeling moisture movement through MSW as a one-domain process accounting for channeling allows for better prediction of moisture movement than modeling flow as a one-domain process neglecting channeling.

Though the above conclusion is reached, it should be noted that the HELP model is limited in its ability to model flow through MSW. As mentioned uniform infiltration is routed by HELP through a homogeneous porous matrix. The rate of infiltration and percolation is controlled by the hydraulic conductivity of the layer so channeled flow can only be approximated by increasing the hydraulic conductivity of a layer. Therefore, it is not possible to simulate infiltration conveyed directly through channels and the resulting short breakthrough time as was observed in the moisture movement experiment. Also, the experimental cells show that drainage occurs shortly after moisture addition and increases until steady state is reached as moisture is redistributed into the matrix. Due to the drainage routine of HELP which permits discharge only at moisture contents at and above field capacity, the observed redistribution is not modeled, and longer breakthrough times are predicted. Shorter breakthrough times may be achieved by lowering the field capacity moisture content, however, once field capacity is reached all infiltration is quickly discharged, as redistribution is neglected. Therefore, though accounting for channeling by adjusting the HELP input parameters gives better prediction of moisture movement than using HELP default parameters, the mechanisms of channeled flow are not well represented by the model.

Hypothesis 6 states that modeling moisture movement through MSW as a two-domain process enables better prediction of moisture movement than modeling moisture movement as a one-domain process accounting for channeling. This hypothesis was tested by comparing PREFLO and HELP simulations to experimental results. Both the HELP and PREFLO "optimized" simulations (using input parameters optimized through a sensitivity analysis) were used for comparison. Other PREFLO simulations which were derived from HELP default and calibration parameters predicted no leachate discharge. The comparison of the models showed that the PREFLO model only predicted breakthrough time better than HELP, while HELP predicted time to reach effective storage, peak volume of leachate discharged, time to reach peak volume, total leachate volume discharged, and duration of the leachate event better than PREFLO. These results do not support hypothesis 6. It can therefore be concluded that modeling moisture movement as a two-domain process, using PREFLO, does not allow better prediction of moisture movement than by modeling it as a one-domain process accounting for channeling. As mentioned, both of these models do not accurately represent the actual mechanism of flow through MSW. Therefore, this hypothesis should be tested with a two-domain flow model developed to represent flow through municipal solid waste.

PREFLO could be used to test this hypothesis again if the channeled flow routine were modified. Channeled flow occurs in PREFLO if infiltration intensity is greater than the saturated hydraulic conductivity of the homogeneous porous matrix. As mentioned, this is not consistent with experimental results which show channeling occur at low infiltration intensities. In order to simulate channeling when modeling the experimental cells it was necessary to artificially lower saturated hydraulic conductivity to less than the infiltration intensity. Therefore, saturated hydraulic conductivity is a fitting parameter with no real physical significance. PREFLO could more accurately reflect the observed flow mechanism if channeled flow began at infiltration rates lower than the matrix saturated hydraulic conductivity. Also channeled flow is redistributed by the model to the porous matrix, with percolation conveyed through the channels only when the matrix is saturated. However, experimental results suggest that at breakthrough discharge is primarily from channels and not from the waste matrix. PREFLO could more accurately represent this experimental flow mechanism if some channeled flow was allowed to percolate through a layer before the matrix was saturated. With these changes to the channeled flow routine the model would better represent the observed channeled flow mechanisms.

In summary, it is concluded that channeling occurs in pilot scale cells, and infiltration intensity and waste density affect moisture movement through MSW, while compaction has no affect on moisture movement. Also, modeling moisture movement as a one-domain process accounting for channeling allows for better prediction of moisture movement than modeling flow as a one-domain process neglecting channeling. It is further concluded that modeling moisture movement as a two-domain process using PREFLO does not allow better prediction of moisture movement than by modeling it as a one-domain process accounting for channeling. Through testing the hypothesis developed from the research objectives, the above conclusions were reached, and the original problem was resolved.

5.2 SIGNIFICANCE AND FURTHER RESEARCH

Because channeling is a significant flow mechanism in pilot-scale cells, it is likely that it is significant in an entire landfill. Therefore, modeling of moisture movement must account for channeling to ensure accurate prediction of leachate generation which is necessary to design leachate collection and treatment systems. Another important design consideration is the head on the landfill liner, as existing legislation limits a maximum head build up. The effects of channeling on moisture movement must, therefore, be included in any simulation to accurately predict the head built up on the landfill liner. Also, if a great deal of channeled flow occurs a smaller cross-sectional area is wetted. Since moisture promotes biodegradation and methane generation, the occurrence of channeling may inhibit the rate of these two processes in a landfill, as some parts of the waste may remain dry. Biodegradation and methane generation may be optimized by minimizing channeling through adjusting various operational and environmental conditions to which the landfill is exposed.

Infiltration intensity encourages channeling. Therefore, based on the experimental results, leachate recirculation rates should be limited to under 7 mm/hr to optimize biodegradation and methane generation. Further research should be conducted to determine the optimum loading rate to minimize channeling and increase the amount of waste exposed to flow. Density is the most important operational condition on moisture movement through MSW, with lower densities encouraging more channeling. In order for biodegradation, and methane generation, to be maximized, waste should be compacted to densities above 500 kg/m^3, based on the experimental results. Further research on the optimum setting of this parameter to minimize channeling should also be conducted. Since compaction does not greatly affect moisture movement, standard compaction using heavy equipment should be sufficient to prevent excessive channeling.

The comparison of the models has shown that the HELP model is an adequate tool for the prediction of time to effective storage, peak volume, time to reach peak volume, total leachate volume generated, and duration of a leachate event. However, the two-domain model PREFLO provides more accurate prediction of breakthrough time. The choice of which model to use to predict moisture movement through MSW should depend on what specific parameter needs to be estimated. If an overall prediction is required the HELP model should be used because it has been specifically developed to model flow through MSW, and has been previously tested. The PREFLO model shows potential, however, as this is the first time it has been modified for use with MSW, further adjustment and testing may be necessary before the model can be used with confidence.

This research has shown that channeling is significant in pilot-scale cells, and that various environmental and operational conditions, specifically infiltration intensity and waste density, affect moisture movement through municipal solid waste. Also, the research has shown and that simulating channeling as a two-domain process allows better prediction of some parameters which characterize leachate generation (e.g., breakthrough time) than simulating channeling as a one-domain process. However, further research should be conducted to ensure even greater predictive ability of moisture movement through MSW. Certainly, better knowledge of the hydraulic properties of MSW are needed. Specifically, moisture content - capillary pressure relationships of the waste matrix and channel-size parameters such as diameter should be further investigated. This would allow for optimization of modified software such as PREFLO to accurately represent municipal solid waste. Also, a two-domain model developed to simulate the actual flow mechanism of moisture movement through solid waste which includes channeled flow at low infiltration rates should be constructed. The input and output parameters should be similar to those used as model criteria (section 3.2). This would allow a user to work with a tool specifically developed for MSW, and would eliminate the need to modify, for example, a soil model to describe flow through waste. With moisture movement through solid waste better understood, contaminant transfer, and the effects of moisture movement on leachate concentration, and methane generation should be further investigated. The results of this investigation could be incorporated into a model which could then accurately predict both flow and concentration of leachate generated from municipal solid waste, as well as predicting leachate generation rates from landfills.

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