THE UNIVERSITY OF CALGARY

An Investigation of Leachate Production from MSW Landfills in Semi-Arid Climates

by

Vanita S. Shroff

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

CALGARY, ALBERTA

MAY, 1999

0-612-48069-0

ABSTRACT

The prediction of peak and average leachate flow rates are important parameters for designing the landfill Leachate Collection and Removal Systems (LCRS's) and the landfill bottom liners. The U.S. EPA's HELP (Hydrologic Evaluation of Landfill Performance) model is the most widely used predictive tool for this purpose. This thesis describes a study on the leachate production patterns from MSW landfill and the applicability of HELP model in semi-arid climates.

Field landfill lysimeter was constructed to study the effect of rainfall/leachate re-circulation on leachate production patterns from a simulated landfill. The MSW parameter values such as the practical field capacity, porosity, and saturated hydraulic conductivity were determined in the laboratory. The HELP model simulations were performed for the field rainfall/leachate re-circulation simulations using the laboratory MSW parameter values, and were compared to the actual field peak and average leachate production.

The test results indicated that the time of placement of final cover was critical in minimizing leachate production in landfills; the sooner the cover is placed, the less is the leachate produced. Practically, under semi-arid climatic conditions such as in Calgary, immediate placement of the final cover could delay leachate production by several years. The density of compacted waste was an important factor in leachate production from MSW landfills. The peak/average leachate production rate determined from the rainfall/leachate re-circulation field simulations was 20 for leachate re-circulation and 7.5 for rainfall infiltration events. The HELP model over-predicted the peak leachate discharge rate and the average leachate discharge rate, and under-predicted the peak/average leachate discharge ratio. It over-predicted the seepage through the barrier layer. The HELP model predictions can be improved by using site-specific waste and cover layer parameter values.

ACKNOWLEDGEMENTS

This research program was conducted under the supervision of Dr. J.P.A. Hettiaratchi. I would like to thank him for his guidance, encouragement, insightful ideas, patience, and availability through every step of the study. The knowledge, experience, and skills that I have developed under his supervision will undoubtedly benefit me for the rest of my life. I would like to thank Dr. G. Achari for his constructive criticism and encouragement throughout the study.

I would like to thank the Department of Civil Engineering for providing all the resources and support necessary to complete this program.

I express my sincere gratitude to Mr. Kiran Dave, Manager, and Mr. Harry Friesen, Head Mechanic, from Grounds Department for their help in conducting the field studies for this research; Dr. Lawrence Nkemdirim and Mr. Rick Smith, from the Department of Geography for providing the weather data for this research; and Harry Pollard and Heather Mills, Department of Civil Engineering, for their contributions in setting up the laboratory.

I am most thankful to my friends Nandana Perera, Prasanna Lal Amatya, Kanishka Perera and others, for all the numerous discussions and co-operation throughout this research. It seems like yesterday only when all were sitting out in the field in the scorching heat of summer afternoon, sorting the waste collected for this research. I am grateful to my parents and my sisters for their inspirational support, throughout this research. Finally, I would like to express my deep gratitude to my husband, Sanjay, for his love, understanding, and co-operation throughout my research.

TABLE OF CONTENTS

CHAPTER FOUR

PRESENTATION AND DISCUSSION OF RESULTS

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 GENERAL

The interaction of landfilled waste with infiltrating moisture leads to the generation of leachate. Improper design and operation of landfills lead to escape of leachate into subsurface soil and poses a threat to groundwater resources (U.S. EPA, 1984).

The volume of leachate generated is a function of parameters such as landfill surface conditions, infiltration, initial moisture content of the waste, and waste characteristics. Landfills are designed and operated to reduce and collect the generated leachate. The primary design components of a landfill are the final cover, the leachate collection and removal system (LCRS), and the bottom liner. The final cover reduces the amount of moisture percolating into waste layers. The moisture percolating across the cover flows through the MSW and into the LCRS. The LCRS aids in collection of leachate generated. The LCRS consists of a drainage layer, a filter layer, and leachate collection pipes. The design of a LCRS is based on peak and average leachate volumes, as well as the duration of peak volumes. The LCRS's are designed to collect the maximum quantity of leachate generated, and minimize the escape of leachate across the bottom liner.

The quantity of leachate escaping the LCRS forms a saturated layer, known as mounding, on the landfill bottom liner. The low hydraulic conductivity of the bottom liner minimizes the migration of leachate into groundwater system, increasing the mounding depth on the liner. Mounding of leachate on the liner, results in the development of hydraulic head which causes leakage of leachate through the liner. The U.S. EPA's RCRA Subtitle D regulations for MSW require that the LCRS be designed, and operated to maintain a maximum mounding depth of 30 cm above the liner. The mounding depth depends on the rate of leachate percolation, the permeability of the drainage layer of LCRS, the spacing of leachate collection pipes of LCRS, and permeability and slope of the bottom liner. The spacing of leachate collection pipes depends on the peak and average leachate flow rates, as well as the duration of peak flow (Korfiatis and Demetracopoulos, 1986; McEnroe, 1989, Tchobanoglous et al., 1993). The lesser the spacing between the collection pipes, the more leachate is collected, decreasing the mounding depth.

The design of the LCRS and the landfill bottom liner depend on the peak and average leachate flow rate and the duration of peak flow. However, MSW landfills display large fluctuations in leachate flow rates. An increase in leachate flow rate is observed following the occurrence of rainfall events (Guyonnet et al., 1998). The LCRS becomes inefficient, if not designed for the peak flow rates. However, when designed for peak flow rates, efficient LCRS causes a temporary increase in the amount of leachate collected. An increase in leachate concentration is expected in the early stages of rainfall, due to the wash-out effect (Kao et al., 1986; Huang, 1987). With further rainfall, a decrease in concentration is expected due to dilution. An understanding of the changes in leachate quality and quantity is necessary in the design of a landfill.

The peak and average leachate flow rates, and the time and duration of peak flow rates, are determined by using the Water Balance Method (WBM) (Fenn et al., 1975), or models such as the U.S. EPA's Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1994), or the Flow Investigation of Landfill Leachate (FILL) model (Khanbilvardi et al., 1995). To determine the leachate volume and flow rates, the models require input values for parameters such as rainfall, runoff from the landfill surface, quantity of leachate re-circulated (if any), groundwater intrusion, evapotranspiration from the landfill, and moisture stored in the landfill system.

The HELP model has been developed as a management and design tool for landfills (Peyton and Schroeder, 1988). It is the most widely used predictive tool for sanitary landfills and is the only one considered for this research. It uses the water-balance technique to determine the volume of leachate generated using the knowledge of climatic and hydrologic parameters, and the properties of the landfill. The model requires values for several input parameters including the daily climatic data, cover system design data, and MSW design data such as: field capacity of the waste layer, wilting point of the waste layer, and saturated hydraulic conductivity of the waste layer. Quite often, it is difficult to obtain the design data for calibration of the model, limiting the applicability of the model. Further, the model requires input parameters that are not directly measurable and are selected based on judgement and past experience. Alternatively, the model provides default values for these parameters that may be used. The model also has an inherent assumption that the landfill conditions remain uniformly constant throughout its life. These and many other assumptions in the HELP model, limit its ability to predict accurate leachate generation rates. Furthermore, very little information is available in literature on the predictive capabilities of models in semi-arid climates such as Calgary where precipitation is low and in-frequent, and initial moisture content of waste is below average during most of the year (Shroff et al., 1998).

1.2 OBJECTIVES

The primary goal of this research is to generate information to increase the predictability of the leachate generation model, HELP in semi-arid climatic conditions. The research aims at understanding the leachate production patterns in landfills and investigating the applicability of HELP model under Alberta conditions. The specific objectives of this research were to study:

- The effect of precipitation, on leachate production in semi-arid climate landfills,
- The effect of leachate re-circulation on leachate production.
- The effect of compaction density on waste characteristics such as field capacity, porsotiy, and saturated hydraulic conductivity.

- The applicability of HELP model to landfills located in semi-arid climates such as in Calgary, Alberta using field lysimeter data and laboratory experimental data.

1.3 THESIS ORGANIZATION

A general description of the problem and the objectives of the thesis are presented in Chapter 1. In Chapter 2, a brief literature review on moisture movement through landfills, factors affecting the movement of moisture through a landfill, and the HELP model are provided. Chapter 3, includes the materials and methods used for laboratory and field experiments. The experimental results and discussion of results are presented in Chapter 4. Chapter 5 presents the HELP model simulations and interpretation of results. The conclusions and recommendations for future research, are presented in Chapter 6.

CHAPTER TWO

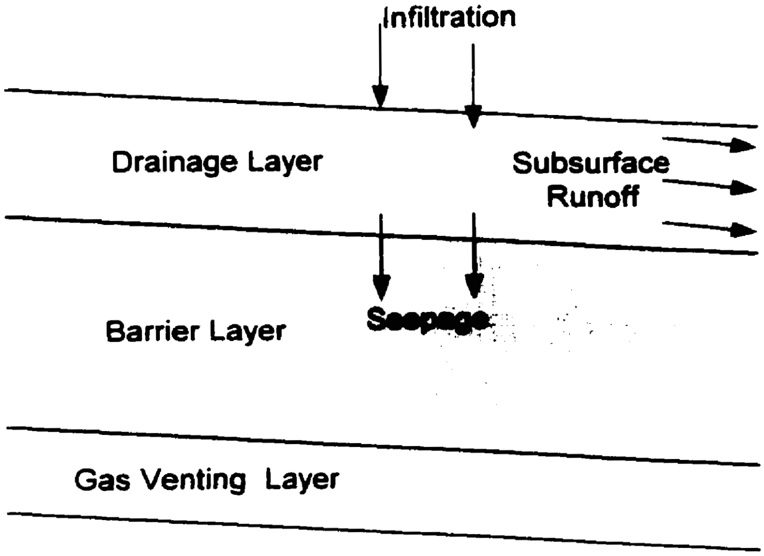
LITERATURE REVIEW

2.1 MOISTURE MOVEMENT THROUGH THE SOIL COVER

Engineered MSW landfill final covers are designed to minimize the percolation of moisture into the waste. The final cover typically consists of a vegetative layer, a protective layer, a drainage layer, and a barrier layer (Sharma and Lewis, 1994). The moisture percolates through the overlying vegetative and protective layer into the drainage layer. The percolated moisture starts mounding on the barrier layer. A portion of the mounded moisture flows laterally as sub-surface runoff (Christensen et al., 1989), and the remaining portion percolates vertically downwards. Thus, the moisture percolating into the drainage layer is apportioned into sub-surface runoff (flowing laterally) and seepage (flowing vertically downwards). The drainage layer encourages sub-surface runoff and reduces the mounding depth of moisture on the barrier layer. This limits the vertical seepage of moisture through the barrier layer into the waste layers. Figure 2.1 shows a schematic diagram of the migration of moisture through drainage layer and barrier layer of the landfill final cover.

The factors affecting the sub-surface flow are the moisture infiltration rate into the drainage layer, the hydraulic conductivity of the granular material in the drainage layer, the gradient of the barrier layer, and the hydraulic conductivity of the barrier layer (McEnroe, 1989). High moisture infiltration rate into the drainage layer, high hydraulic conductivity of the drainage layer, and high gradient of the barrier layer, decreases the mounding depth over the barrier layer and increases the sub-surface flow.

Figure 2.1: Schematic Diagram Showing the Moisture Migration at the Interface of Drainage Layer and Barrier Layer of the Landfill Final Cover



It has been found that infiltration rates of the same order of magnitude as the hydraulic conductivity of the barrier layer fail to produce a significant head over the barrier layer, thus encouraging vertical seepage and inhibiting sub-surface flow (Korfiatis and Demetracopoulos, 1986). If the hydraulic conductivity of the barrier layer is lower than the infiltration rate, significant sub-surface runoff occurs, and leachate generation rates are reduced (Sweeney et al., 1982). However, barrier layers having low gradients increase the mounding depth and decrease the sub-surface flow. Also, a higher hydraulic conductivity of the drainage layer lowers the mounding depth and vertical seepage through the barrier layer. McEnroe (1989) observed that for coarse sand with a hydraulic conductivity of 0.01 cm/sec and percolation rate less than 110 cm/yr., the mounding depth did not exceed 30 cm.

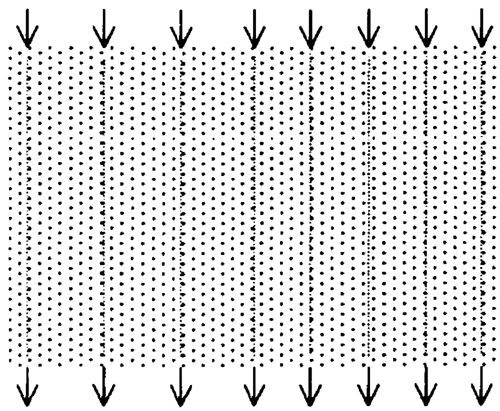
Several moisture apportionment models have been developed to predict the seepage through the barrier layer. All these models assume a saturated barrier layer, and are developed for steady flow conditions. Wong (1977) provided an approximate solution for seepage resulting from a single, instantaneous, moisture input event. He assumed steady-state flow where moisture mounding on the barrier layer instantaneously develops a phreatic surface parallel to the barrier layer. The U.S. EPA's HELP model assumes the sub-surface runoff to be quasi-steady. The model assumes that the steady-state relationship between the lateral drainage rate and the average saturated depth over the barrier also holds for unsteady flow conditions existing in the landfill final cover. The model under-estimates the sub-surface runoff when the saturated depth is building on the liner and over-estimates when the depth is falling. However, in semi-arid and arid regions, significant infiltration through the final cover is infrequent and short-lived. Hence, estimates based on steady flow conditions, yield unrealistic apportionment results (McEnroe, 1989).

2.2 MOISTURE MOVEMENT THROUGH MUNICIPAL SOLID WASTE (MSW)

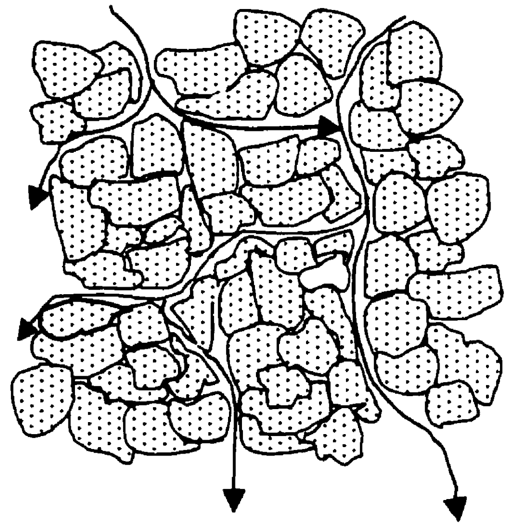
Soil is a homogeneous porous matrix. Moisture flows between the solid particles of unsaturated soil as a uniform wetting front (Noble and Arnold, 1991; Khanbilvardi et. al., 1995). The moisture movement through micropores occurs due to the hydraulic head gradient consisting of elevation head and capillary pressure head.

Most researchers assume that flow through unsaturated MSW also occurs as a uniform wetting front. This implies that the waste is a homogeneous porous matrix. However, MSW is heterogeneous and moisture movement occurs through preferential pathways (Fungaroli and Steiner, 1971; Rovers and Farquhar, 1973; Korfiatis et al., 1984; Oweis and Khera, 1990; Noble and Arnold, 1991). The flow of moisture through these preferential pathways, or macropores, is called channeling. Moisture flows normally as unsaturated flow in micropores and as more rapid saturated flow in macropores. Figure 2.2 presents the schematic diagram showing the uniform moisture front in soils and preferential flow through channels in MSW.

Figure 2.2: Schematic Diagram Showing Uniform Moisture Front in Soils and Preferential Flow Through Channels in MSW



(a) Homogeneous Uniform Moisture Front in Soil



(b) Preferential Flow Through Channels in MSW

Most flow models used to quantify leachate generated from MSW landfills assume the waste to be a homogenous, unsaturated, non-deformable, porous medium with uniform flow. These models assume that the moisture movement through the waste layer is an unsaturated Darcian flow through the micropores. These models do not account for the potential occurrence of flow through macropores of MSW due to channeling. Like most other flow models, the HELP model also assumes the waste to be a homogenous porous media with uniform flow. According to Poiseuille's equation (Serway and Faughn, 1985), the volumetric flow through the porous media is directly proportional to the fourth power of radius of the pore. This means that the flow through a pore of a particular diameter is 16 times higher than the flow through an equivalent pore of half the diameter. The volume of moisture flowing through the macropore is greater than the assumption of MSW as a homogeneous porous matrix. Also, homogenous soil matrix consists of pores of small radius, and capillary pressure head gradient governs the flow. MSW is heterogenous and flow occurs through larger pores. Elevation head gradient governs the flow through these macropores (Chen and Wagenet, 1992). Therefore, a uniform moisture front is not an accurate representation of channeled flow.

2.3 FACTORS AFFECTING MOISTURE MOVEMENT IN LANDFILLS

2.3.1 MSW Composition and Properties

Typically, MSW is composed of food waste, yard waste, plastic, paper, metal, textile, lumber and others (Klee, 1993, Tchobanoglous et. al., 1993). The composition varies by location and by season (Brunner and Ernst, 1986). This leads to variations in MSW properties such as initial moisture content, field capacity, porosity, and saturated hydraulic conductivity (Carpenter et al., 1990). The quantity and quality of leachate generated depends on the initial moisture content of the waste, the water holding capacity of the waste, ease with which moisture flows through the MSW, climatic conditions, and landfilling conditions, etc.

2.3.2 Landfill Operating Practices

The landfill operating practices such as the type of waste accepted by the facility, and the processing of waste (such as shredding and compaction density), affect the quantity of leachate produced in a landfill (Wall, 1993). Certain types of wastes, such as food wastes, have high moisture contents. The acceptance of such waste, as well as liquid waste, by the facilities decrease the moisture storing capacity of the landfilled waste. Waste processing, such as shredding, reduces the particle size of the waste, and causes garbage bags to open exposing the waste inside. The exposed waste absorbs moisture. The presence of large quantity of paper and cardboard in the waste increases the absorbing capacity of the waste (Chen and Chynoweth, 1995). Thus, landfill operating practice affects the amount of leachate generated.

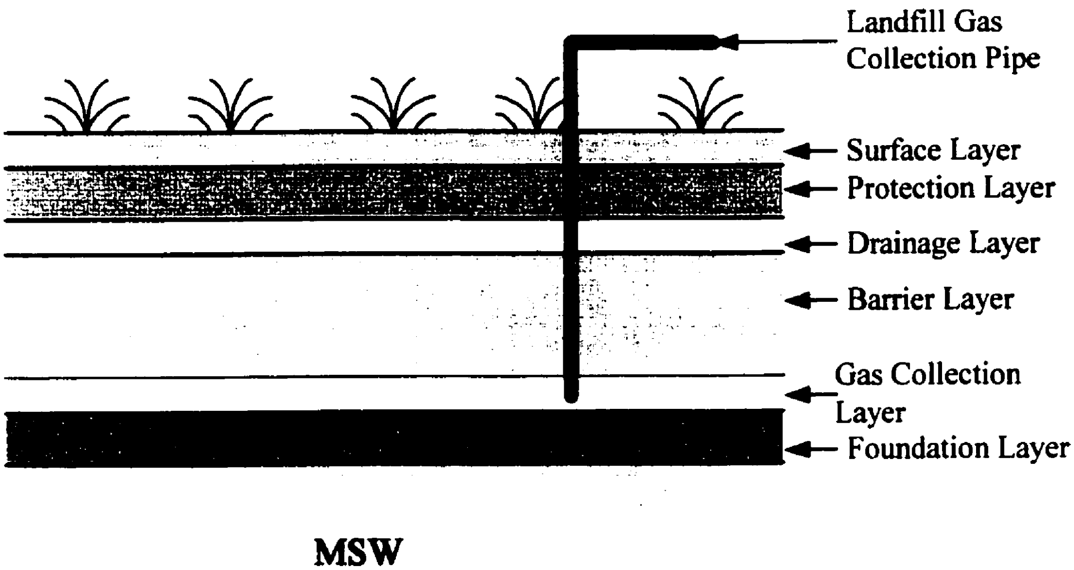
2.3.3 Compaction Density of the Waste

Density of the waste is related to void ratio and pore geometry (Hillel, 1971) of the waste. Density affects the moisture absorption capacity of waste, the porosity of the waste, the hydraulic conductivity of waste, and the quantity of leachate generated from MSW landfills. Research has shown that direct relationship exists between density and absorptive capacity of waste (Blakey, 1982). Compaction increases the density of MSW and tears open plastic "garbage bags". Compacted wastes have higher absorptive capacity due to an increase in the surface area of waste exposed to moisture by tearing of garbage bags. Zeiss and Major (1993) showed that an increase in waste density decreased the porosity (from 0.58 to 0.47 for densities in the range of 170 to 305 kg/m^3). Therefore, increased density may result in lower hydraulic conductivity and decreases the quantity of leachate generated. The compacted MSW landfills with low waste densities have higher saturated hydraulic conductivity of about 2.5 x 10^{-1} cm/s (Ettala, 1987). A saturated hydraulic conductivity of 10^{-3} cm/sec is a reasonable estimate for typical MSW at standard compacted density of 650 kg/m^3 (Oweis et. al., 1990).

2.3.4 Landfill Final Cover

The final cover over MSW prevents the percolation of moisture into the underlying waste and minimizes the generation of leachate. Typically, a final cover system consists of a surface layer, a protection layer, a drainage layer, a barrier layer, a gas collection layer, and a foundation layer (see Figure 2.3). The surface layer consists of topsoil and is vegetated to minimize erosion and promote transpiration. The protection layer protects the layers underneath. The drainage layer laterally drains the rainwater and snowmelt percolating through the cover material and reduces the mounding on the barrier layer, thus minimizing infiltration into the barrier layer. The barrier layer is generally the most critical component of the final cover system. It minimizes infiltration of moisture through the cover, thereby

Figure 2.3: Schematic Diagram of a Landfill Final Cover System



promoting storage or drainage of moisture in the overlying layers. The gas collection layer aids in gas collection from the underlying waste. The foundation layer contours the surface of the landfill and serves as a subbase for the overlying layer.

The percentage rainfall percolating through the landfill final cover into the waste layers depends primarily on the time of placement of final cover, and type and depth of final cover (Campbell, 1982). The final covers for MSW landfills are constructed after a landfill cell is filled to design grades. Over time, waste degrades and the cover undergoes settlement due to primary and secondary compression of the waste. Primary compression is compaction due to the dissipation of pore water and gas from the void spaces. The magnitude of primary compression is greater and masks the effects of secondary compression in the initial period of the waste placememnt. Secondary compression is generally due to biological decay of MSW. Settlement due to secondary compression can account for a significant portion of the total landfill settlement and can take place over many years (Wall and Zeiss, 1995). The differential settlement may result in "cracking" of the cover and the development of preferential pathways for moisture and gas. This results in an increase in infiltration into the waste layer, and an increase in leachate production.

Generally the barrier layer is made of 60 cm thick compacted clay. Low hydraulic conductivity of the barrier layer in the final cover reduces migration of moisture into the waste. As the barrier layer is not saturated, less percolation is observed during the initial period after construction (Daniel and Gross, 1996). Later on, the percolation increases with the precipitation events due to saturation. The evaporation of moisture from the surface of clay layer during the summer period reduces the moisture content of the surface layer. This results in reduction of hydrostatic pressure of the surface layer. Moisture flows from lower layers to the surface, reducing the hydrostatic pressure of lower layers. Moisture gradients are created in the clay layer which produces stresses. These stresses cause cracking of the clay layer (Macey, 1942). Research has shown that the drying of the clay barrier in the summer period results in an almost tenfold increase in infiltration (Koerner and Daniel, 1997). Freezing temperatures can also cause cracking of compacted clay barrier layers (Hamilton, 1996).

Cracking of final cover due to waste settlement, dessication, and freeze-thaw allows rapid and deep infiltration of moisture into the clay layer that gradually deepens and widens with time. The swelling of fine-grained clay soil occurs during wet periods. This closes the cracks and homogenizes the soil layer. However, these cracks do not fully heal when the clay is under low overburden stress (Othman et al., 1993; Elsbury et al., 1990). These conditions increase the hydraulic conductivity of the barrier layer.

2.3.5 Percolation Rate Through the Cover

Moisture percolating through the cover contributes to the amount of leachate produced from a MSW landfill. The more the moisture percolating into waste layers, the higher is the leachate generated (Chian et al. 1985). Percolation rate influences the degree of channeling that occurs within the waste; high rates result in higher degree of channeling. Uguccioni

(1995) observed that precipitation rate is a more important factor affecting moisture migration through the waste, than precipitation frequency.

Uguccioni (1995) showed that percolation rate had a significant effect on breakthrough time, time to reach steady state, and quantity of leachate generated. Low infiltration rates such as the low intensity rainfall, are less likely to lead to pronounced channeling than high rates, because slow application of moisture allows more time for moisture absorption into waste particles, and capillary action in the smaller pores redistributes the moisture so that the matrix flow regime in the waste layer contributes more to the overall discharge. This slow increase in moisture content forms a wetting front that moves according to the Richard's equation (Fetter, 1993) for Darcy flow in an unsaturated zone which is given by:

$$\frac{\partial\theta}{\partial t} = \nabla(-K(\Psi)\nabla(h)) \tag{1}$$

where,

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

t = time (T)

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

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

The lower infiltration rates result in more interaction with the waste leading to increased dissolved constituents in the leachate. High infiltration rates such as high intensity rainfaill, increase the channeling within the waste. During periods of high infiltration, additional moisture migration pathways are developed, effectively increasing the amount of leachate transmitted (Jasper et al., 1985). Compaction of waste reduces channeling and lessens the effect of rainfall peaks on leachate flow rates (Campbell, 1982).

2.3.6 Field Capacity of the Waste

The field capacity of the waste affects the moisture movement through the waste. A decrease in field capacity decreases the breakthrough time of leachate discharge. Field capacity has been defined in a number of ways. Field capacity is defined as the maximum moisture that the porous medium can retain against gravitational forces without producing a downward flow of liquid (Bagchi, 1994). It is the moisture content of a porous media at 0.33 atm of pressure (Freeze and Cherry, 1979; Schroeder et al., 1994), or the moisture content corresponding to the point on the drainage curve at which free drainage of an initially saturated media ceases (Schroeder et al., 1994). It is also defined as the ratio of volume of moisture retained in the porous media after gravity drainage ceases to the total volume occupied by the soil (Schroeder et al., 1994). In a broad sense, these definitions have similar meaning.

In a homogenous soil medium, moisture flows from one layer to another as a uniform wetting front, draining or releasing moisture at field capacity. Although MSW is assumed to behave in a manner similar to soil in relation to its moisture retention and transmission capabilities, the waste particles have a greater moisture absorptive capacity than soil particles and would therefore have a greater capacity to store and retain moisture under similar conditions (Leskiw, 1992). Research has shown that for MSW channeling releases moisture prior to reaching field capacity. Zeiss and Major (1993) proposed the parameter 'Practical Field Capacity' (PFC), which is analogous to field capacity and accounts for channeling effect within the waste. PFC is the moisture content at which leachate is first discharged after moisture application to initially unsaturated waste. This parameter corresponds to the point of first drainage on the imbibition curve of the waste. This parameter differs from the HELP model field capacity or theoretical field capacity (TFC) that is a point on the drainage curve where drainage ceases (typically at 0.33 atm). The waste moisture content is expected to be lower for flow during the wetting cycle or the imbibition than during the drainage cycle. Thus, PFC is lower than the TFC. Moreover, rapid vertical percolation of moisture confined to narrow flow preferential pathways occurs in the waste layer and results in a much lower PFC for waste because only the surface area surrounding the channels is wetted.

Table 2.1 shows the values of key parameters measured by different researchers. The table indicates that the PFC measured on the wetting curve was less than the HELP model field capacity (TFC) that is measured on the drainage curve. The measured waste characteristic parameter values consisted of a PFC of 0.10 to 0.136, a pore size distribution index (λ) of 0.50 to 0.65, and initial hydraulic conductivity of 4.46 x 10^{-3} to 1.18 x 10^{-5} cm/sec for different infiltration intensities. The pore size distribution index (λ) was defined as the negative slope of the effective degree of saturation versus matric suction curve (Fredlund and Rahardjo, 1993). The more uniform the distribution of the pore sizes, the larger is the value of λ.

Further absorption of moisture, once leachate is generated at PFC, cannot be ruled out because of the additional storage occurring in the less easily accessible matrix pores. The volumetric moisture content of the waste increases until the discharge rate equals the infiltration rate.

Some researchers (Campbell ,1982; El-Fadel et al., 1997) found it more appropriate to characterize the waste by its absorptive capacity. Absorptive capacity is defined as the maximum volume of liquid a given mass of waste will absorb. Field capacity is then quantified as the amount of moisture a given mass of material has absorbed when the quantity of leachate produced due to gravitational forces is equal to the quantity infiltrated. Uguccioni and Zeiss (1996) defined it as effective storage, i.e. the ultimate moisture content when storage has reached its maximum. The effective storage, which is reached at steady state, is therefore higher than the PFC and lesser than the porosity.

Table 2.1: Values of Key Parameters for Unsaturated Flow in MSW

(Modified from: Zeiss and Major, 1995)

Parameters	Source of Parameter Values			
	HELP model Layer No. 18	HELP model Layer No.19	Zeiss & Major (1993)*	Zeiss & Uguccioni (1995)**
Flow cross-sectional area (%)	100 %	25 %	23-34 %	25-35 %
Porosity (vol./vol.)	0.67	0.17	0.53	0.52
Field Capacity*** (vol./vol.)	0.292	0.073	0.136	0.1
Pore Size Distribution Index(λ)	0.45	0.53	0.50	0.65
Unsaturated HC cm/s				
Initial K_{us}****, cm/s	1.26×10^{-5}	1.86×10^{-6}	4.46×10^{-3}	1.18×10^{-5}
Ultimate K_{us}*****, cm/s	1.26×10^{-6}	1.86×10^{-6}	1.12×10^{-3}	6.08×10^{-6}

Notes:

* Parameter values for infiltration rate of 95 mm/hr., and density of 166, 187, 305 kg/m^3.

** Parameter values for infiltration rate of 0.2 mm/hr., and density of 141 kg/m^3.

*** HELP model field capacity measured on the drainage curve, whereas the practical field capacity measured on the imbibition (wetting) curve.

**** The initial hydraulic conductivity corresponds to the effective velocity at the first breakthrough, that is, when the moisture content is at the practical field capacity PFC.

***** The ultimate hydraulic conductivity corresponds to the steady-state discharge rate when the moisture content is at the maximum absorption capacity.

The moisture absorption capacity of MSW depends on a variety of factors such as type and age of waste, initial moisture content, degree of compaction, pre-treatment, and infiltration of rainfall and other liquids (Blakey, 1982) and can range from 0.020 to 0.380 vol./vol. of dry waste (El-Fadel et al., 1997). Moisture content of fresh domestic waste is lower than the field capacity (Blakey, 1982). This results in moisture absorption until the field capacity is reached. Moisture contents of the waste at the time of placement have been found to range between 0.1 vol./vol. and 0.3 vol./vol., and field capacity to range between 0.30 vol./vol. and 0.45 vol./vol. (Leskiw, 1992). The initial moisture content and field capacity of MSW (excluding the daily cover soil) as reported in several studies are summarized in Table 2.2.

Table 2.2: Initial Moisture Content and Field Capacity of MSW as a Function of Density

(Modified from: Bagchi, 1994)

Wet Density (kg/m^3)	Dry Density (kg/m^3)	Initial Moisture Content (vol./vol.)	Field Capacity (vol./vol.)	Source
314	Not Available	0.160	0.302	Rovers et al. (1973)
479	312	0.167	0.318	Walsh et al. (1979)
473	308	0.165	0.404	Walsh et al. (1981)
390	303	0.083	0.367	Wigh (1979)
334	282	0.052	0.342	Fungaroli (1979)

Table 2.2 indicates that at an average initial moisture content of 0.125 (vol./vol.), the average field capacity (absorptive capacity) of MSW is 0.345 (vol./vol.). Thus, on an average, MSW can absorb an additional 0.220 (vol./vol.) of moisture.

The absorptive capacity of MSW also depends on the thickness of the waste layer (Guyonnet et al., 1998). The thicker is the waste layer, the longer is the travel path, and the greater is the absorption.

2.4 THE HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL

The determination of velocity and discharge rate of moisture through layers of MSW is crucial for the prediction of the time of first discharge, and the quantity of leachate flow from landfills. These values are used to design the leachate treatment plants and the various components of the leachate collection system.

Water balance method or WBM developed, by Fenn et al. (1975), used to predict leachate volume, is an application of the principle of conservation of mass and continuity of flow through landfills. It consists of simple addition and subtraction of the hydrologic components of a landfill, such as precipitation, evapotranspiration, surface runoff, and soil moisture storage. The principal source of moisture is precipitation. Some portion of this moisture results in surface runoff, some portion is returned back to the atmosphere in the form of evapotranspiration from the soil and plants surfaces, and the remainder adds to the soil moisture storage. Whenever storage moisture exceeds the field capacity of the soil, moisture percolates towards the waste layers. The addition of moisture to waste over a period of time saturates the waste to its field capacity moisture content. At that stage, moisture from the waste will be released in the form of leachate. The rate of moisture percolation to the waste, after an initial delay, is then equal to the rate of leachate generation. The water balance of the landfill, can be expressed as (Dass et al., 1977):

$$Perc = P - R - AET - \Delta S \qquad (2)$$

where,

Perc = moisture percolated from the landfill surface

P = precipitation

R = surface runoff

AET = actual evapotranspiration over the landfill surface.

ΔS = the gain in the moisture storage within the soil.

The U.S. EPA's HELP (Hydrologic Evaluation of Landfill Performance) model (Schroeder et al., 1994) is an application of the water-balance method to sanitary landfills. The HELP model is a quasi-two-dimensional model that computes leachate flow in a quasi-steady-state flow condition (Ahmed et al., 1992). The hydrologic processes modeled by the program can be divided into two categories: surface processes and sub-surface processes (refer Figure 2.4). The surface processes modeled are snowmelt, interception of rainfall by vegetation, surface runoff and evaporation of moisture, interception and snow from the surface. The sub-surface processes modeled are evaporation of moisture from the soil, plant transpiration, vertical drainage, geomembrane liner leakage, barrier soil liner percolation and lateral saturated drainage. Vegetative growth and frozen soil models are also included in the program to aid modeling of the moisture routing processes.

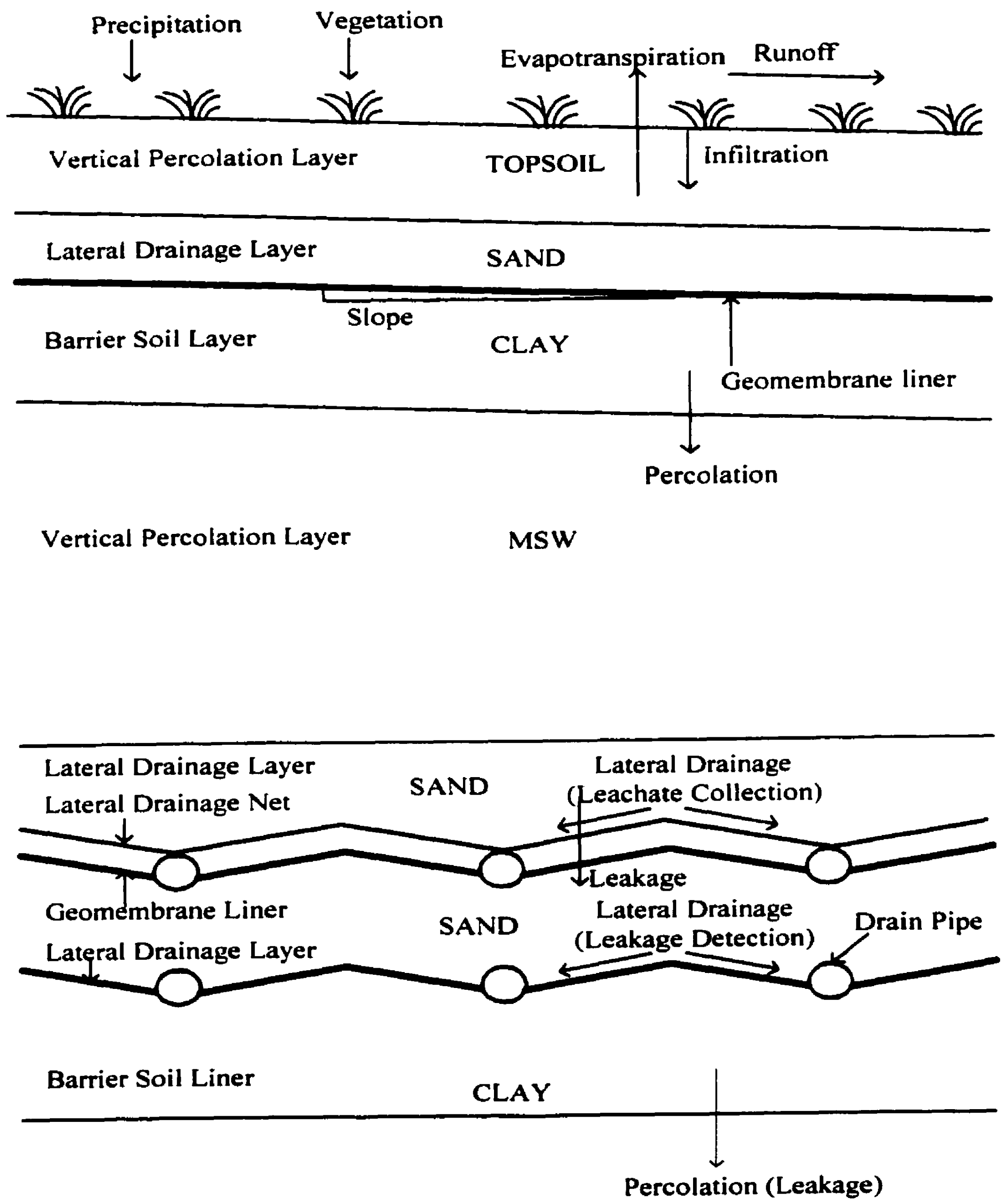
2.4.1 Surface Processes

The surface processes such as snowmelt, interception of rainfall by vegetation, and surface runoff and evaporation of water affect the moisture migration into the sub-surface layers. In the HELP model, the soil is assumed to enter a frozen state when the average temperature of the previous 30 days first drops below 0°C. During the time in which the soil is considered to be frozen, the infiltration capacity of the soil is reduced by increasing the calculated runoff. The interception by vegetation is calculated daily based on the above ground biomass (CV) value using a vegetative growth model included in the HELP program. Runoff is simulated using the Soil Conservation Service (SCS) curve number method. The evapotranspiration demand in the sub-surface layers, is met by the evaporation of the surface moisture.

2.4.1.1 Snowmelt

Studies have shown that the temperature at which precipitation is equally likely to be rain or snow is in range of 0°C to 2.2°C. A delineation temperature of 0°C is used in the HELP

Figure 2.4: Schematic Profile View of a Typical MSW Landfill (Modified from Schroeder et al., 1994)



model, that is, when the daily mean temperature is below this value, the program stores precipitation on the surface as snow. When the average daily air temperature rises above 0°C, HELP model computes potential daily snow melt using (Khire et al., 1997):

$$M = F_m T_d \qquad (3)$$

where,

M = potential daily snow melt, cm/day

F_m = function of month (e.g. for February, F_m = 0.24 cm/day/°C)

T_d = average daily air temperature.

The variation in the melt factor is represented by a sine function and it varies between 5.2 mm/day-°C to 2.0 mm/day-°C (based on the seasonal variation in solar radiation). At latitudes greater than 50°, the seasonal variation of the melt factor becomes less sinusoidal, and the HELP model makes adjustments to represent this gradually "flattening out" of the melt factor for prolonged winter conditions (Dozier, 1992). When rain-on-snow occurs, the quantity of rain is added to the surface melt, from which refreeze and retention in the snow cover may also occur.

The amount of water present in the snow cover at the end of day i, is the difference of the water present in the snow cover at the end of day i-1, and the snowmelt plus evaporation on day i.

The model simulations show no runoff during winter months since the model assumes that precipitation is stored on the surface as snow when average temperatures are below freezing. Khire et al. (1997) concluded that HELP model overpredicted the overland flow due to it's inability to predict whether snow melt occurred, and when melt did occur, whether the melt water infiltrated or was shed as overland flow.

2.4.1.2 Interception of Rainfall by Vegetation

During a rainfall event, nearly all rainfall striking foliage is assumed to be intercepted at the beginning. The fraction of rainfall intercepted is assumed to decrease rapidly as the storage capacity of the foliage is reached. The interception storage decreases when considerable rainfall has reached the ground surface. This process is modeled using the following equation (Schroeder et al., 1994):

$$INT_i = INT_{\max_i}\left[1 - e^{-\left[\frac{R_i}{INT_{\max_i}}\right]}\right] \quad (4)$$

where,

INT_i = interception of rainfall by vegetation on day i, inches

INT_{maxi} = interception storage capacity of the vegetation on day i, inches

R_i = rainfall on day i (not including rainfall on snow), inches

The HELP model relates INT_{maxi} to the above ground biomass on the vegetation, CV using the empirical relationships given below (Schroeder et al.,1994):

$$INT_{\max_i} = 0.05\left(\frac{CV_i}{14000}\right) \quad \text{for } CVi < 14000 \quad (5)$$

$$INT_{\max_i} = 0.05 \quad \text{for } CVi >= 14000$$

where,

CV_i is the above ground biomass on day i in kg/ha.

INT_{maxi} is constant for a given biomass, whereas INT_i varies depending on the amount of rainfall on that particular day.

2.4.1.3 Surface Runoff and Evaporation of Water

The HELP model has adopted the Soil Conservation Services (SCS) curve-number (National Engineering Handbook, USDA, SCS, 1985) method for the rainfall-runoff process simulation. This procedure has been selected for four reasons: (1) it is widely accepted, (2) it is computationally efficient, (3) the required input is generally available, and (4) it can conveniently handle a variety of soil types, land uses and management practices. However, this method excludes time as a variable and thus, ignores the rainfall intensity.

The plot of accumulated runoff versus accumulated rainfall has shown that runoff starts after some rain accumulates (there is an "initial abstraction" of rainfall). In a storm in which rainfall and runoff begin simultaneously (initial abstraction is zero), the relation between rainfall, runoff, and retention (the rain not converted to runoff) can be expressed as (Schroeder et al., 1994):

$$\frac{F}{S} = \frac{Q}{P} \tag{6}$$

where,

F = actual retention after runoff begins.

S = potential maximum retention after runoff starts (S>=F).

Q = actual runoff.

P = rainfall (P>=Q).

The retention, S is a constant for a particular storm because it is the maximum that can occur under the existing conditions if the storm continues without limit. S is mainly the infiltration occurring after runoff begins. This infiltration is limited by the rate of infiltration at the soil surface or by the rate of transmission in the soil profile or by the water-storage capacity of the profile. The retention, F, varies because it is the difference between P and Q at any point on the runoff-rainfall curve, or:

$$F = P - Q \tag{7}$$

If an initial abstraction (I_a) greater than zero is considered, the amount of rainfall available for runoff is ($P - I_a$) instead of P. Substituting this and Equation (7) in Equation (6) gives:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{8}$$

The initial abstraction consists mainly of interception, infiltration, and surface storage, all of which occur before runoff begins. A relation between I_a and S developed by means of rainfall and runoff data for experimental small watersheds is given as (Schroeder et al., 1994):

$$I_a = 0.2S \tag{9}$$

Substituting this in equation (8) gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{10}$$

The HELP model program computes the runoff, Q_i on day i, using the above equation based on the net rainfall, P. The net rainfall is zero when the mean temperature is less than or equal to 0°C; is equal to the precipitation when the mean temperature is above 0°C and no snow cover is present; or is equal to the outflow from the snow cover when a snow cover is present and the mean temperature is above 0°C (Schroeder et al., 1994).

The value of the retention parameter, S, for a given soil is assumed to vary with soil moisture as follows:

$$S = S_{mx}\left[1 - \frac{SM - [(FC + WP)/2]}{UL - [(FC + WP)/2]}\right] \qquad \text{for SM} > (\text{FC+WP})/2 \tag{11}$$

$$= S_{mx} \qquad \text{for SM} <= (\text{FC+WP})/2$$

where,

S = retention parameter, inches.

S_{mx} = maximum value of S, inches

SM = soil water storage in the vegetative or evaporative zone, inches

UL = soil water storage at saturation, inches

FC = soil water storage at field capacity (the water remaining following gravity drainage in the absence of other losses), inches

WP = soil water storage at wilting point (the lowest naturally occurring soil water storage), inches (The HELP model defines wilting point as the volumetric water content at a capillary pressure of 15 bars. It is the moisture content of the soil at which the root system no longer sucks water from the soil and the plant dies of moisture deficiency (Rode, 1969).

S_{mx} is the retention parameter S, for a dry condition. In the SCS method, the change in S_{mx} is based on antecedent moisture condition (AMC). The model computes the runoff curve number for two different antecedent moisture conditions (AMC). CN_{II} corresponds to the average AMC. CN_{II} is computed on the basis of the value of vegetative cover type, soil type, and surface slope conditions (input by the user). The value of CN_{II} is then used to compute CN_I. CN_I corresponds to the dry conditions AMC (refer Schroeder et al., 1994, Engineering Documentation for further details). As the soil has maximum retention under dry conditions, S_{mx} is computed using CN_I in the following equation:

$$S_{mx} = \frac{1000}{CN_I} - 10 \qquad (12)$$

This value of S_{mx} is used in Equation (11) to calculate the value of S.

In the HELP model, the soil is assumed to enter a frozen state when the average temperature of the previous 30 days first drops below 0°C. When the soil is considered to be frozen, the infiltration capacity of the soil is reduced by increasing the calculated runoff (i.e. increasing the CN). When the soil is assumed frozen, HELP model increases the SCS runoff curve number to 98, if the CN is originally above 80 to shed the melt water as overland flow. If the CN for soil is less than or equal to 80, the CN is set at 95. The user has the option to input the CN.

Since soil water is not distributed uniformly through the soil profile, and since the soil moisture near the surface influences infiltration more strongly than soil moisture located elsewhere, the retention parameter S, is depth-weighted. The soil profile of the vegetative or evaporative zone depth in the HELP model is divided into seven segments. The thickness of the top segment is $1/36^{th}$ of the thickness of the vegetative or evaporative depth. The thickness of the second segment is $5/36^{th}$ of the thickness of the vegetative or evaporative zone depth. The thickness of each of the bottom five segments is $1/6^{th}$ of the thickness of the vegetative or evaporative zone depth. The user specified evaporative depth, is the maximum depth from which moisture can be removed by evapotranspiration. For the assumed segment thicknesses, the weighting factors are 0.111, 0.397, 0.254, 0.127, 0.063, 0.032 and 0.016 for segments 1 through 7 (Knisel, 1980). The value of retention parameter S_j, is computed for each segment by substituting the corresponding parameter values for each segment j in Equation (11)

The depth-weighted retention parameter is then computed using the following equation (Knisel, 1980):

$$S = \sum_{j=1}^{7} W_j S_j \tag{13}$$

where,

S_j = retention parameter for segment j

W_j = weighting factor for segment j

Substituting this value of S in Equation 10 gives the value of runoff on a given day.

The evapotranspiration demand in excess of available water at the landfill surface (i.e.water available through rainfall, interception by vegetation, ponded water, snowmelt or accumulated snow) is met by the evaporation of surface moisture.

2.4.2 Sub-surface Processes

The sub-surface routing of moisture proceeds one subprofile at a time, from top to bottom. Moisture is routed downward from one segment to the next using a storage routing procedure, with storage evaluated at the mid-point of each time step. Mid-point routing produces relatively smooth, gradual change in flow conditions, and avoids the more abrupt change that results from applying the full amount of moisture to a segment at the beginning of the time step. Mid-point routing is based on the following equation of continuity for a segment:

$$\Delta\text{Storage} = \text{Drainage In} - \text{Drainage Out} - \text{Evapotranspiration} + \text{Leachate Re-circulation} + \text{Sub-surface Inflow}$$

2.4.2.1 Evapotranspiration

Potential evapotranspiration from the soil is a function of the available energy and the mean air temperature. The amount of energy available is the potential evaporative energy less the energy dissipated in the melt of snow and evaporation of surface water. Moisture is removed by evapotranspiration only from the evaporative depth of the cover. The HELP model provides default values for the evaporative depth based on the location of the site and the condition of the vegetative cover.

The quantity of moisture removed by evapotranspiration is computed using an approach recommended by Ritchie (1972) and is a function of potential evapotranspiration (maximum possible evapotranspiration) and the availability of moisture from soil water storage. The daily potential evapotranspiration demand is applied to any free moisture available on the surface, thereby reducing the computed infiltration or the amount of snow on the surface. The evapotranspiration demand in excess of free surface moisture is exerted on the soil column for direct soil evaporation and transpiration through surface vegetation.

The potential evapotranspiration is computed as:

$$E_{oi} = \frac{LE_i}{25.4\,L_v} \tag{14}$$

where,

L_v = latent heat of vaporaization, langleys per millimeters

LE_i = energy available on day i for potential evapotranspiration in the absence of snow cover, langleys

The energy available for evapotranspiration is calculated using a modified form of Penman's (1963) equation which is given as:

$$LE_i = PENR_i + PENA_i \tag{15}$$

where,

$PENR_i$ = radiative component of the Penman equation on day i, langleys

$PENA_i$ = aerodynamic component of the Penman equation on day i, langleys

$PENR_i$ of Equation 14 represents that portion of the available evaporative energy due to the radiation exchange between the sun and the earth. $PENA_i$ represents the influence of humidity and wind on LE. These two components are evaluated as follows:

$$PENR_i = \frac{\Delta_i}{(\Delta_i + \gamma)} R_{n_i} \tag{16}$$

$$PENA_i = \frac{15.36\gamma}{(\Delta_i + \gamma)} (1 + 0.1488u)(e_{o_i} - e_{a_i}) \tag{17}$$

where,

R_{ni} = net radiation received by the surface on day I, langleys

Δ_i = slope of the saturation vapor pressure curve at mean air temperature on day i, millibars per degree C

γ = constant of the wet and dry bulb psychrometer equation, assumed to be constant at 0.68 millibars per degree C

u = wind speed at a height of 2 meters, in kilometers/hour (average annual wind speed used in model)

e_{oi} = saturation vapor pressure at mean air temperature on day o, millibars

e_{ai} = mean vapor pressure of the atmosphere on day i, millibars

2.4.2.2 Vertical Drainage

If the layer is a vertical percolation layer, moisture is routed based on Darcy's law for unsaturated flow. In the HELP model, moisture movement through the waste layer is predicted as Darcian flow through a homogeneous, unsaturated porous medium with constant porosity, pore size distribution, bubbling pressure and residual saturation. The flow is treated as one dimensional with a vertical hydraulic gradient of unity. Due to these assumptions, the rate at which moisture moves through the porous media is given by Darcy's equation as a function of the unsaturated hydraulic conductivity:

$$q = K_{us} . \frac{dh}{dl} \tag{18}$$

where,

q = rate of flow (discharge per unit time per unit area normal to the direction of flow), cm/s.

K_{us} = unsaturated hydraulic, cm/s.

dh/dl = hydraulic gradient, equals unity for downward flow in waste layer

The unsaturated hydraulic conductivity varies with the moisture content. Adjustment of the unsaturated hydraulic conductivity is made through the application of the combined Brooks-Corey and Campbell equations to values for solid waste characteristics. The Brooks-Corey's equation models the interactions of liquid and gas flows to establish relationship between capillary pressure and effective saturation as a function of the pore size distribution λ. HELP model uses this equation with the effective saturation determined from actual water content, θ, residual water content θ_r, and porosity as follows (Brooks and Corey, 1964):

$$\frac{[\theta-\theta_r]}{[\phi-\theta_r]}=\left[\frac{\Psi_b}{\Psi}\right]^{\lambda} \qquad (19)$$

where,

θ = actual water content, vol./vol.

θ_r = residual volumetric water content, vol./vol.

Φ = total porosity,vol./vol.

ψ_b = bubbling pressure, minimum capillary pressure on the drainage cycle for which a continuous non-wetting phase exists [cm].

ψ = capillary pressure [$= P_c/\gamma$], [cm]

With known residual soil moisture content, porosity and bubbling pressure and with measurements of two sets of soil moisture content and corresponding capillary pressure, (field capacity FC at 0.33 atm.and wilting point WP at 15 atm in HELP model), the data can be plotted as a straight line on a log-log graph of the effective saturation and capillary pressure. The absolute value of the slope is the pore size distribution index λ with the bubbling pressure ψ_b as the intercept with capillary pressure at effective saturation of unity.

The pore size distribution index is then used in the Campbell's equation in conjunction with the effective saturation to determine the correlation factor to be multiplied with the saturated hydraulic conductivity to determine the unsaturated hydraulic conductivity at the actual soil moisture content:

The Campbell's (1974) equation which is given by:

$$K_{us} = K_s \left[\frac{\theta - \theta_r}{\phi - \theta_r} \right]^{3+\frac{2}{\lambda}} \tag{20}$$

where,

K_{us} = unsaturated hydraulic conductivity [cm/s].

K_s = saturated hydraulic conductivity [cm/s].

θ = actual volumetric water content (vol./vol.)

θ_r = residual volumetric water content (vol./vol.), the ratio of moisture volume to total soil volume at the point where permeability to the wetting fluid, here water, equals zero (amount of water remaining in a layer under infinite capillary suction).

Φ = total porosity, vol./vol.

λ = pore-size distribution index, dimensionless

The saturated hydraulic conductivity is computed using the Kozeny-Carman equation given by Freeze and Cherry (1979):

$$Ks = \left(\frac{g}{\nu}\right)\left[\frac{\phi^3}{(1-\phi)^2}\right]\left(\frac{d_g{}^2}{1.80x10^{-4}}\right) \tag{21}$$

where,

Ks = saturated hydraulic conductivity, cm/sec.

g = acceleration due to gravity = 981 cm/sec^2

v = kinematic viscosity of water, cm^2/sec

ϕ = total porosity, vol./vol.

d_g = geometric mean soil particle diameter, mm

The unsaturated hydraulic conductivity is equal to zero when soil moisture is at or below field capacity and is equal to the saturated hydraulic conductivity when the soil is fully saturated. Although the unsaturated hydraulic conductivity is a non-linear function of soil moisture, the HELP model simplifies unsaturated flow by assuming a linear relationship with moisture content. The vertical flow is approximated as the hydraulic conductivity times a unit hydraulic gradient.

If the layer is a barrier soil liner, the saturated hydraulic conductivity and the depth of ponding of water on the surface of the barrier soil liner are used with Darcy's law to compute percolation.

2.4.2.3 Lateral Saturated Drainage

Lateral drainage from porous media is modeled by the Boussinesq equation (Darcy's law coupled with the continuity equation), employing the Dupuit-Forcheimer (D-F) assumptions. The Boussinesq equation is given as (Schroeder et al., 1994):

$$f\frac{\partial h}{\partial t} = K_D\frac{\partial}{\partial l}\left[(h - l\sin\alpha)\frac{\partial h}{\partial l}\right] + R \qquad (22)$$

where,

f = drainable porosity (i.e. porosity minus field capacity), dimensionless

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

t = time, sec

K_D = saturated hydraulic conductivity of drain layer, cm/sec

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

α = inclination angle of liner surface

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

The D-F assumptions are that, for gravity flow to a shallow sink, the flow is parallel to the liner and that the velocity is in proportion to the slope of the water table surface and independent of depth of flow. These assumptions imply that the head loss due to flow normal to the liner is negligible which is valid for drain layers with high hydraulic conductivity and for shallow depths of flow, depths much shorter than the length of the drainage path.

2.4.3 HELP Model Input Parameters

The input parameters for the HELP model are:

(i) Soil Properties: Porosity, Field Capacity, Wilting Point, Saturated Hydraulic Conductivity.

(ii) Vegetation Data: Evaporative Depth, Root Zone Depth, Leaf Area Index, Growing Season (Julian Day)

(iii) Climate Data: Precipitation, Air Temperature, Solar Radiation, Wind Speed, Quarterly Relative Humidity, Altitude

(iv) Cover Data: Layer Thickness, Cover Slope

(v) Initial Boundary Conditions: Initial Moisture Content of the layers

2.4.4 Methods of Solution Used in the HELP Model

The modeling procedures developed in HELP model are based on many simple assumptions (Schroeder et al., 1994). Calculations are performed on a daily basis.

Infiltration is assumed to equal the sum of rainfall and snowmelt, minus the sum of runoff, surface storage and surface evaporation. No moisture is held in surface storage from one day to the next, except in the snow cover. Snowfall and rainfall are added to the surface snow storage, if present, and then snowmelt plus excess storage of rainfall is computed. The total outflow from the snow cover is then treated as rainfall in the absence of a snow cover for the purpose of calculating runoff. A rainfall-runoff relationship is used to determine the runoff. Surface evaporation is then computed. Surface evaporation is not allowed to exceed the sum of surface snow storage and intercepted rainfall. Interception is computed only for rainfall, and not for outflow from the snow cover. The snowmelt and rainfall that does not run off or evaporate is assumed to infiltrate into the landfill. Computed infiltration in excess of the storage and drainage capacity of the soil is routed back to the surface and is added to the runoff or held as surface storage.

Unsaturated vertical drainage is computed for each modeling segment starting at the top of the subprofile. proceeding downward to the liner system or bottom of the subprofile. The program performs a water balance on each segment to determine the water storage and drainage for each segment, accounting for infiltration or drainage from above. sub-surface inflow. leachate re-circulation, moisture content and material characteristics.

The program uses a design dependent time step, varying from 30 minutes to 6 hours.

2.4.5 Field Application and Limitations of the HELP Model

The HELP model has been the most widely used tool for prediction of leachate generated from a landfill. However, the past research has shown the following limitations of the HELP model:

- Peyton and Schroeder (1988) simulated 17 landfill cells at six sites and compared the actual quantity of leachate generated to the HELP model simulations. The model simulations showed no runoff during the winter months since the model assumed that precipitation is stored on the surface as snow when average temperatures are below freezing, and when the air temperatures increase above freezing, all precipitation stored at the surface by the model either flows as runoff or infiltrates. However, significant runoff did occur in the field when the average temperature was below freezing. Therefore, the HELP model over-predicted runoff. However, Khire et al. (1997) observed that the model under-predicted the runoff. The primary reason why HELP over- or underpredicted surface runoff was its inability to accurately predict whether snow melt occurred and, when melt did occur whether the melt water infiltrated or was shed as surface runoff. Moreover, Khire et al. (1997) showed that the HELP model under-predicted the runoff for storms of higher intensity. The model does not consider the intensity of precipitation event. Uguccioni (1995) observed that precipitation intensity was a more important factor affecting moisture migration through the waste, than precipitation frequency.

- Peyton and Schroeder (1988) observed that the model under-predicted the lateral sub-surface runoff when the moisture infiltration rate on the barrier layer was low and the mounding depth of moisture above the barrier layer approached zero. Under these conditions the model assumed that the lateral sub-surface runoff is zero, and moisture percolates through the barrier layer at a rate equal to the saturated hydraulic conductivity times a unit hydraulic gradient. The barrier layer is assumed to be saturated. Hence, the moisture percolating through the barrier layer, infiltrates into the waste layer without any moisture absorption in the barrier layer. Moreover, the model overpredicts the lateral drainage when the moisture infiltration rate on the barrier layer is high and the mounding depth is high (Peyton and Schroeder, 1988).
- Peyton and Schroeder (1988) observed that the hydraulic conductivity of the cover soil, affected the lateral sub-surface predictions by the HELP model. An increase in the hydraulic conductivity of the soil cover, increased the sub-surface runoff. They claimed that a good agreement between predicted and measured values can be obtained by calibrating the hydraulic conductivity of the cover material while staying within the range of hydraulic conductivity values reported in the literature for those materials.

- Khire et al., (1997) observed that the HELP model overpredicted evapotranspiration in semiarid climates. The HELP model calculates evapotranspiration on the basis of available energy. In a semiarid environment, 86% to 91% of the precipitation received by the landfill cover, evaporates from these unvegetated landfill covers (Nyhan et al., 1997). Thus, under semi-arid climatic conditions, evapotranspiration is controlled by the availability of water and not the availability of energy (De Bruin, 1987) as modeled in the HELP model. Hence, the HELP model overpredicts evapotranspiration.
- The moisture movement through unsaturated MSW has been assumed as a uniform wetting front moving through the homogeneous media. However, as the moisture flow in MSW is through macropores, preferential pathways are formed. MSW characteristics itself vary with source and other landfill operating conditions. These factors affect the hydraulic properties of the waste. HELP model assumes the landfill conditions to be constant over time and uses built-in default waste parameters.
- The HELP model has built-in default value for field capacity of the waste. However, Zeiss and Uguccioni (1995) showed that the practical field capacity of the waste is significantly lower than the HELP model default value. Hence, leachate is produced earlier than that predicted by the HELP model.
- As with other sophisticated models, a lack of detailed data has greater impact on simulations made by the HELP model (Khire et al., 1997).
- Lange et al. (1997) observed that better definition of the landfill geometry and materials specifications can improve the accuracy of the HELP model leachate generation rate predictions. They observed that the input parameter area of the landfill and the percentage of the area from which runoff is allowed in the model, is a driving factor for leachate generation predictions. As the area of the landfill varies with the operational development stage of the landfill, they proposed a methodology for leachate predictions based on operational development stages of a landfill. They modeled the landfill as five vertical 'elements' of operational stages:

    (1) Element 0 - area with no waste in place, only the leachate collection system,

    (2) Element A – working area, exposed waste,

    (3) Element B – area with daily cover,

(4) Element C – area with intermediate cover, and

(5) Element D – area with vegetated intermediate cover.

This methodology more closely approximated the actual conditions. They demonstrated that HELP model can be calibrated to more accurately model actual field conditions with minor adjustments to the site-specific inputs, and more accurate predictions can be made without extensive additional time and cost during the design phase of a landfill.

2.5 SUMMARY

Predictive models are used to estimate the quantity of leachate generated and peak flow rates from landfills. The most used HELP model has the ability to account for elaborate cover systems. The model divides the moisture movement into surface and sub-surface processes such as snowmelt, runoff, and evapotrasnpiration. Calgary has a semi-arid climatic conditions with frequent freeze-thaw cycles due to chinook. A chinook is a warm dry wind that descends the eastern slopes of the Rocky Mountains in the winter and can raise the temperature by more than 34°C in one day.

The aim of this research was to measure the effectiveness of leachate prediction model, HELP under Alberta conditions.

CHAPTER THREE

MATERIALS AND METHODS

The experimental programme consisted of two components: laboratory studies and field studies. The laboratory studies were undertaken to study:

- the apportionment of moisture migrating through landfill covers into sub-surface runoff and vertical seepage.
- the effect of waste density on practical field capacity, porosity, and saturated hydraulic conductivity of the waste.

The field studies were undertaken to study:

- the effect of rainfall, and leachate re-circulation in a simulated landfill lysimeter on leachate production patterns.

The data generated from laboratory and field studies were then used to study the applicability of the HELP model to semi-arid conditions.

3.1 LABORATORY EXPERIMENTS

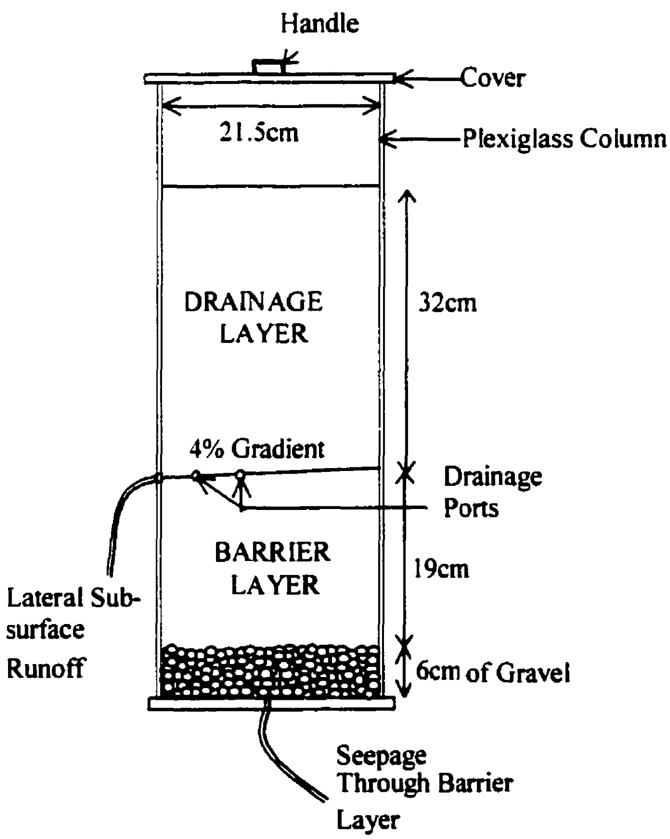
3.1.1 Moisture Apportionment in the Laboratory Soil Column

Most of the moisture infiltrating into the drainage layer of a landfill cover may flow laterally as sub-surface runoff. An experiment to study the apportionment of moisture at the interface of drainage layer and barrier layer of a final cover under low hydraulic heads was undertaken. The change in hydraulic head over the barrier layer with time was not measured in this experiment. Results could be used to determine the fraction of infiltrating moisture that will seep through the barrier layer of the final cover. The purpose of the experiment was to study the apportionment of moisture in the final cover. The data obtained from this experiment was not used in the HELP model simulations.

3.1.1.1 Experimental Setup

The laboratory moisture apportionment experiment was carried out in a plexiglass column, 21.5 cm (8.5") in diameter and 68.0 cm (27") deep. Schematic diagram of the laboratory soil solumn experimental setup is shown in Figure 3.1.

Figure 3.1: Schematic Diagram Showing the Laboratory Soil Column for Experiments on Moisture Apportionment



The soil column consisted of three layers: a gravel layer, a layer of compacted sandy clay loam and a layer of compacted sandy loam. The sandy clay loam layer and the sandy loam layer simulated the barrier layer and the drainage layer of a landfill final cover, respectively.

A 6 cm (2.5") thick gravel bed was placed at the base of the column to act as a drainage medium to collect the seepage through the barrier layer, as well as to act as a support media for the two layers above it. The compacted sandy clay loam layer (barrier layer), 19cm (7.5") thick with initial moisture content of 11.2% and an initial compacted density of 1850 kg/m^3 (attain optimum compacted density), was placed on the gravel bed. The sandy loam layer (drainage layer), 32cm (12.5") with initial moisture content of 14.75% and an initial compacted density of 1550 kg/m^3, was placed over the sandy clay loam layer.

The column had six drainage ports to collect the moisture migrating through the soil column. Five lateral drainage ports of 1 cm diameter each, were located at the interface of the drainage layer and the barrier layer. The top surface of the barrier layer had an average gradient of 4% towards these drainage ports. The moisture draining through the lateral drainage ports was collected and measured, and was termed as sub-surface runoff. The sixth drainage port of 1 cm diameter was located at the base of the column. The moisture seeping through the barrier layer was collected through this drainage port and measured. A plexiglass cover was placed on the column to prevent the loss of moisture throughout the experimental period.

3.1.1.2 Methodology

Once the experimental column was setup, moisture was added from the top of the column at a rate of 1.5 litres/hour. Moisture was added until ponding of moisture at the surface was observed. "Breakthrough" occurred at the first appearance of moisture through the drainage ports. Moisture infiltration was continued after the initial breakthrough. Moisture draining from lateral drainage ports and basal drain port was collected and measured. Moisture infiltration experiments were continued until the total moisture collected from the drainage ports was equal to the total moisture infiltrated (or steady-state conditions were reached). It is assumed that under steady-state conditions these results can be extended to a large scale field conditions.

3.1.2 MSW Properties

The quantity of leachate produced in a landfill is usually predicted on the basis of the soil and waste properties using tools such as the HELP model. Laboratory experiments were carried out to determine MSW properties, such as practical field capacity, porosity, and saturated hydraulic conductivity at two different waste densities of 375 kg/m^3 and 525 kg/m^3. The waste was compacted to density of 375 kg/m^3 to simulate the compacted waste density attained in the field lysimeter (discussed later in Section 3.2.1) constructed to perform the field studies. The 525 kg/m^3 compacted waste density was selected to study the effect of higher compaction on MSW properties.

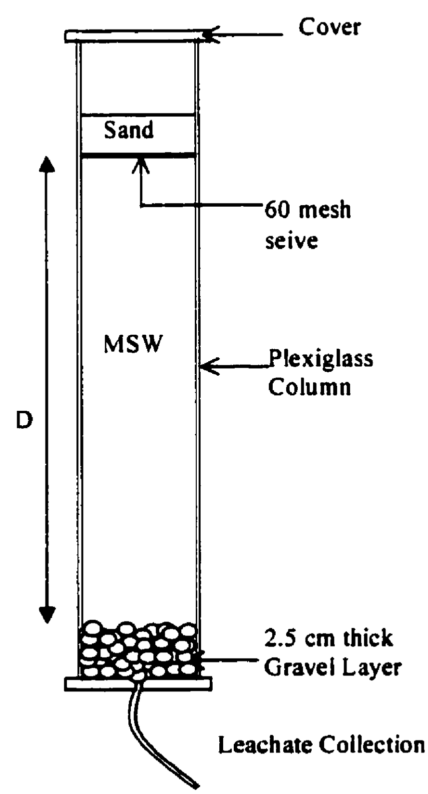
3.1.2.1 Experimental Setup

In order to determine the experimental values of MSW properties at two different waste compacted densities, four plexiglass columns were used. Table 3.1 provides information on column diameter, depth of waste and the compacted density of MSW columns. A schematic diagram of the laboratory column used to determine MSW properties, is provided in Figure 3.2.

Table 3.1: Design Details of Laboratory Columns to Determine MSW Properties

Column No.	Column Diameter (cm)	Depth of the Waste (D) (cm)	Density kg/m^3
1	13.9	35.5	375
2	12.6	28.5	375
3	21.5	35.0	525
4	13.9	28.5	525

Figure 3.2: Schematic Diagram Showing Details of the Laboratory Column for Determining MSW Properties



Of the four columns used for this experiment, two had a diameter of 13.9 cm (5.5") and the other two had diameters of 12.6 cm (5.0") and 21.5 cm (8.5") respectively. Two MSW columns had waste compacted to a density of 375 kg/m^3 and the other two had waste compacted to density of 525 kg/m^3 (refer Table 3.1). The columns had a drainage port at the base to collect the leachate. In order to prevent clogging of the drainage port, a 60-mesh sieve was laid at the base of the column. A 2.5 cm (1") thick gravel bed was placed on the sieve. The gravel bed acted as a drainage layer as well as the support medium to the MSW.

The solid waste used in the columns was collected from the University of Calgary campus, and was considered to be representative of MSW. The composition of MSW used in these columns was similar to the field lysimeter MSW composition (discussed later in this section; refer Table 3.2 for MSW composition). The MSW placed in each column consisted of paper, cardboard, metal, foodwaste, yardwaste, plastic, glass and wood. The paper used in each MSW column consisted of 80% glossy paper and 20% newspaper. Paper and cardboard required for each column was shredded to an approximate size of 4 cm x 4 cm. Metal cans were cut into small pieces to an approximate size of 5 cm x 4 cm. Foodwaste was placed in the mixing tray in required quantity. In order to simulate the garbage bags present in landfills, approximately 40% of the total paper placed and 80% of the total foodwaste placed in each column, was closed in plastic bags of size 10 cm x 6 cm. Broken glassware and wooden pieces were cut to small pieces of 3 cm x 3 cm. The waste required for each column was properly mixed in a mixing tray, and weighed to determine the initial weight of MSW placed in each column. Moisture was added to the dry waste to achieve good mixing and workability for compaction of dry waste. The moisture content of the waste after moisture addition was 0.045 vol./vol. The waste was again mixed. The waste was then loaded separately in each of the columns in five different lifts and was compacted to the pre-determined density (refer Table 3.1).

A layer of sand was placed on the top of the compacted waste to act as a drainage layer for moisture. A plexigalss cover was placed on the top of each column to prevent loss of moisture from the system.

3.1.2.2 Methodology

Once the waste was placed in the column, moisture was applied directly on to the sand drainage layer. Moisture was added in small quantities at pre-determined time intervals. The moisture was added until "breakthrough" occurred. "Breakthrough" was said to have occurred when steady discharge of leachate was first observed at the base. The leachate was collected and measured. The breakthrough moisture content was defined as the Practical Field Capacity (PFC).

Once breakthrough had occurred, the drainage port was sealed and moisture addition was continued until the waste reached saturation. Thereafter, the drainage port was opened and a falling head permeability test was performed on the waste to determine the saturated hydraulic conductivity. After determining the saturated hydraulic conductivity, the drainage port was sealed at the base again and moisture addition was continued until the saturation point was reached for a second time. The drainage port was then opened and moisture was drained until there was no moisture head on the drainage layer. At this point, the total volume of moisture in each column represented one pore volume. Once the pore volume was determined, the columns were allowed to drain freely overnight. The difference between total moisture added and total moisture drained, constituted the moisture content at theoretical field capacity (TFC) of the waste.

3.2 FIELD LANDFILL LYSIMETER STUDIES

The field studies were conducted to study;

- Leachate production under natural weather conditions of Calgary, from a closed landfill lysimeter,
- The effect of simulated rainfall on leachate production from an open landfill and the effect of simulated leachate re-circulation on leachate production.

In order to perform the above field studies, a field landfill lysimeter was constructed, in the University of Calgary premises.

3.2.1 Experimental Setup

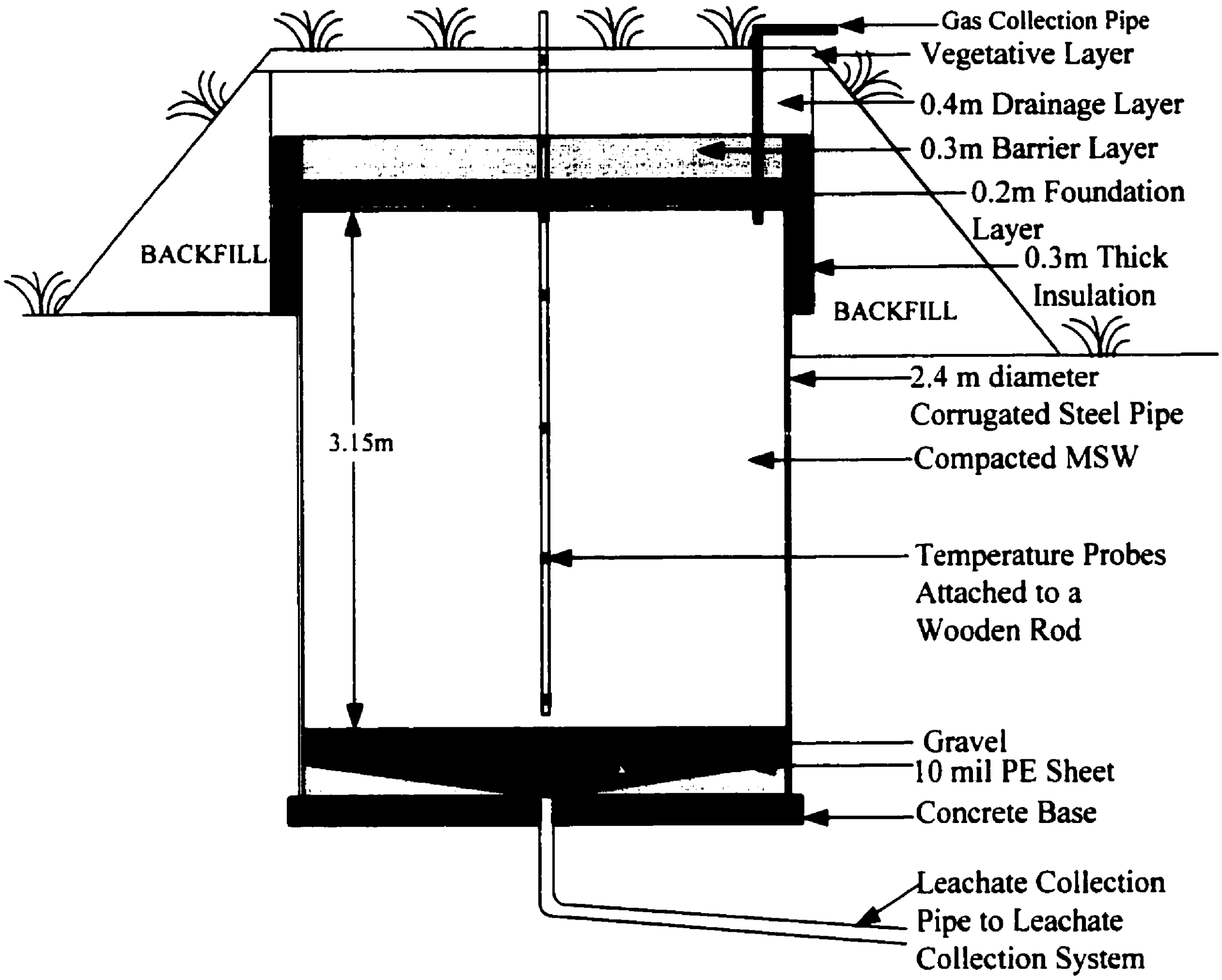
3.2.1.1 Construction of the Lysimeter

The field landfill lysimeter was constructed using a corrugated steel pipe of 2.4m diameter and 4m in height (refer Figure 3.3 for construction details of the lysimeter). Tchanobaglous et al. (1993) observed that the average size of the individual components in residential MSW lies between 17.8 cm and 20.3 cm. The steel pipe diameter selected, therefore, was greater than 10 times the average particle size and exceeded the minimum ratio of 5:1 to prevent wall effects.

An area was excavated up to 1.5 m below the ground level and concrete blocks were placed at the base. The corrugated steel pipe was placed on the concrete base. A 25 cm diameter drainage port was constructed at the center of the base to collect the leachate. The base of the lysimeter had a 4% gradient, sloping towards the drainage port. Two layers of LDPE sheets of 10 mil thickness were placed on the base to prevent leachate escape into the sub-surface and to aid the flow of leachate towards the leachate collection port. A gravel layer of an average thickness of 22.5 cm was placed on the base to act as a drainage layer for collection of leachate.

A 30 cm thick, styrofoam insulation was placed on the outer periphery of the corrugated pipe to prevent frost penetration into the lysimeter. A total of 4.5 tonnes of MSW required for this lysimeter was collected from the University campus (institutional waste) and University family housing (residential waste) by the Waste Collection Systems of Calgary and was then delivered to the lysimeter site.

Figure 3.3: Schematic Diagram Showing the Details of the Field Landfill Lysimeter



Some of the MSW received at the site was in closed garbage bags. A representative grab sample weighing 1.0 tonne was collected to determine the composition of the received MSW. The waste was manually sorted into seven waste components. Table 3.2 presents the results on composition of MSW placed in the landfill lysimeter. The composition of the waste was representative of "typical" municipal solid waste. Samples were taken from each segregated component for determination of initial moisture content of MSW. The weight of each individual component of the segregated sample was determined. The samples were then dried to a constant weight at 103°C. The weighted average moisture content of the waste was determined to be 29% on wet weight basis (0.08 vol./vol.). The initial density of solid waste was determined collecting a known weight of representative sample and measuring the volume occupied. In this manner, the initial density of solid waste was determined to be 110 kg/m^3.

After determining the composition and initial uncompacted density of MSW, a total of 4.5 tonnes of MSW at 0.08 vol./vol. of initial moisture content, was loaded in the lysimeter in nine different lifts using a front-end loader. Waste was loaded without opening the garbage bags. A mechanical compactor was used for compacting the MSW at the end of each lift. Some garbage bags had ripped open while compacting the waste. The compacted MSW had a final compaction density of about 315 kg/m^3. The final depth of the waste layer in the lysimeter was 3.15m after compaction. The lysimeter was closed immediately with a final cover, representative of a "typical" landfill cover system.

Table 3.2 : Field Landfill Lysimeter: MSW Composition

Waste Component	Composition of MSW Placed in the Lysimeter		Typical Composition** of MSW
	Tonnes	**%**	**%**
Paper	1.85	41.0	34.0
Cardboard	0.59	13.0	6.0
Metal	0.20	4.5	9.5
Food-waste	0.95	21.0	9.0
Yard-waste	0.05	1.0	18.5
Plastic, glass, etc.	0.73	16.5	21.0
Wood	0.13	3.0	2.0
Total	**4.50**	**100.0**	**100.0**

** Modified from: Tchabanoglous et. al., (1993) The final cover consisted of four layers. Just above the waste layer, a 0.2m thick foundation layer of soil was placed. A 0.3 m thick barrier layer soil with 10% initial moisture content was placed over the foundation layer. Table 3.3 shows the properties of the foundation soil and barrier soil placed in the final cover, and Figure 3.4 and Figure 3.5 show the grain size distribution for foundation soil and barrier soil, respectively. As per USDA classification, the foundation soil was characterized as sandy loam and the barrier soil was characterized as sandy clay loam. A neutron probe analysis showed that the placed compacted sandy clay loam had a density of 1550 kg/m^3. A 0.4m thick drainage layer of sandy loam, was placed on the top of the barrier layer. Finally, a 0.1 m thick vegetative layer was placed on the top.

Table 3.3: Properties of the Soil Placed as Cover Material in the Field Lysimeter

Properties	Sandy Loam Soil	Sandy Clay Loam
% Sand	63.0	39.0
% Silt	22.0	21.0
% Clay	6.0	20.0
Dry Density (kg/m^3)	1905.0	1804.0
Optimum Moisture Content, %	10.6	12.25
Liquid Limit, %	19.5	28.6
Plastic Limit, %	14.9	15.0
Plasticity Index %	4.6	13.6

Figure 3.4: Grain Size Distribution for Sandy Loam Soil

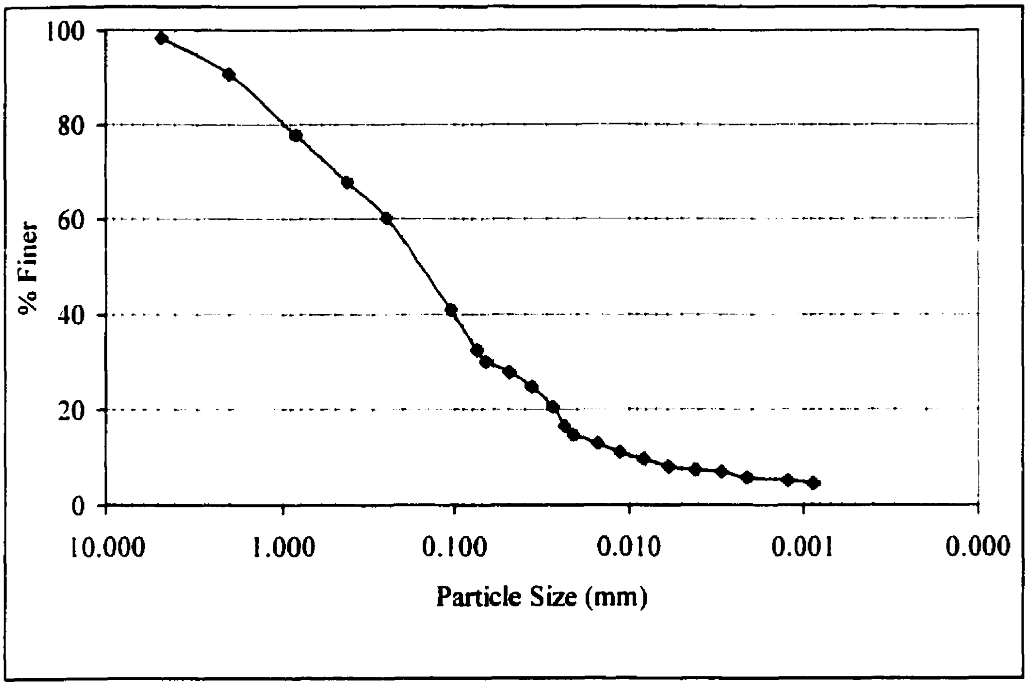
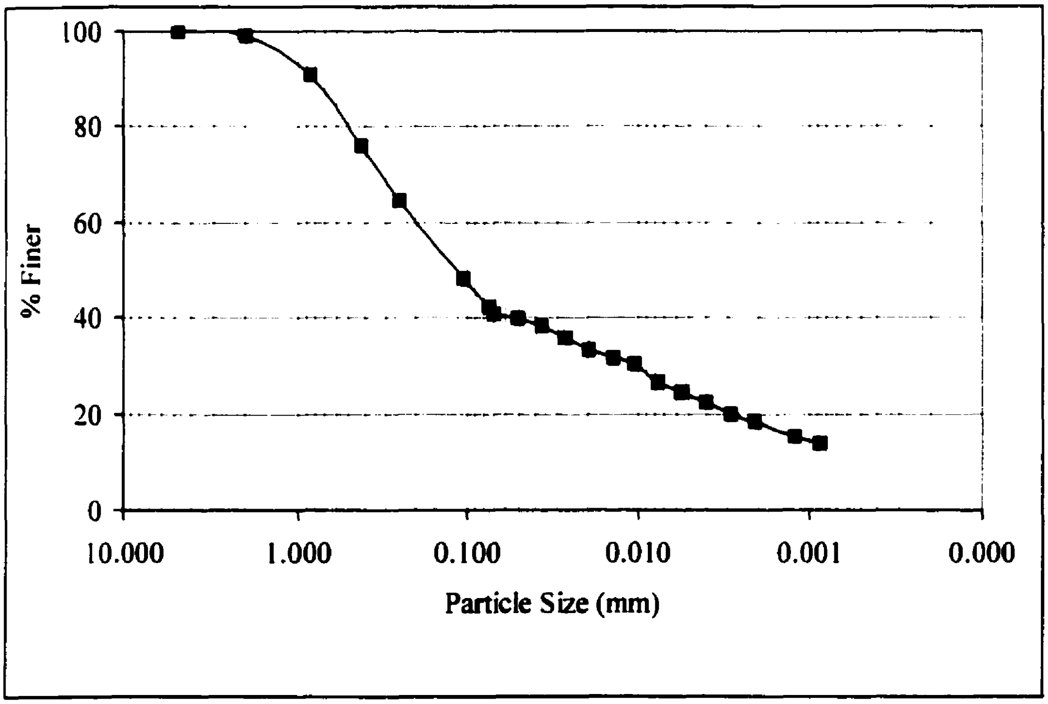


Figure 3.5: Grain Size Distribution for Sandy Clay Loam Soil



3.2.1.2 Instrumentation

Seven thermocouples were installed while constructing the landfill lysimeter to study the temperature variations within the lysimeter. Six thermocouples were fixed on a wooden rod at depths of 0.1m, 0.5m, 1.5m, 2.0m, 3.0m and 3.5m from the top of the lysimeter.
The wooden rod was placed, vertically, at the center of the lysimeter before loading the lysimeter with MSW (refer Figure 3.3). The seventh thermocouple was placed at the depth of 0.1m from the top surface of the cover, in the sandy loam drainage layer to study the surface temperature and the movement of the freezing front through the cover.

3.2.2 Methodology

The construction of the test lysimeter was completed in October, 1997. Field infiltration studies were performed in five phases. The first phase of the study was performed on a closed lysimeter. In order to perform the second, third and fourth phases of study on an open landfill, the final cover was removed. The lysimeter was then closed again with the final cover to perform the Phase-5 of field studies.

The five phases of field studies were undertaken;

- Phase-1: to study leachate production patterns from a closed landfill subjected to natural precipitation
- Phase-2: to study leachate production patterns from an open landfill subjected to simulated rainfall
- Phase-3: to study leachate production patterns from an landfill subjected to simulated leachate re-circulation
- Phase-4: to study leachate production patterns from an open landfill reconstituted with new waste lift and subjected to further simulated rainfall
- Phase-5: to study leachate production patterns from a closed landfill subjected to simulated rainfall.

During the Phase-2, Phase-3, and Phase-4 experiments, the lysimeter was kept covered, to reduce evaporation. During each experiment, moisture was added until breakthrough was observed. The breakthrough was defined as the time of the first increase in leachate flow rate after the initiation of the rainfall/re-circulation simulation. In this research, moisture content has been expressed on dry weight basis for soil and volume basis for MSW. Moreover, moisture has been defined as water in a liquid state (precipitation and leachate).

3.2.2.1 Phase-1 Leachate Production from a Closed Landfill Lysimeter

In the first phase of field studies, natural precipitation was allowed to percolate into the waste layer across the cover system. The lysimeter was monitored for leachate production, gas production and temperature variations from October, 1997 to July, 1998. The lysimeter received a total precipitation of 371.5 mm (or about 1675 L, considering the area of the lysimeter) during this period. No leachate was produced during the monitoring period.

3.2.2.2 Phase-2 Leachate Production: Rainfall Simulation Studies (RF-1 to RF-4)

The second phase of lysimeter field studies was performed to study the leachate production patterns from the waste placed in an open landfill (landfill without the final cover). The cover was removed and waste layer kept open for this study. While removing the final cover, a soil sample from the sandy clay loam layer (barrier layer) was taken for moisture content measurement. The moisture content in the sandy clay loam had increased from 10.0% to 16.0% wt./wt. This indicated that the wetting front had progressed into the barrier layer. However, there was no visible indication of moisture infiltration into the waste layer during the Phase – 1 experiment. Hence, the initial moisture content of the waste for second phase of experimentation was assumed to be the same as the placement moisture content.

The rainfall simulation studies were performed as four different experiments: RF-1 to RF-4. During each experiment, moisture was infiltrated at a controlled rate over the entire surface area. The medium infiltration rate long duration simulations were based on 25 year 1-4 hour storm event, the medium infiltration rate medium duration simulations were based on 25 year 30-60 minutes storm event, the medium infiltration rate short duration simulations were based on 2 year 10 minutes storm event, the low infiltration rate long duration simulations were based on 25 year 1-6 hour storm event, and low infiltration rate medium duration simulations were based on 2 year 30-60 minutes storm event, for Calgary. Table-3.4 presents the experimental protocol for different simulations performed during Phase-2. In Phase-2, a total of 1109L of moisture was infiltrated into the waste.

Rainfall Simulation RF-1

Rainfall simulation RF-1 was performed to study the effect of a high intensity rainfall event on leachate production from relatively dry waste placed in an open landfill. A total of 560 L of moisture was infiltrated at an intensity of 7 litres/min (92.8 mm/hour, or 1.6 litres/min/m^2) for a duration of 80 minutes.

Table 3.4: Phase-2 Rainfall Simulations - Experimental Protocol

Parameters	**Rainfall Simulation**						
	RF-1	**RF-2**		**RF-3**		**RF-4**	
	Event-1	**Event-1**	**Event-2**	**Event-1**	**Event-2**	**Event-1**	**Event-2**
Infiltration Intensity	High	Medium	Medium	Low	Medium	Low	Medium
(litres/min)	7.0	3.8	3.0	1.2	2.8	0.8	2.5
(mm/hr)	92.8	50.4	39.8	15.9	37.1	10.6	33.2
(litres/min/m^2)	1.6	0.8	0.7	0.3	0.6	0.2	0.5
Infiltration Duration	Medium	Medium	Medium	Long	Medium	Medium	Short
(min)	80	20	40	160	30	65	10
Infiltration Volume (L)	560	76	120	192	84	52	25

Rainfall Simulation RF-2

Leachate production had stopped at the end of rainfall simulation RF-1. Rainfall simulation RF-2 was then performed to study the effect of further infiltration of moisture at medium (relatively low) rainfall intensity on leachate production. The simulation was undertaken as two separate events, simulating an individual rainfall event. In Event-1, 76 L of moisture was infiltrated at an intensity of 3.8 litres/min (50.4 mm/hour, or 0.80 litres/min/m^2), for a duration of 20 minutes. Event-2 was performed on the same day. In Event-2, 120L of moisture was infiltrated at an intensity of 3 litres/min (39.8 mm/hour, or 0.7 litres/min/m^2) for a duration of 40 minutes.

Rainfall Simulation RF-3

Simulation RF-3 was commenced immediately after leachate production from RF-2 had ceased. Simulation RF-3 was also undertaken to represent two separate events. In Event-1, 192 L of moisture was infiltrated at an intensity of 1.2 litres/min (15.9 mm/hour, or 0.3 litres/min/m^2) for a duration of 160 minutes. This event simulated a low-intensity, long-duration rainfall event. Event-2 was performed on the same day, to study the effect of medium-duration medium-intensity rainfall event after the long-duration low-intensity rainfall event. In Event-2, 84L of moisture was infiltrated at an intensity of 2.8 litres/min (37.1 mm/hour, or 0.6 litres/min/m^2) for a duration of 30 minutes.

Rainfall Simulation RF-4

Simulation RF-4 was commenced immediately after leachate production from RF-3 had ceased. Again, two events were simulated. In Event-1, 52 L of moisture was infiltrated at an intensity of 0.8 litres/min (10.6 mm/hour, or 0.2 litres/min/m^2) for a duration of 65 minutes to study the effect of low-intensity, medium-duration rainfall event on leachate production. Event-2 was performed on the same day, to study the effect of short-duration medium-intensity rainfall event following the medium-duration low-intensity rainfall event.

In Event-2, 25 L of moisture was infiltrated at an intensity of 2.5 litres/min (33.2 mm/hour) for a duration of 10 minutes.

3.2.2.3 Phase-3 Leachate Production: Leachate Re-circulation Simulations(RCL-1 to RCL-3)

Three simulations RCL-1 to RCL-3 were undertaken during this phase to study the effect of leachate re-circulation on leachate production. The purpose was to study the quantity (and patterns) of leachate production and not the quality. Tap water was used as the fluid for these simulations. During each simulation, moisture was infiltrated at a controlled rate on a predetermined area of the lysimeter. Location and surface area used for leachate re-circulation experiments represented "point" injection and "area" injection of leachate. In Phase-3, a total of 252 L of moisture was re-circulated into the waste. Table-3.5 presents the experimental protocol for different simulations performed during Phase-3.

Table 3.5: Phase-3 Leachate Re-circulation Simulations - Experimental Protocol

Parameters	**Leachate Re-circulation Simulations**				
	RCL-1		**RCL-2**		**RCL-3**
	Event-1	**Event-2**	**Event-1**	**Event-2**	**Event-1**
Re-circulation Intensity	Low	Medium	Low	Medium	Low
(litres/min)	0.8	2.5	1.2	2.5	1.1
(mm/hr)	10.6	33.2	15.9	33.2	14.7
(litres/min/m^2)	4.0	12.7	6.1	12.7	0.24
Re-circulation Duration	Medium	Short	Medium	Short	Long
(minutes)	60	10	45	10	90
Re-circulationVolume (L)	48	25	54	25	100
Re-circulation Area (m^2)	0.2	0.2	0.2	0.2	4.5

Leachate Re-circulation Simulation RCL-1

The leachate re-circulation simulation RCL-1 was performed to study the effect of "point injection" of moisture, on leachate production. During this simulation, moisture was injected in a 0.20 m^2 area at the center of the lysimeter. Two events were performed during this simulation. Event-1 was a low-intensity, medium-duration leachate re-circulation event. In Event-1, 48 L of moisture was re-circulated at an intensity of 0.8 litres/min (10.6 mm/hour, or 4 litres/min/m^2), for a duration of 60 minutes. Event-2 was performed on the same day. Event-2 was performed to study the effect of medium-intensity, short-duration leachate re-circulation event, after very low-intensity, medium-duration event, on leachate production. In Event-2, 25 L of moisture was re-circulated at an intensity of 2.5 litres/min (33.2 mm/hour, or 12.7 litres/min/m^2) for a duration of 10 minutes.

Leachate Re-circulation Simulation RCL-2

Leachate re-circulation simulation RCL-2 was also performed to study the effect of point injection of re-circulated leachate, on leachate production. However, moisture was injected in a 0.20 m^2 area at a different location, on the periphery of the lysimeter. Two events were performed during this simulation. Event-1 was performed to study the effect of low-intensity, medium-duration leachate re-circulation event on leachate production. In Event-1, 54 L of moisture was re-circulated at an intensity of 1.2 litres/min (15.9 mm/hour, or 6.1 litres/min/m^2) for a duration of 45 minutes. Event-2 was performed to study the effect of medium-intensity, short-duration leachate re-circulation event on leachate production. In Event-2, 25 L of moisture was infiltrated at an intensity of 2.5 litres/min (33.2 mm/hour, or 12.7 litres/min/m^2), for a duration of 10 minutes.

Leachate Re-circulation Simulation RCL-3

RCL-3 is a simulation of "area" injection of leachate. During this experimental simulation, moisture was re-circulated over the entire plan area of the lysimeter. The experimental set consisted of a single low-intensity, long-duration leachate re-circulation event. About 100 L of moisture was infiltrated at an intensity of 1.1 litres/min (14.7 mm/hour, or 0.24 litres/min/m^2) for a duration of 90 minutes.

3.2.2.4 Phase-4 Leachate Production: Rainfall Simulations (RFR-1 to RFR-2)

The purpose of these simulations was to study the effect of a new waste lift on the existing wet MSW on leachate production. Although, this new waste lift does not represent actual field operations, the aim was to study the impact of new and drier waste overlying a saturated area of a landfill. Two simuations, RFR-1 and RFR-2 were performed. A total of 1008 L of moisture was infiltrated into the waste during these two simulations. Table-3.6 presents the experimental protocol for the two sets of experimental simulations performed.

Table 3.6: Phase-4 Rainfall Simulations – Experimental Protocol

Parameters	**Further Rainfall Simulations**	
	RFR-1	**RFR-2**
Infiltration Intensity	Medium	Medium
(litres/min)	1.6	2.6
(mm/hr)	21.2	34.5
(litres/min/m^2)	0.4	0.6
Infiltration Duration	Long	Long
(minutes)	140	340
Infiltration Volume (L)	224	884

<u>*Rainfall Simulation RFR-1*</u>

Prior to this simulation, additional 800 kg of waste consisting of 500 kg of paper, 260 kg of grass, and 40 kg of food waste was placed in the lysimeter, over the existing 4.5 MT of

MSW. The initial moisture content of the newly added waste was 0.04 vol./vol. The total quantity of waste after addition, was 5.3 MT. A single experimental event was performed on the reconstituted lysimeter, during this simulation. About 224 L of moisture was infiltrated at a medium intensity of 1.6 litres/min (15.9 mm/hour, or 0.4 litres/min/m^2), for a long duration of 140 minutes.

Rainfall Simulation RFR-2

RFR-2 simulation was also performed to study the effect of rainfall infiltration on the reconstituted landfill lysimeter. Additional 140 kg of waste, consisting of 15 kg of paper, and 125 kg of grass was placed in the lysimeter, over the existing 5.3 MT of MSW. The initial moisture content of the newly added waste was 0.04 vol./vol. The final depth of waste in the lysimeter after this addition was 3.15 m (note that the waste in the lysimeter settled by 0.30 m with time, and addition of this waste also helped to maintain a consistent waste layer thickness). A single experimental event was performed on the reconstituted lysimeter. About 884 L of moisture was infiltrated at an intensity of 2.6 litres/min (34.5 mm/hour, or 0.6 litres/min/m^2) for a duration of 340 minutes.

3.2.2.5 Phase-5: Leachate Production: Rainfall Simulations on a Closed Lysimeter

This rainfall simulation was undertaken after closure of the lysimeter, to study the effect of simulated rainfall infiltration through the final cover placed on a relatively saturated landfill. The final cover, in this case, consisted of 0.6 m of sandy loam and 0.2 m of compost based top soil. The sandy loam layer was compacted on placement to a density of 1550 kg/m^3 at a placement moisture content of 11% using a mechanical hand vibrator. During this simulation, a total of 330L of moisture was infiltrated through the cover for a duration of 4 hours/day over an 8 day period.

3.2.3 Leachate Characteristics

The leachate samples were collected all throughout the experimental simulations and were analyzed in the laboratory for parameters such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Electrical Conductivity (EC), and pH as per The Standard Methods for the Examination of Water and Wastewater (Lenore et al., 1998).

CHAPTER FOUR

PRESENTATION AND DISCUSSION OF RESULTS

4.1 LABORATORY EXPERIMENTS

The primary purpose of the laboratory experimental programme was to generate;

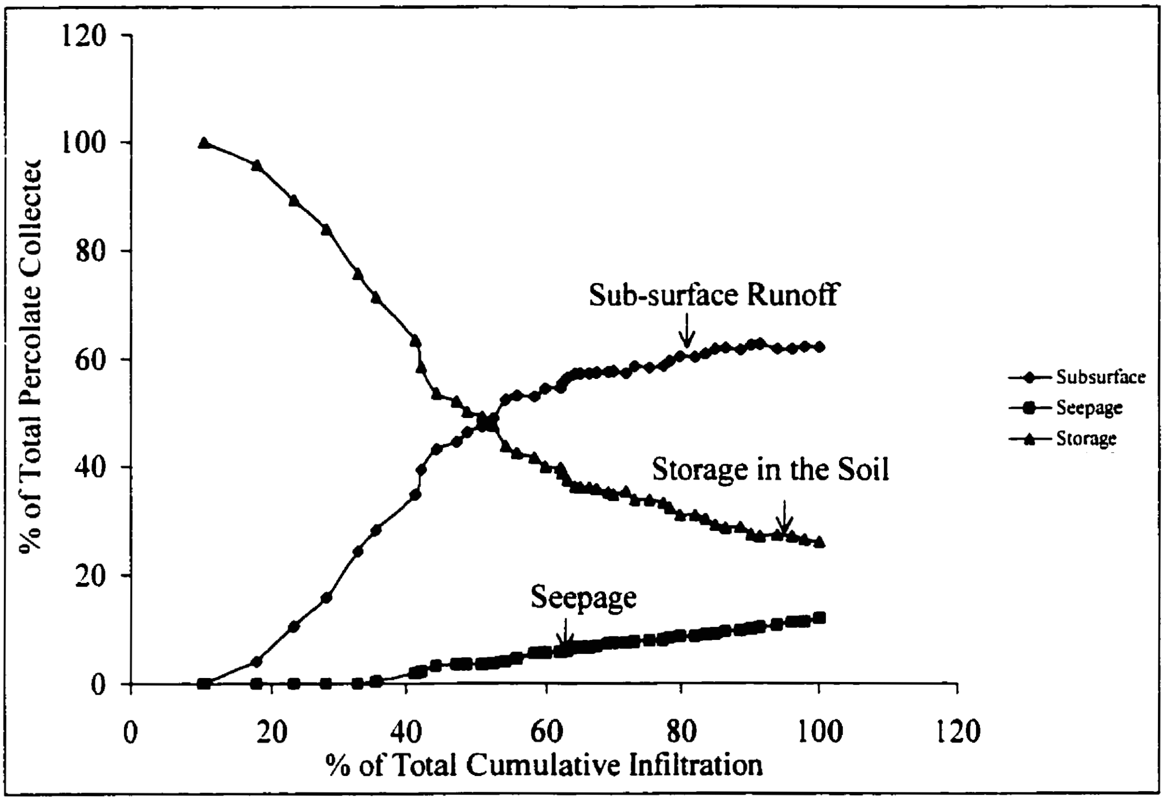
- information to explain the moisture migration behavior within the soil cover used in the field studies, and
- specific information on waste parameters relevant to the field studies.

4.1.1 Moisture Apportionment in the Laboratory Soil Column

A total of 7500 mL of moisture was added to the laboratory soil column. Breakthrough occurred from the drainage layer after 1090 mL, and from the barrier layer after 2650 mL (this includes the 1090 mL required for breakthrough in the drainage layer) of moisture addition. Thus, in a closed system, where moisture was not lost through evaporation and runoff, breakthrough occurred from the barrier layer after 73mm (based on the area of the column and the volume of moisture infiltrated) of infiltration.

The experimental results, in the form of percentages of moisture percolation through the drainage and the barrier layers, are presented in Figure 4.1. The moisture migrating through the top sandy loam layer, or the drainage layer, and collected from the ports at the side of the column (see Figure 3.1), is termed "sub-surface runoff". The moisture migrating through the sandy clay loam soil, or the barrier layer, and collected from the base of the column is termed "seepage".

Figure 4.1: Moisture Collected as Subsurface Runoff, Seepage, and Storage in the Laboratory Soil Column: % Total Percolate Collected vs. % of Total Cumulative Infiltration



A total of 62% of the total moisture infiltrated was collected as sub-surface runoff and 12% of the total moisture infiltrated was collected as seepage. Thus, the rest of 26% of the total moisture added, was retained as storage in the drainage and barrier soil.

The saturated hydraulic conductivities of the sandy loam soil used as drainage layer and the sandy clay loam soil used as the barrier layer were calculated to be 1.2×10^{-2} cm/sec and 5×10^{-5} cm/sec, respectively. The higher hydraulic conductivity of drainage layer produces sufficient head for sub-surface runoff to occur (Korfiatis et al., 1986). Mounding on the barrier layer leads to a steady-state migration through a saturated barrier layer.

Steady-state condition was reached in the soil column after infiltration of 200 mm (or 7500 mL) of moisture. Under steady state conditions, the drainage layer soil and barrier layer soil had a combined field capacity of 18.5%. At steady state, sub-surface runoff was 85% of the infiltrated moisture, and seepage through the barrier layer was 15% of the infiltrated moisture.

As evident from these laboratory results, the majority (up to 85%) of the infiltrating moisture, migrates as sub-surface runoff in a lateral direction. If not collected, this runoff will flow laterally along the barrier layer and will re-infiltrate into the landfill waste layers at another location. Therefore, landfill designers are well advised to provide draining systems to remove sub-surface flow.

4.1.2 MSW Properties

The results from experiments on four MSW columns are presented in Table 4.1. Waste compacted to a density of 375 kg/m^3 had an practical field capacity (PFC) of 0.20 ± 0.01 vol./vol. whereas the PFC of the waste compacted to a density of 525 kg/m^3 was 0.225 ± 0.005 vol./vol. The PFC increased by 18% for a 40% increase in waste density.

Density affects the void ratio and pore geometry of the layer. Certain individual components of MSW absorb moisture. For example, paper and cardboard present in MSW absorbs moisture in addition to the moisture held in the pore spaces against gravity. Hence, an increase in density of MSW increases the mass of absorbing material present per unit volume of waste. Moreover, compaction of MSW may increase the area of waste exposed to moisture by opening the garbage bags and re-aligning the individual particles. The increase in density also reduces channeling within the waste (Campbell, 1982), and increases the availability of absorption sites. The end result is an increase in the PFC of the waste. Evidently, PFC is a function of waste density. Furthermore, it is a function of waste

Table 4.1: Results from Laboratory Experiments to Determine MSW Properties

Column No.	Diameter of the Column (cm)	Depth of the Waste (cm)	Compacted Density (kg/m^3)	Practical Field Capacity (vol./vol.)	Theoretical Field Capacity (vol./vol.)	Porosity (vol./vol.)	Hydraulic Conductivity (cm/sec.)
1	13.9	35.5	375	0.19	0.39	0.54	1.00×10^{-2}
2	12.6	28.5	375	0.21	0.36	0.56	1.33×10^{-2}
3	21.5	35.0	525	0.23	0.42	0.51	8.46×10^{-3}
4	13.9	28.5	525	0.22	0.41	0.53	7.10×10^{-3}

type. Therefore, it may be difficult to use a single PFC value for a given landfill. Instead, a range of values could be used.

The theoretical field capacity (or TFC) of the waste compacted to a density of 375 kg/m^3 was 0.375 ± 0.015 vol./vol. and that for the waste compacted to a density of 525 kg/m^3 was 0.415 ± 0.005 vol./vol. The TFC increased by 11% for an 40% increase in waste density and was higher than the corresponding PFC. TFC is the effective storage of the waste, or the moisture content at which there is no further absorption. It is the maximum absorption capacity of the waste or the maximum quantity of moisture the waste can hold against gravity. Similar to the PFC, increase in density of MSW, increases the available absorption site which results in an increase in TFC.

The porosity of the waste compacted to a density of 375 kg/m^3 was 0.55 ± 0.01 vol./vol. and the porosity of the waste compacted to a density of 525 kg/m^3 was 0.52 ± 0.01 vol./vol. The porosity decreased by 6% for a 40% increase in waste density.

The saturated hydraulic conductivity of the waste compacted to a density of 375 kg/m^3 was $1.17 \times 10^{-2} \pm 0.17 \times 10^{-2}$ cm/sec, and that of the waste compacted to a density of 525 kg/m^3 was $7.78 \times 10^{-3} \pm 0.68 \times 10^{-3}$ cm/sec. The average saturated hydraulic conductivity decreased by 33%. The hydraulic conductivity of MSW is affected by packing density and the composition of MSW (Chen and Chynoweth, 1995). In soils, moisture movement occurs through the available pore spaces. However, the moisture movement through MSW can be either through the macropores or through the waste matrix itself. A decrease in saturated hydraulic conductivity, with an increase in density, results in reduced channeling.

The experimental results indicated that density of compacted waste is an important factor governing leachate production from MSW landfills. The HELP model uses parameters such as saturated hydraulic conductivity and field capacity to indirectly accommodate the effect of density of compacted waste. The HELP model has default values for these parameters. The results suggest that leachate generation prediction models, such as the HELP model, may have to incorporate waste properties as variables to accurately predict the leachate generation from a given landfill. Since waste density may change with time in a given landfill (as new waste lifts are added), time dependent variation in waste density (and associated parameters) needs to be considered.

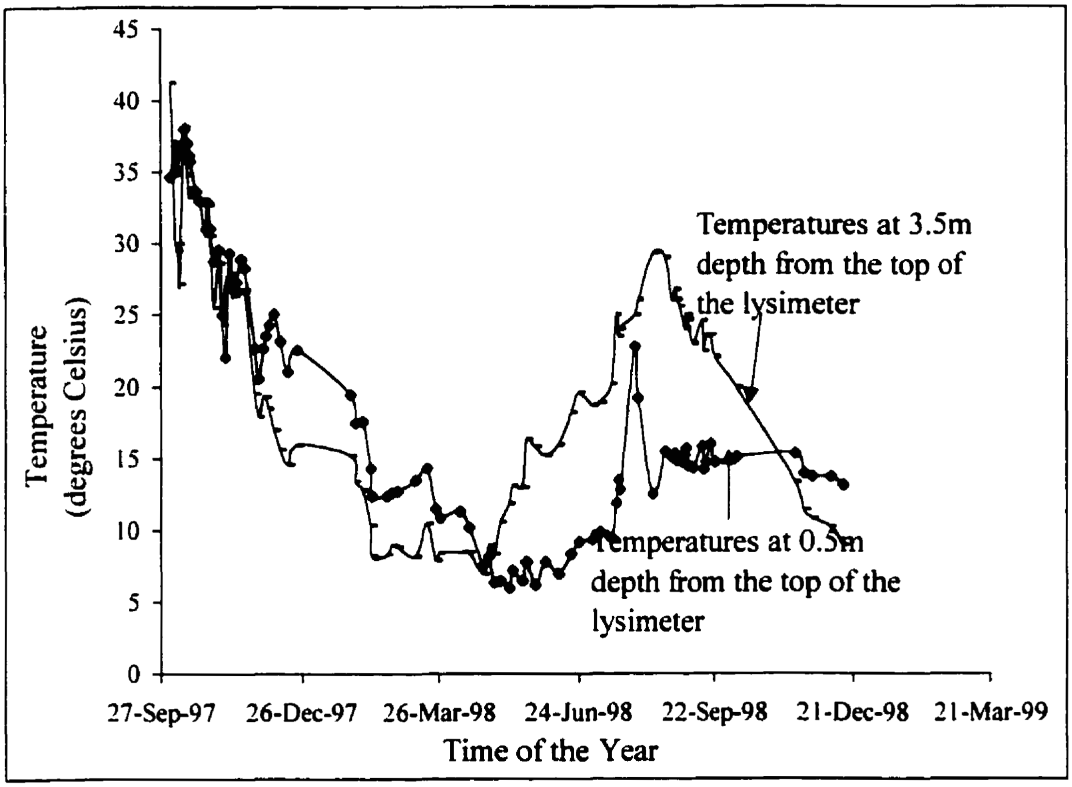
4.2 FIELD LANDFILL LYSIMETER STUDIES

4.2.1 Phase-1 Leachate Production from a Closed Landfill Lysimeter

A total of 500 mL of leachate was produced within three days of placement and compaction of waste. This was the primary moisture available that was released from MSW on compaction. No leachate was produced during the monitoring period of over 10-month after construction of the lysimeter. The total precipitation recorded at the lysimeter site during this period was 371.5 mm.

The initial average temperature of the lysimeter in October-97 was 46.4°C. The average temperature of the lysimeter gradually dropped to 7.5°C by the beginning of May-98 and then again increased to a maximum of 25°C in the month of July-98. The lysimeter cap, including the drainage layer, was frozen for certain periods of the year. The optimum temperature range for degradation of waste is the 30°C to 38°C of the mesophilic range (20°C to 50°C), and 55°C to 60°C of the thermophilic range (45°C to 75°C) (Tchobanoglous et al., 1993). The low average temperature in the waste and no gas production, indicated low biological activity. Figure 4.2 shows the variation of temperature with time at a depth of 0.5m and 3.5m from the top of the lysimeter, throughout the monitoring period. The figure shows that the top of the landfill lysimeter was more sensitive to the atmospheric temperature changes than the bottom of the lysimeter. Thus, the depth of the landfill affects the biological activity within the waste. Appendix 4.1 presents the temperatures observed within the lysimeter during the 10-month monitoring period.

Figure 4.2: Temperature Variation in the Field Lysimeter with Time of the Year



The biological activity of the waste is most affected by the moisture content of the waste. Moisture infiltrates into a landfill during precipitation events. Parsons (1995) observed that a certain minimum rainfall is required for infiltration to occur through the final cover. The minimum rainfall value depends on the existing conditions at the site and the rainfall intensity. Parsons (1993) proposed that the minimum rainfall for infiltration to occur lies between 10 mm per event to 30 mm per event. The low biological activity within the lysimeter indicated low or no infiltration of the precipitated moisture into the waste layer. This fact was confirmed by the observation of no leachate production during this period. The immediate capping of the lysimeter minimized the percolation of moisture into the waste layer. The moisture content of the barrier layer soil in the lysimeter cover increased from 10 % wt./wt. to 16.0 %wt./wt. at the end of the monitoring period. However, the infiltrated moisture was insufficient to produce leachate.

Theoretically, leachate would be produced only after the field capacity of the waste is exceeded. However, due to channeling, leachate can be produced prior to this. Manual tabular computations indicating the time required for the lysimeter to produce leachate at HELP model default field capacity using the water balance technique (without any losses) is given in Table 4.2.

Table 4.2. A Manual Calculation to Show Time to Generate Leachate from the Field Lysimeter

Parameter	**Value**
Area of the Lysimeter (m^2)	4.5
Depth of Waste in the Lysimeter (m)	3.15
Depth of Cover Soil (m)	0.9
Initial Moisture Content of the Cover Soil (vol./vol)	0.15
Field Capacity of Cover Soil (vol./vol)	0.2
Moisture Deficit in the Cover Soil (m^3)	0.2025
Initial Moisture Content of the Waste (vol./vol)	0.08
Field Capacity of Waste (vol./vol), HELP model default value	0.292
Moisture Deficit in the Waste (m^3)	3.0051
Total Moisture Deficit (m^3)	3.2076
Average Annual Precipitation in Calgary (m)	0.45
Average Infitration through the Cover (m) (5 % of Average Annual Precipitation)	0.0225
Time Period Necessary to Produce Leachate (years)	**31.5***

* 19 years if the laboratory determined field capacity value of 0.20 vol./vol. is used.

A calculation using the HELP model default field capacity of 0.292 vol./vol. for MSW without channeled flow and the placement initial moisture content, showed that 2735L of percolation of moisture into the MSW layer was required to produce leachate. If it is assumed that the quantity of precipitation percolating from the landfill final cover into the MSW layer is 5% of the total precipitation, it will take more than 31.5 years before leachate production starts at the lysimeter. If a field capacity value of 0.20 vol./vol. is used (a value determined by laboratory experiments), the predicted time for leachate generation will be 19 years.

This calculation and the field lysimeter results showed that the time of placement of final cover may be critical in minimizing leachate production at landfills; the sooner the cover is placed, the less is the leachate produced, and the more is the breakthrough time. Under semi-arid climatic conditions in Alberta, immediate placement of the final cover may delay leachate production by several years in landfills. However, immediate placement of final cover is not practically feasible. Hence, it can be inferred that constructing smaller landfill cells may minimize the leachate produced at landfills.

During the 10-month monitoring period, the lysimeter waste had undergone a primary settlement of 0.30m or more than 10% of the waste thickness. The compacted density of the waste was re-calculated considering settlement and was determined to be 350 kg/m^3 in July 1998.

4.2.2 Phase-2 Leachate Production: Rainfall Simulation Studies(RF-1 to RF-4)

The waste was at the initial moisture content of 0.08 vol./vol. when the four simulated rainfall studies RF-1 to RF-4 were initiated . During the rainfall simulations, moisture was infiltrated over the total surface area of the lysimeter. A total of 1109 L of moisture was infiltrated (refer Table 3.4). Table 4.3 presents the results in terms of change in moisture content (MC), and the change in MC/FC (FC is the Practical Field Capacity determined in the laboratory) ratio of the waste, before and after the four simulated rainfall infiltrations.

Table 4.3: Phase-2 Field Lysimeter Studies - Changes in MC and MC/FC Ratio During Rainfall Simulations

Parameters	Rainfall Simulations						
	RF - 1	RF - 2		RF -3		RF - 4	
	Event-1	Event-1	Event-2	Event-1	Event-2	Event-1	Event-2
Infiltration Volume (L)	560	76	120	192	84	52	25
MC before infiltration experiment, (vol./vol.)	0.08	0.123	0.129	0.139	0.154	0.157	0.161
MC after infiltration experiment, (vol./vol.)	0.123	0.129	0.139	0.154	0.157	0.161	0.163
MC*/FC** ratio before infiltration	0.40	0.62	0.65	0.70	0.77	0.79	0.81
MC*/FC** ratio after infiltration	0.62	0.65	0.70	0.77	0.79	0.81	0.82

* MC = Moisture Content
** FC = Field Capacity (FC is 0.20 vol./vol. from laboratory experiments)

After the four simulations, the MC of the waste increased from 0.08 vol./vol. at placement to 0.163 vol./vol. at the end of RF-4 simulation. The MC/FC ratio increased from 0.4 at placement to 0.82 at the end of RF-4 simulation. The MC/FC ratio indicates the moisture content relative to the field capacity, and is an important measure of propensity to produce leachate.

Table 4.4 presents results on leachate discharge volume, average rate of leachate discharge, peak leachate discharge rate, and breakthrough time for the four rainfall simulations.

The waste placed in the lysimeter had low initial moisture content. Hence, the moisture infiltrated during RF-1 was almost totally absorbed by the waste. However, a total of 2.2 L of leachate was produced at an average leachate discharge rate of 0.28 litres/hour. Leachate production occurred after a delay, or a "breakthrough time" of 85 minutes from the start of

Table 4.4: Phase-2 Field Lysimeter Studies: Leachate Production

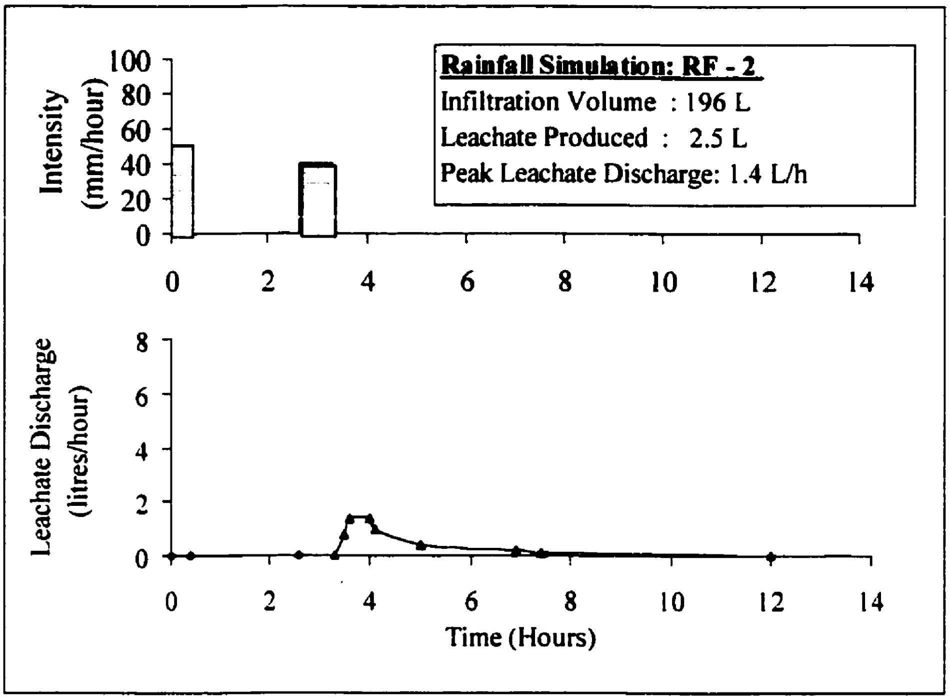
Parameters	Rainfall Simulations			
	RF-1	**RF-2**	**RF-3**	**RF-4**
Total Infiltration Volume (L)	560	196	276	77
Total Infiltration Duration (minutes)	80	60	190	75
Leachate Produced (L)	2.20	2.50	41.80	1.58
Duration of Leachate Discharge (hours)	8.00	20.75	59.50	62.00
Breakthrough Time (minutes)	85	195	195	-
Average Leachate Discharge Rate *(lph)	0.28	0.24	1.08	0.03
Peak Leachate Discharge Rate (litres/hour)	0.91	1.40	8.00	0.13
Ratio of Peak/Average Leachate Discharge Rates	3.25	5.83	7.41	4.33

*Note: Hours of nominal leachate production (< 0.1 L/h) was not considered for average rate calculations.

the simulation RF-1, and continued for 8 hours. Figure 4.3 shows that the peak leachate discharge was observed after 40 minutes of breakthrough event. Simulation RF-1 was terminated, when no further leachate was produced. Experimental simulation RF-1 showed that even at high infiltration intensity, the newly placed raw waste absorbs most of the infiltrated moisture. During the simulation, MC/FC increased from 0.40 to 0.62. At an average MC/FC ratio of about 0.51, the ratio of peak/average leachate discharge rate was 3.25. Ratio of peak/average is an important design parameter for designing the LCRS. This value changes with MC/FC ratio.

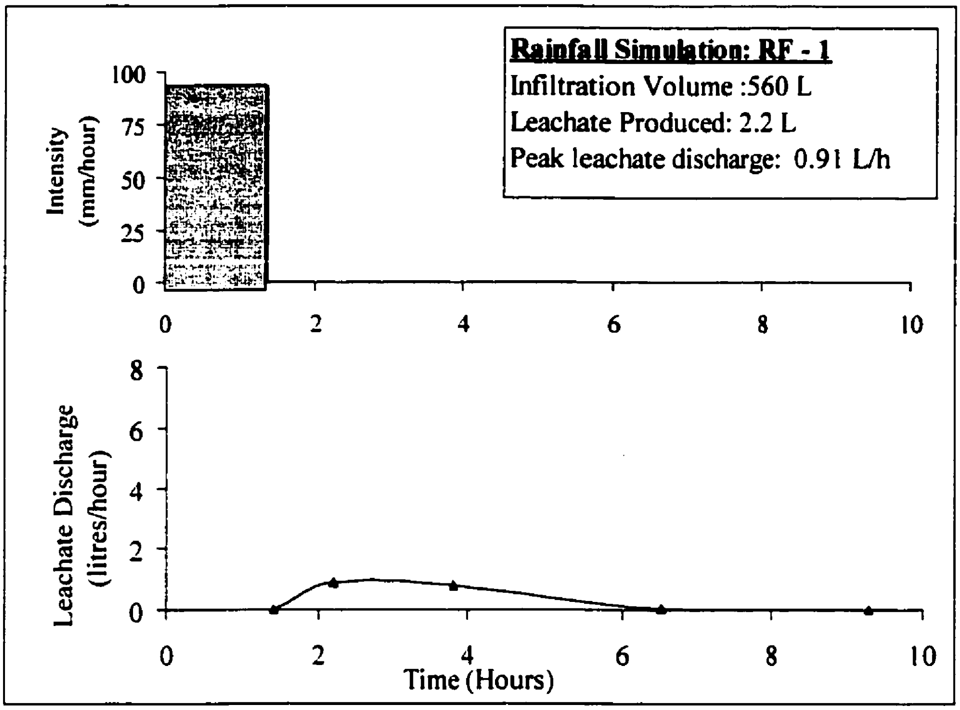
Rainfall simulation RF-2 was performed at a lower infiltration intensity, as compared to RF-1. About 2.5 L of leachate was produced during RF-2, at an average leachate discharge rate of 0.28 litres/hour.

Figure 4.4: RF - 2 - Infiltration Intensity and Leachate Discharge Rate vs. Time



RF-3, at an average leachate discharge rate of 1.08 litres/hour. The average leachate discharge rate was higher than in simulation RF-2, indicating that the moisture absorbance capacity of waste had decreased. The peak/average leachate discharge rate ratio was 7.41 and was much higher than that of RF-2. The long-duration low-intensity rainfall event, produced higher peak/average leachate discharge ratio. The MC/FC ratio at the end of simulation RF-3 was 0.79. Again, leachate production occurred after a delay, or a breakthrough time of 195 minutes from the start of the infiltration simulation and continued for 59.5 hours. However, leachate was produced at a nominal rate of 0.1 litres/hour after 35 hours of breakthrough (refer Figure 4.5). Results of the experimental simulation RF-3 agreed with the results from RF-2 that at low infiltration intensities, waste absorbs moisture and releases it over a longer duration of time.

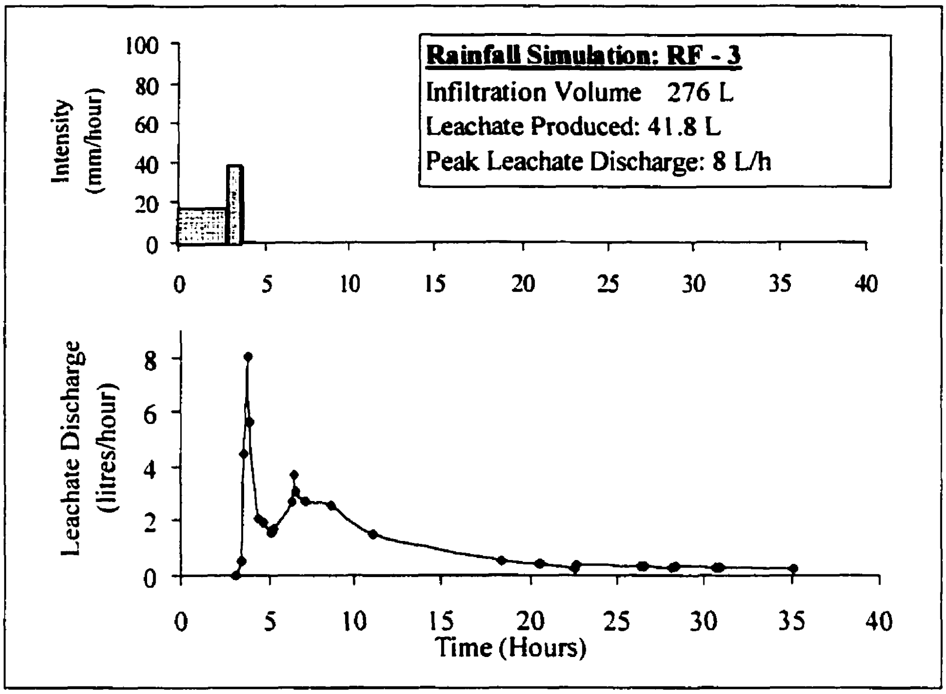
Figure 4.3 : RF - 1 - Infiltration Intensity and Leachate Discharge Rate vs. Time



The MC/FC ratio increased from 0.62 to 0.70. At average MC/FC ratio of about 0.66, the peak/average leachate discharge rate ratio was 5.83. As the MC/FC increased from 0.62 to 0.70, the peak/average discharge rate ratio also increased from 3.25 to 5.83. Leachate production occurred after a delay, or a breakthrough time of 195 minutes, from the start of the infiltration simulation and continued for 20.75 hours. However, leachate discharged at a nominal rate (<0.1 lph) after 12 hours (refer Figure 4.4). During simulation RF-2, no leachate was produced on infiltration of 76 L of moisture during Event-1. However, at the end of Event-2 of this simulation, leachate was produced at a higher peak/average ratio for a longer duration of time, as compared to RF-1. These results showed that at low infiltration intensities and low moisture content, the waste absorbs moisture and produces leachate after a certain minimum infiltration quantity.

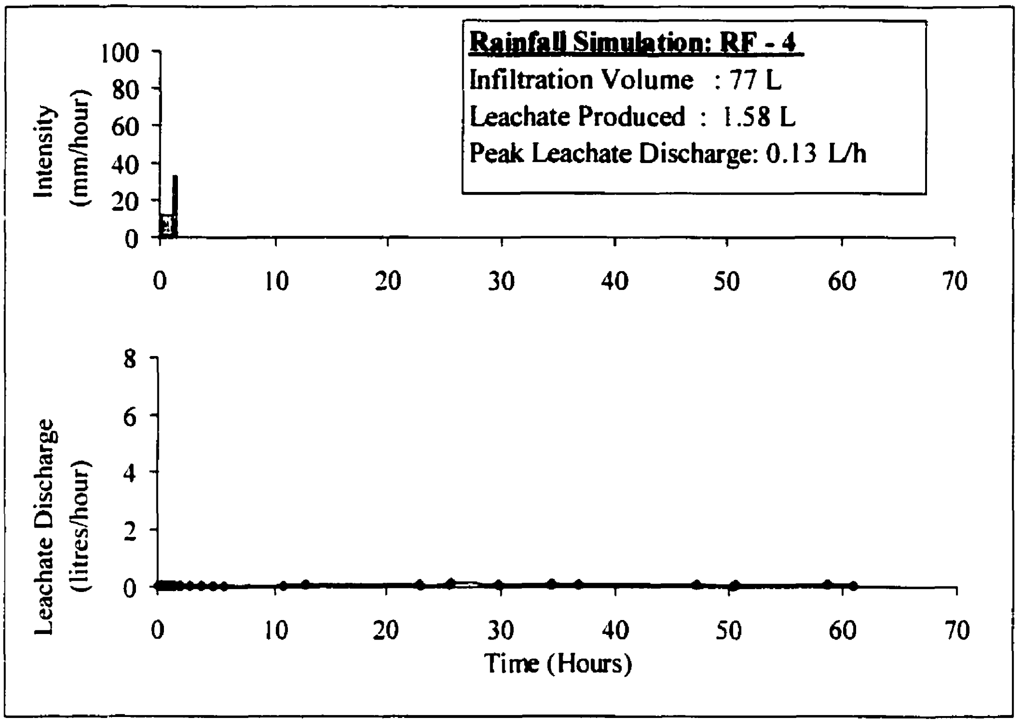
Rainfall simulation RF-3 was performed at a lower infiltration intensity than RF-2 and was performed over a longer duration of time. A total of 41.8 L of leachate was produced during

Figure 4.5: RF - 3 - Infiltration Intensity and Leachate Discharge Rate vs. Time



Rainfall simulation RF-4 was performed at low infiltration intensity for a medium duration of time. A total of 1.58 L of leachate was produced during RF-4, at an average leachate discharge rate of 0.03 litres/hour. The peak/average leachate discharge rate ratio was 4.33. The leachate produced in this simulation was low and was comparable to the leachate produced in RF-1 and RF-2. The peak/average leachate discharge ratio was also comparable to the peak/average leachate discharge in RF-1 and RF-2. Figure 4.6 shows the rate of leachate discharge with respect to time. Leachate was produced over a duration of 62 hours. Experimental simulation RF-4 results were comparable to Event-1 of RF-2. During RF-4, a total of 77L of moisture was infiltrated (in Event-1 of RF-2, a total of 76L of moisture infiltrated). Both the simulations produced similar results (refer Table 4.3). This indicated that at lower infiltration volume, moisture was better distributed in the waste leading to more absorption by the waste. The leachate was produced after a certain threshold quantity was infiltrated, and was independent of MC/FC ratio. Moreover, the

Figure 4.6 : RF - 4 Infiltration Intensity and Leachate Discharge Rate vs. Time



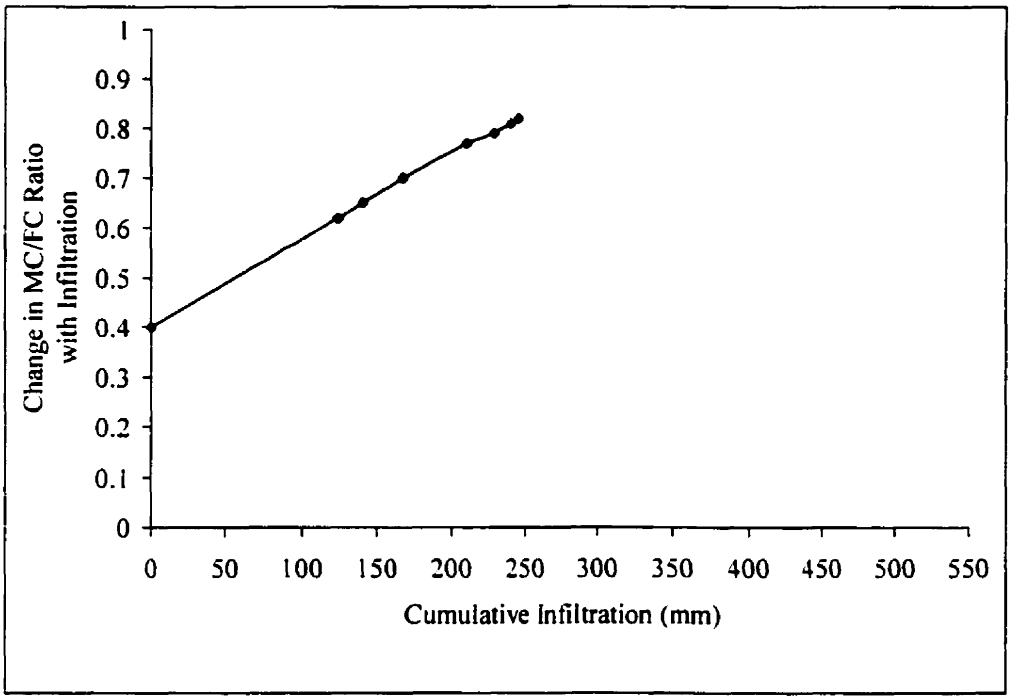
peak/average leachate discharge ratio for RF-4 was comparable to the peak/average leachate discharge ratio of RF-1.

4.2.2.1 Rainfall Simulations RF-1 to RF-4: Overall Evaluation

Figure 4.7 presents the change in MC/FC ratio with cumulative infiltration. The initial MC/FC ratio was 0.40, and reached 0.82 after 245 mm of infiltration. There was almost a linear increase in MC/FC ratio, but did not reach 1 even after 245 mm of infiltration. An extrapolation of the linear portion of the curve shows the lysimeter reaching MC/FC=1, when infiltration is about 350 mm.

The results from the rainfall simulation experiments showed that initial breakthrough was observed only after the infiltration of about 124 mm (560L) of moisture directly into the

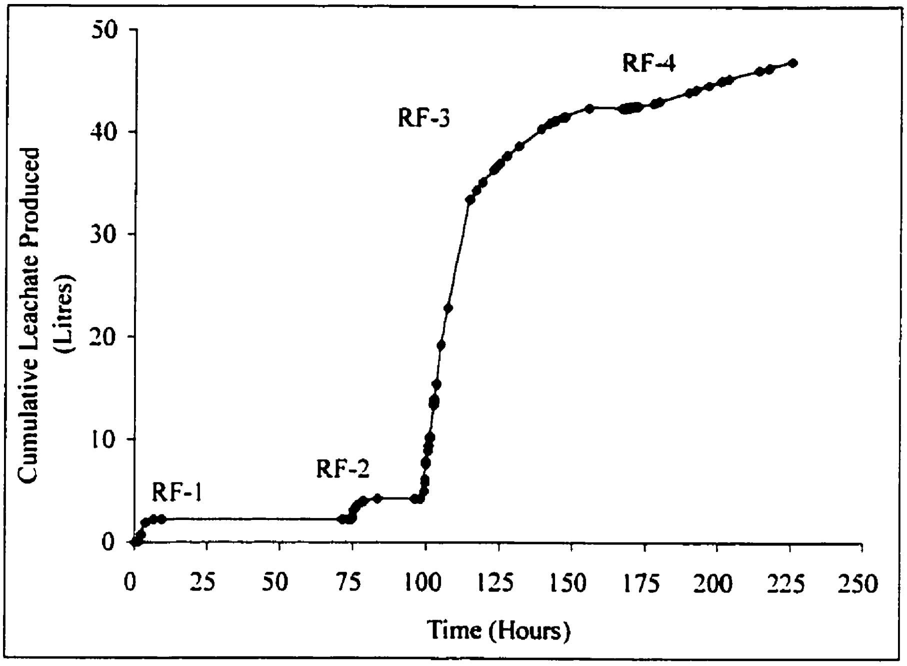
Figure 4.7: Change in MC/FC Ratio vs. Cumulative Infiltration for RF-1 to RF-4



waste layer, at a MC/FC ratio of 0.62 (well before the theortetical breakthrough time). Assuming, 5% of precipitation as percolation through the cover into the waste (typical of most landfill covers), breakthrough may occur after a total of 2480 mm of precipitation. Considering that Calgary has an average annual precipitation of 450 mm, and assuming a complete cell of waste covered prior to a precipitation event, leachate will be produced in a Calgary landfill after about 5.5 years. However, the quantity of leachate produced initially could be nominal, approximately 0.44 L/m^2. A continuous flow of leachate may not be established. The leachate will be produced probably due to channeling within the waste.

At the end of rainfall simulations, the MC/FC ratio was 0.82 after cumulative infiltration of 245mm (or 1109L). A total of 10.6mm (or 48.08 L) of leachate was generated during the four rainfall simulations. This was 4% of the moisture added. However, a continuous flow of leachate was not established, indicating the sporadic nature of leachate production in response to precipitation events. Figure 4.8 shows the trend for cumulative leachate generated for RF-1 to RF-4 as a function of time. The figure indicates that maximum leachate was produced during RF-3.

Figure 4.8: Rainfall Simulations RF-1 to RF-4-Cumulative Leachate Produced vs. Time



4.2.3 Phase-3 Leachate Production: Leachate Re-circulation Simulations (RCL-1 to RCL-3)

Simulations RCL-1 to RCL-3 were performed to simulate leachate re-circulation by two methods, point injection and area injection. Point and area injection are the most common methods used by landfill designers. In RCL-1, moisture was re-circulated at a point (area 0.2 m^2) in the center of the lysimeter. About 73 L of moisture was re-circulated in this manner (refer Table 3.5). Table 4.5 presents the results; in terms of change in moisture content (MC), and the change in MC/FC ratio of the waste, before and after the re-

Table 4.5: Phase 3 - Field Lysimeter Studies - Changes in MC and MC/FC Ratio During Leachate Recirculation Simulations

Parameters	Recirculation Simulations				
	RCL - 1		RCL - 2		RCL - 3
	Event-1	Event-2	Event-1	Event-2	Event-1
Recirculation Volume (L)	48	25	54	25	100
MC before recirculation (vol./vol.)	0.163	0.167	0.167	0.172	0.172
MC after recirculation (vol./vol.)	0.167	0.167	0.172	0.172	0.175
MC*/FC** ratio before recirculation	0.82	0.84	0.84	0.86	0.86
MC*/FC** ratio after recirculation	0.84	0.84	0.86	0.86	0.88

* MC = Moisture Content

** FC = Field Capacity (FC is 0.20 vol./vol. from laboratory experiments)

circulation simulations. Leachate volumes, average rate of leachate discharge, peak leachate discharge rate, and breakthrough time for the three leachate re-circulation simulations are presented in Table 4.6.

RCL-1 was performed at a very low re-circulation intensity of 10.6 mm/hour in Event-1. A total of 25.7 L of leachate was produced during RCL-1 at an average leachate discharge rate of 0.72 litres/hour. The peak/average leachate discharge ratio was 25.14, much higher than the observed ratios for rainfall simulation experiments. This indicates higher incidence of channeling during point injection of moisture.

Table 4.6: Phase-3 Field Lysimeter Studies: Leachate Production

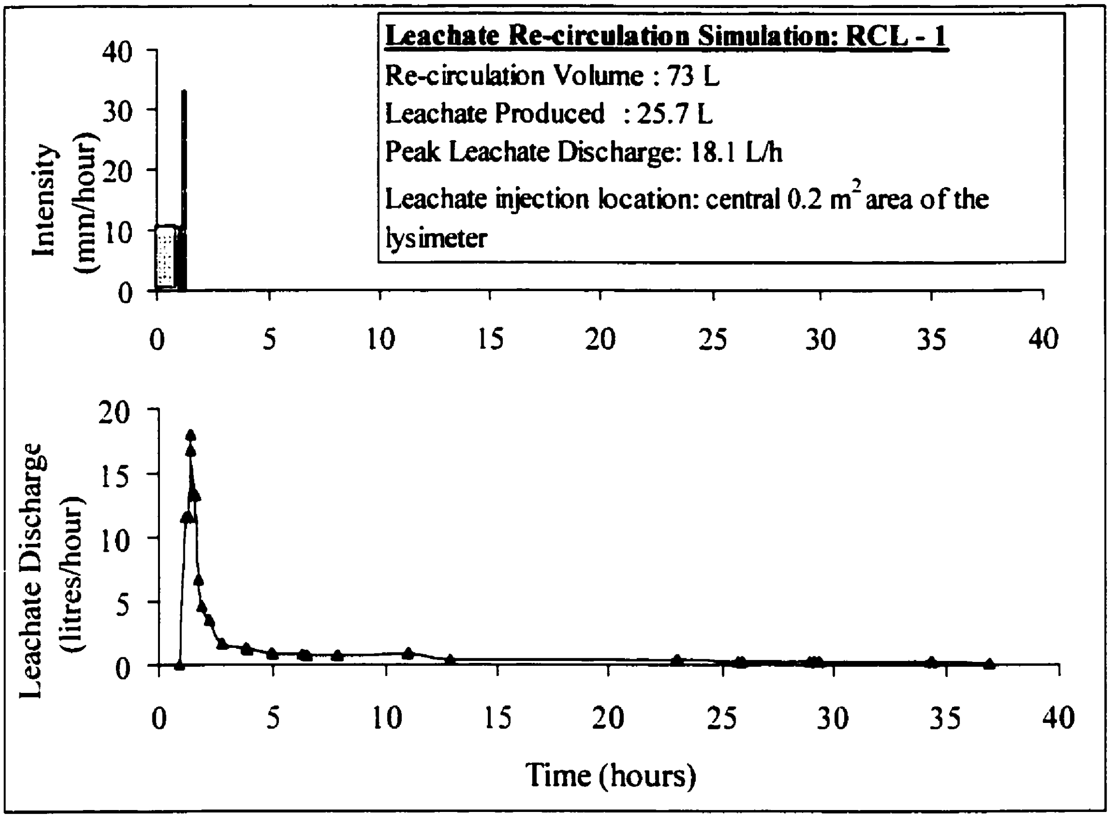
Parameters	**Re-circulation Simulations**		
	RCL-1	**RCL-2**	**RCL-3**
Re-circulation Volume (L)	73	79	100
Re-circulation Duration (minutes)	60	45	90
Leachate Discharged (L)	25.7	32.9	58.1
Duration of Leachate Discharge (hours)	92.6	160	260.6
Breakthrough Time (minutes)	74	53	45
Average Leachate Discharge Rate (L/h)*	0.72	0.34	0.38
Peak Leachate Discharge Rate (L/h)	18.1	5.2	3.7
Peak/Average Leachate Discharge Rate Ratio	25.14	15.29	9.74

*Note: Hours of nominal leachate production (<0.1 L/h) was not considered for average rate calculations.

For RCL-1, leachate production occurred after a breakthrough time of 74 minutes and continued for 92.6 hours. Leachate was produced at a nominal flow rate of 0.1 litres/hour after 37.5 hours. Figure 4.9 shows that the peak leachate discharge rate was 18.10 litres/hour, much higher than those observed during the four rainfall simulations.

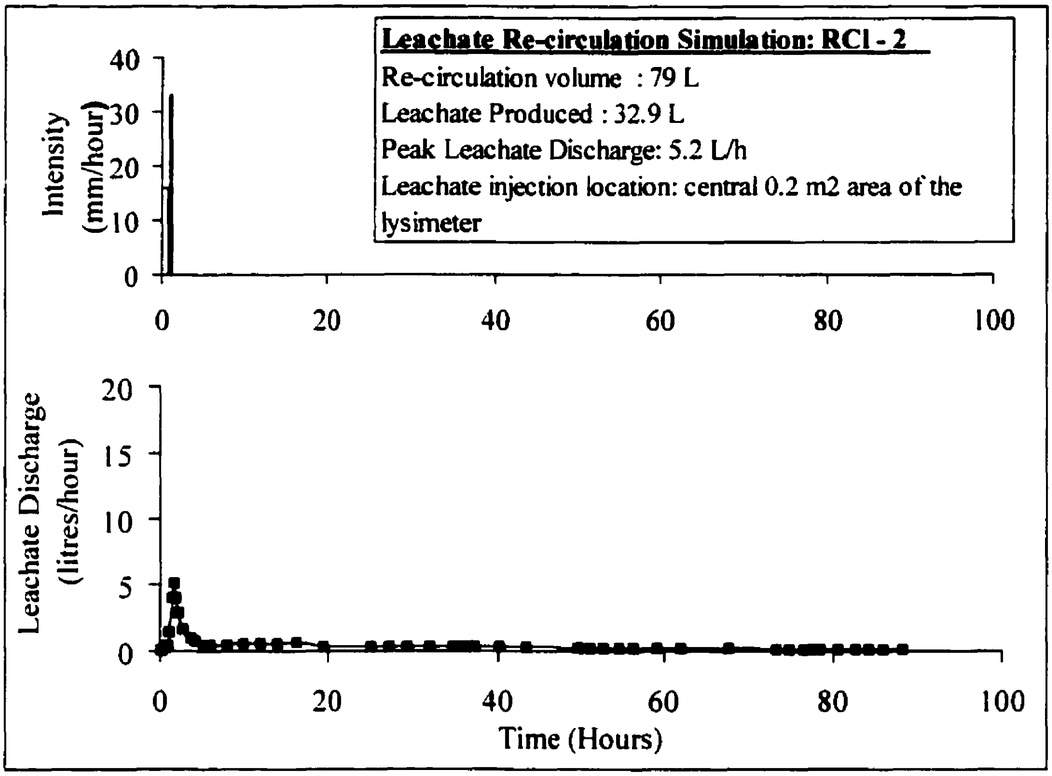
Since an equal volume of moisture was re-circulated at a same intensity as RF-4, comparisons can be made between RCL-1 and RF-4. RCL-1 produced leachate at a higher peak leachate discharge rate than RF-4. The peak/average discharge ratio of RCL-1was much higher than RF-4. The volume of leachate produced was also higher than RF-4 and leachate was produced over a longer duration of time. The MC/FC ratio at the end of this simulation was 0.84. Since MC/FC ratio also influences leachate production, these observations can be somewhat explained by the increase in this parameter. Still, the effect of point injection of moisture (on leachate production) is quite evident.

Figure 4.9: RCL-1 - Re-circulation Intensity and Leachate Discharge Rate vs. Time



The simulation RCL-2 was similar to RCL-1 except that the moisture was re-circulated on a 0.2 m^2 area on the periphery of the lysimeter. About 79 L of moisture was re-circulated (Table 3.5), and about 32.9 L of leachate was produced at an average leachate discharge rate of 0.34 litres/hour. About 42% of the re-circulated moisture resulted in leachate. The peak/average leachate discharge rate ratio was 15.29 and was lower than that of RCL-1. Leachate production occurred after a delay, or a breakthrough time of 53 minutes and continued for 160 hours. The leachate was produced at a nominal rate of 0.1 litres/hour after 88 hours. Peak leachate discharge rate was 5.2 litres/hour (Figure 4.10) and was less than that of RCL-1. Although in RCL-2 equal volume of moisture was re-circulated at almost the same intensity as RCL-1, this simulation produced leachate at a comparatively less peak leachate discharge rate.

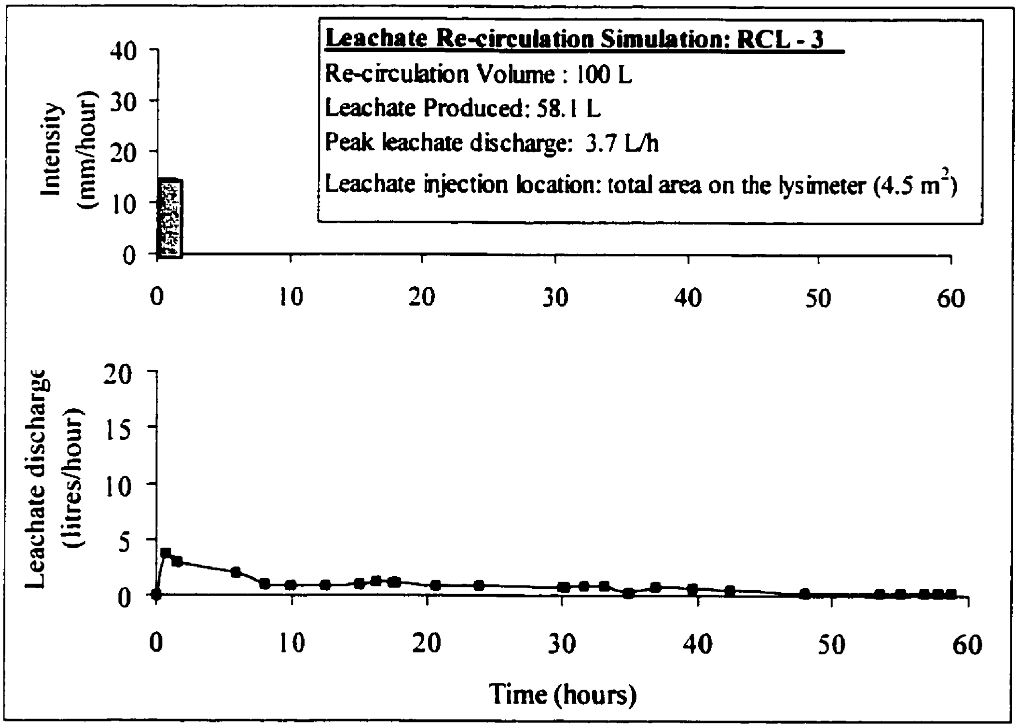
Figure 4.10: RCL -2 - Re-circulation Intensity and Leachate Discharge Rate vs. Time



Although both RCL-1 and RCL-2 simulated "point injection", the point of injection in RCL-2 was closer to the edge of the lysimeter, where the MC is potentially less than that in the middle of the lysimeter. The overall volume of leachate produced was higher than RCL-1 and leachate was produced over a longer duration of time. The MC/FC ratio at the end of simulation was 0.86.

In simulation RCL-3, moisture was re-circulated over the entire 4.5 m^2 plan area of the lysimeter representing "area injection". A total of 100 L was re-circulated. About 58.1 L of leachate (i.e. 58% of the re-circulated moisture) was produced at an average leachate discharge rate of 0.38 litres/hour. The peak/average leachate discharge rate ratio was 9.74. Leachate production occurred after a delay, or a breakthrough time of 45 minutes from the start of the infiltration event and continued for 260.6 hours. However, majority of the leachate was produced over the first 110 hours. Thereafter, leachate continued to be produced at a nominal rate of 0.1 litres/hour. Figure 4.11 shows that the peak leachate discharge rate was 3.70, less than RCL-2. This is due to moisture being infiltrated on the entire surface area instead of at a "point". Since moisture was re-circulated over the entire surface area of the lysimeter, RCL-3 was similar to the simulations RF-1 to RF-4.

Figure 4. 11 : RCL - 3 - Re-circulation Intensity and Leachate Discharge Rate vs. Time



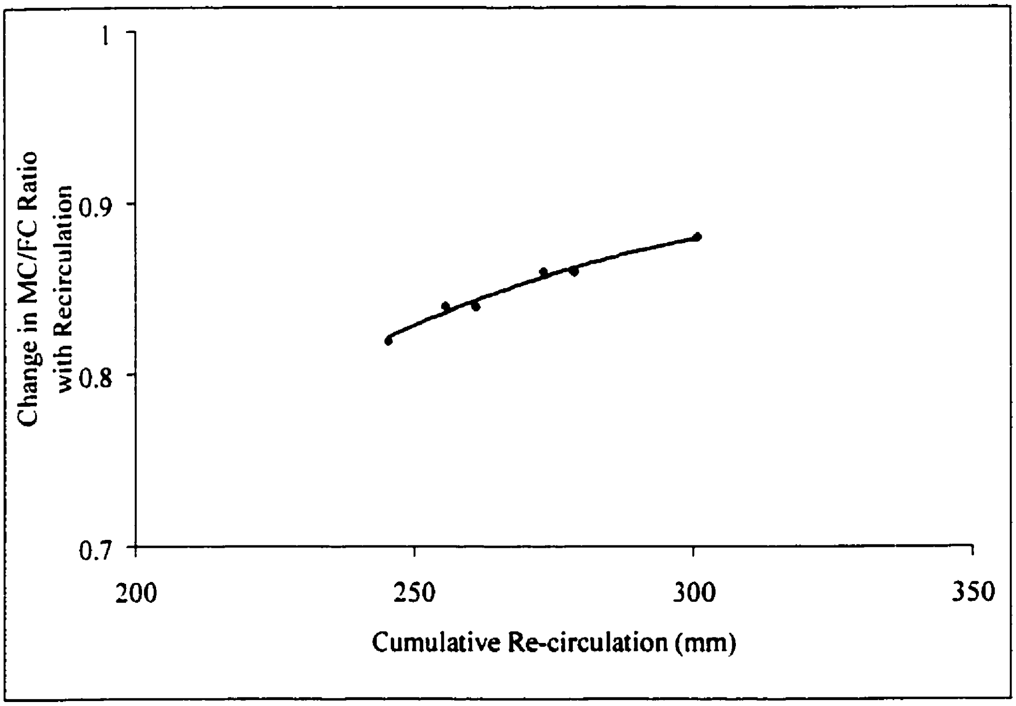
The peak/average ratio for "point injection" of leachate re-circulation was much higher than "area injection" of re-circulated leachate. However, the volume of leachate produced in RCL-3 simulation was higher than RCL-1 or RCL-2, and leachate was produced over a longer duration of time. In this simulation, 58% of the infiltrated moisture was produced as leachate. The results also indicated that "almost" continuous flow was established, and the waste may have attained the "Practical Field Capacity", or PFC. As the waste reaches a

MC/FC value of 1, leachate production will achieve continuity. MC/FC is a parameter that provides valuable information on leachate production behavior of a landfill.

4.2.3.1 Leachate Re-circulation Simulations: Overall Evaluation

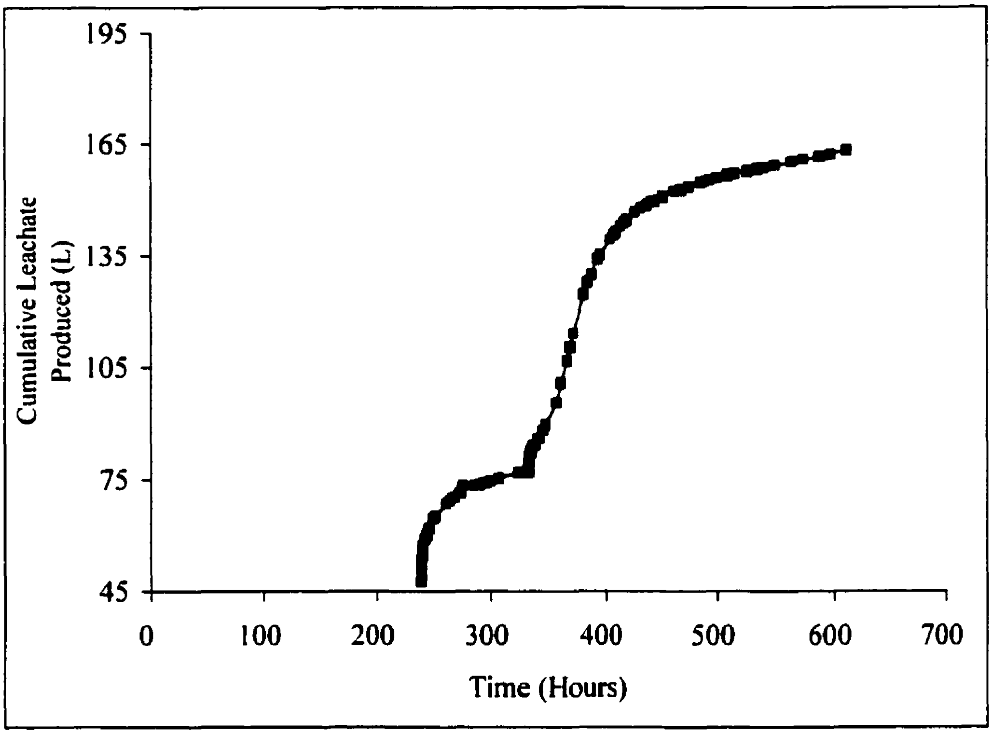
Figure 4.12 shows the change in MC/FC with cumulative re-circulation. The initial MC/FC ratio at the beginning of RCL-1 was 0.82. The MC/FC increased to 0.88 at the end of the re-circulation simulations, after the addition of 56 mm (252 L) of moisture.

Figure 4.12: Change in MC/FC Ratio vs. Cumulative Re-circulation for RCL-1 to RCL-3



A total of 26mm (116.7 L) of leachate was generated at the end of re-circulation simulations (refer Figure 4.13). This was 45% of the total re-circulated volume of moisture. The percentage of leachate produced, increased from 0.4% in RF-1 to 58% in RCL-3 and the peak/average leachate discharge ratio increased from 3.25 to 9.74 (not considering the "point injection" simulations). A continuous flow of leachate was almost established at the end of this simulation after the infiltration of a total of 301 mm of moisture into the lysimeter (245 mm of simulated rainfall and 56 mm of leachate re-circulation). A total of 12% (36.6mm/301mm) of infiltrated/re-circulated moisture was discharged as leachate.

Figure 4.13 : Leachate Re-circulation Simulations RCL-1 to RCL-3 - Cumulative Leachate Produced vs. Time



These results indicate that a LCRS for a leachate re-circulation landfill should be designed using different parameter values than a landfill without re-circulation. For example, peak/average leachate ratio should be as high as 20 for leachate re-circulation "point injection" landfills as compared to a value of upto 7.5 for standard landfills. In a typical design, HELP model can be used to calculate the average leachate flow rate into the LCRS system. However, a landfill designer should use his judgement, based on the peak/average ratio, to design the LCRS.

Based on the rainfall and leachate re-circulation simulation results, the following inferences can be made. If a Calgary landfill is capped immediately and if 5% of the total precipitation is assumed to percolate into the waste through the final cover, (at an annual average precipitation of 450 mm in Calgary), it may take approximately 14 years for continuous flow of leachate to be established and attain field capacity. The moisture content at this continuous flow condition will be 0.175 vol./vol. when the waste has reached moisture content of 88% of the field capacity of the waste. At this moisture content the waste had absorbed 0.3L of moisture per kg of the placed MSW.

4.2.4. Phase-4 Leachate Production: Rainfall Simulations (RFR-1 and RFR-2)

Prior to the simulations RFR-1 and RFR-2, new waste lift was placed in the lysimeter (see Chapter 3 for details of this new waste layer). The purpose was to simulate leachate production after the placement of a new lift of dryer waste on existing wet waste in a landfill cell.

Table 4.7 presents the results, in terms of change in the moisture content (MC), and the change in MC/FC ratio of the waste, before and after infiltration of moisture. Results on leachate discharge volume, average rate of leachate discharge, peak leachate discharge rate, and breakthrough time for the two rainfall simulations on the reconstituted landfill lysimeter are presented in Table 4.8.

A total of 224 L of moisture was infiltrated during the rainfall simulation RFR-1 (refer Table 3.6). About 2.2 L of leachate was produced at an average leachate discharge rate of 0.02 litres/hour. The peak/average leachate discharge rate ratio was 1.5. Figure 4.14 shows the rate of leachate production during this simulation event. Since the new waste was dry at placement, this simulation produced results similar to RF-1.

Table 4.7: Phase-4 Field Lysimeter Studies - Changes in MC and MC/FC Ratio During Rainfall Simulations

Parameters	Rainfall Simulations	
	RFR - 1	RFR - 2
Infiltration Volume (L)	224	884
MC before infiltration (vol./vol.)	0.162	0.169
MC after infiltration (vol./vol.)	0.169	0.21
MC*/FC** ratio before infiltration	0.81	0.845
MC*/FC** ratio after infiltration	0.85	1.05

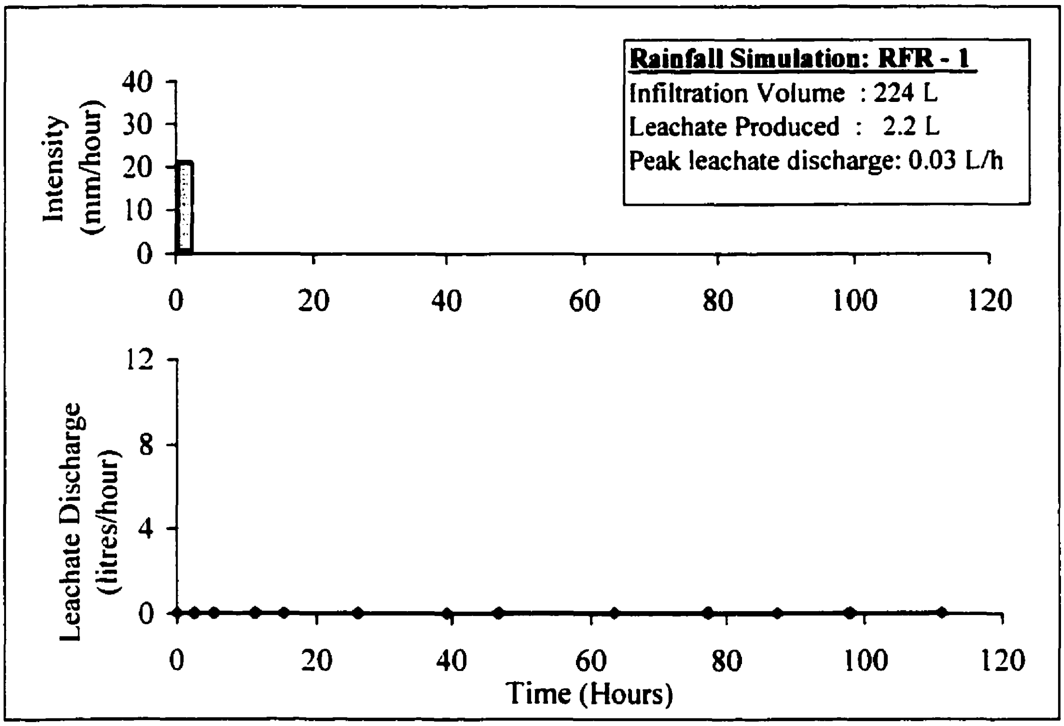
* MC = Moisture Content
** FC = Field Capacity (FC is 0.20 vol./vol. from laboratory experiments)

Table 4.8: Phase 4-Field Lysimeter Studies: Leachate Production

Parameters	Rainfall Simulations	
	RFR-1	RFR-2
Infiltration Volume (L)	224	884
Infiltration Duration (minutes)	140	340
Leachate Discharged (L)	2.20	275
Duration of Leachate Discharge (hours)	111	3620
Breakthrough time (minutes)	-	321
Average Leachate Discharge Rate (L/h)*	0.02	1.44
Peak Leachate Discharge Rate (L/h)	0.03	12
Peak/Average Leachate Discharge Ratio	1.5	8.3

*Note: Hours of nominal leachate production (< 0.1 L/h) was not considered for average rate calculations.

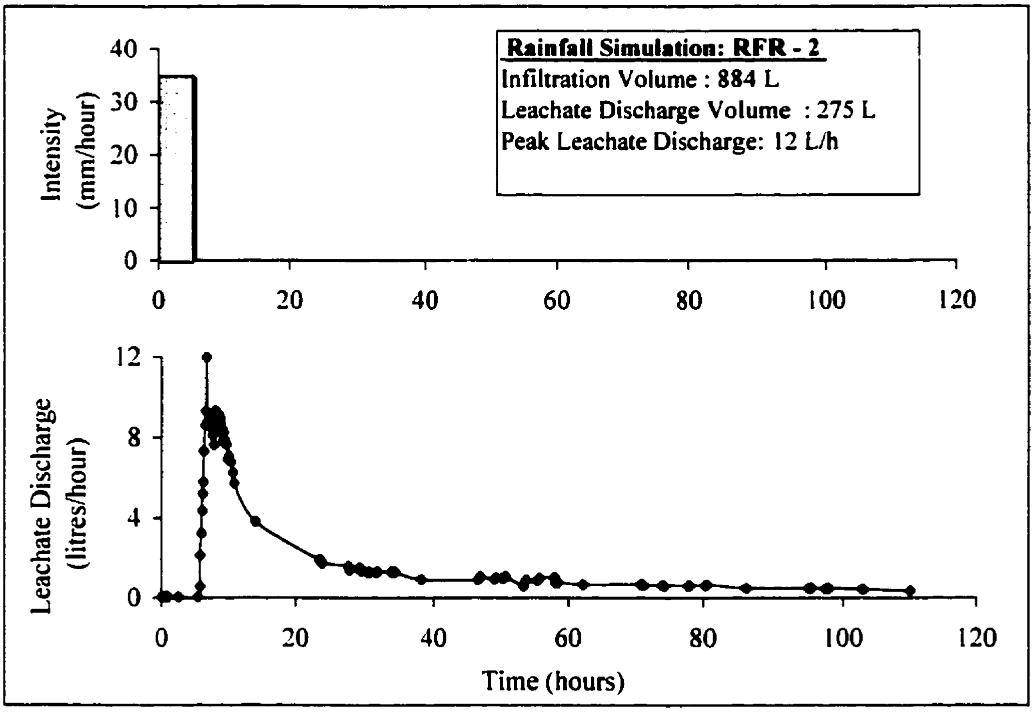
Figure 4.14 : RFR -1 - Infiltration Intensity and Leachate Discharge Rate vs. Time



A total of 884 L of moisture was infiltrated during RFR-2 (refer Table 3.5) and 275 L of leachate was produced at an average leachate discharge rate of 1.44 litres/hour. The peak/average leachate discharge rate ratio was 8.3. Figure 4.15 shows that leachate production occurred after a delay, or a breakthrough time, of 321 minutes.Leachate production continued for a period of 3620 hours. However, the majority of the leachate was produced during the first 110 hours. The leachate production continued at an average nominal rate after 110 hours. Moisture was added for a longer duration of time and at a higher intensity as compared to RFR-1. The newly added waste lift absorbed moisture and released it over a long duration of time.

As the waste reached MC/FC ratio of 1, quantity of leachate discharged increased and leachate was produced over longer duration of time. The peak/average leachate discharge ratio in RFR-2 was comparable to RF-3 and RCL-3. Thus, the average peak/average leachate discharge ratio for standard landfills is approximately upto 7.5.

Figure 4.15 : RFR -2 - Infiltration Intensity and Leachate Discharge Rate vs. Time



4.2.4.1 *Rainfall Simulations RFR-1 to RFR-2: Overall Evaluation*

Figure 4.16 shows the changes in MC/FC ratio with cumulative infiltration. The waste had reached the field capacity (i.e. MC/FC = 1) at the end of RFR-2. Continuous flow was almost established. A total of 60.8 mm (277.2 L) of leachate was discharged (refer Figure 4.17) over a long period of time. This was 25% of the infiltrated moisture.

Figure 4.16: Change in MC/FC Ratio vs. Cumulative Infiltration for RFR-1 to RFR-2

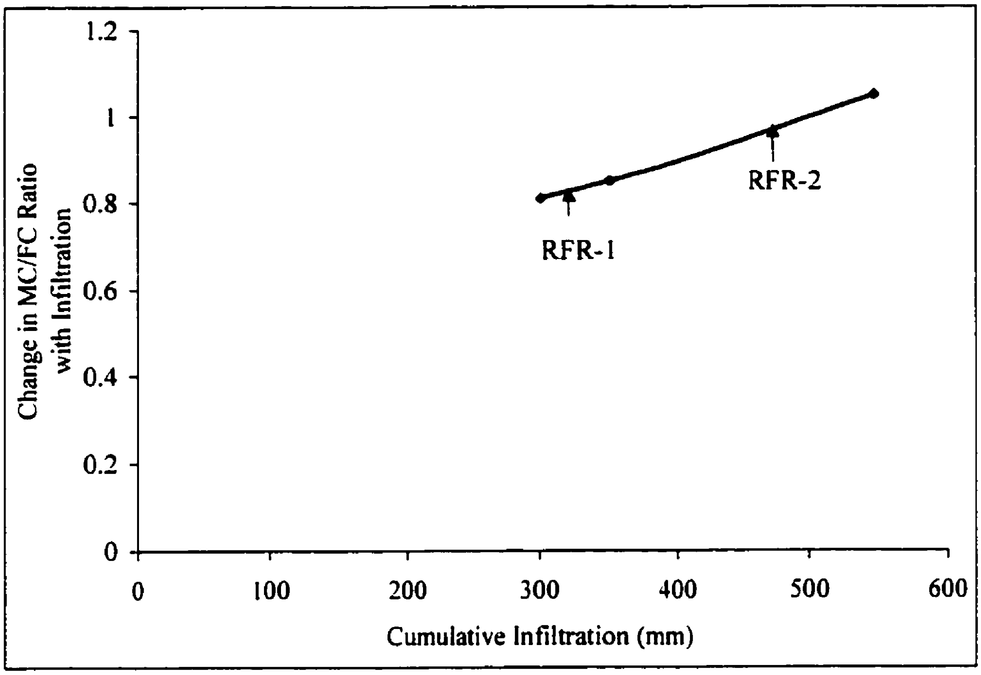
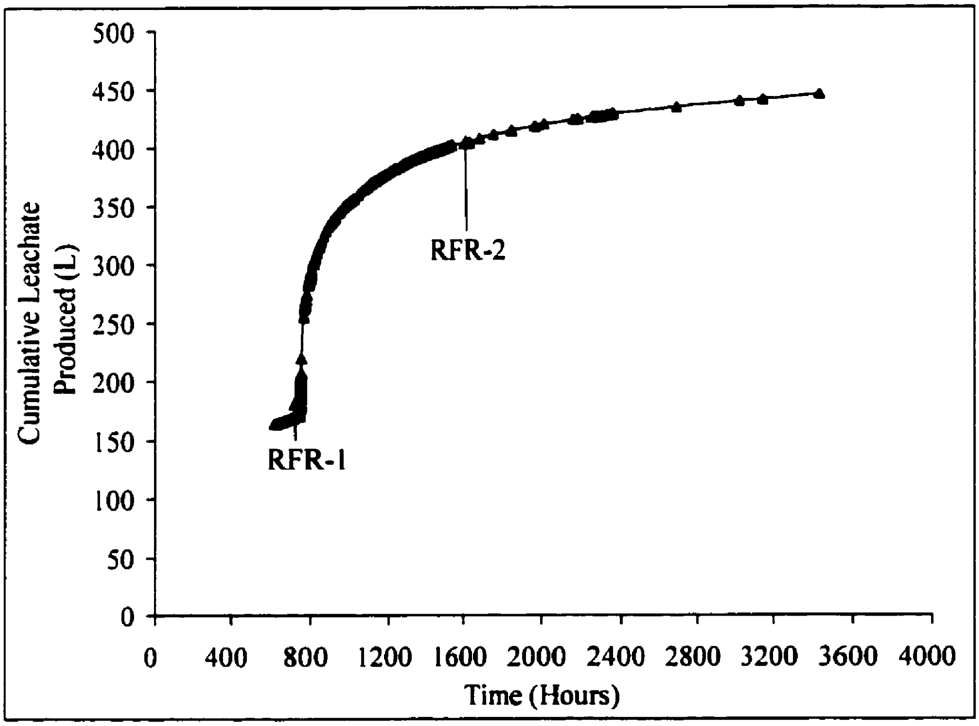


Figure 4.17 : Rainfall Simulation RFR-1 and RFR-2 - Cumulative Leachate Produced vs. Time



4.2.5 Phase 5: Leachate Production: Rainfall Simulations on a Closed Landfill Lysimeter

This experimental simulation was performed on the final cover. The lysimeter was producing leachate at a nominal rate from the previous experimental simulations, when this simulation was performed. A total of 330 L of moisture was infiltrated in this simulation. There was no increase in leachate flow rate observed during this experimental simulation. The lysimeter cover was unsaturated and the added moisture was absorbed by the cover to reach its field capacity.

4.2.6 Rainfall/Leachate Re-circulation Simulations: Overall Evaluation

The waste almost reached the practical field capacity (i.e. MC/FC = 1) after absorbing 0.33 L of moisture/kg of MSW on an average. Figure 4.18 shows that the waste reached a MC/FC ratio of 1.05 at the end of RFR-2 simulation. A total of 546 mm (2469 L) was infiltrated/re-circulated during the Phase-2 to Phase-4 experimental simulations. Figure 4.19 shows that a total of 97.4 mm (442 L) of leachate was produced. This accounted for 18% of the total infiltrated/re-circulated moisture. The leachate production increased from 48.08 L (10.6 mm) in Phase-2 to 277.2 L (60.8 mm) in Phase-4.

Figure 4.20 shows variations in the rate of leachate discharge throughout infiltration/re-circulation simulations. The highest peak leachate discharge rate was observed during the re-circulation simulation RCL-1, in which point injection was simulated. The peak/average leachate discharge rate was approximately upto 7.5 for area injection of moisture, as compared to approximately 20 for point injection of moisture. Since a high peak/average leachate discharge ratio is detrimental if the landfill is used as a treatment medium for leachate, area injection is preferred over point injection.

Figure 4.18 : Change in MC/FC Ratio vs. Cumulative Infiltration/Re-circulation for RF-1 to RF-4, RCL-1 to RCL-3, RFR-1, and RFR-2

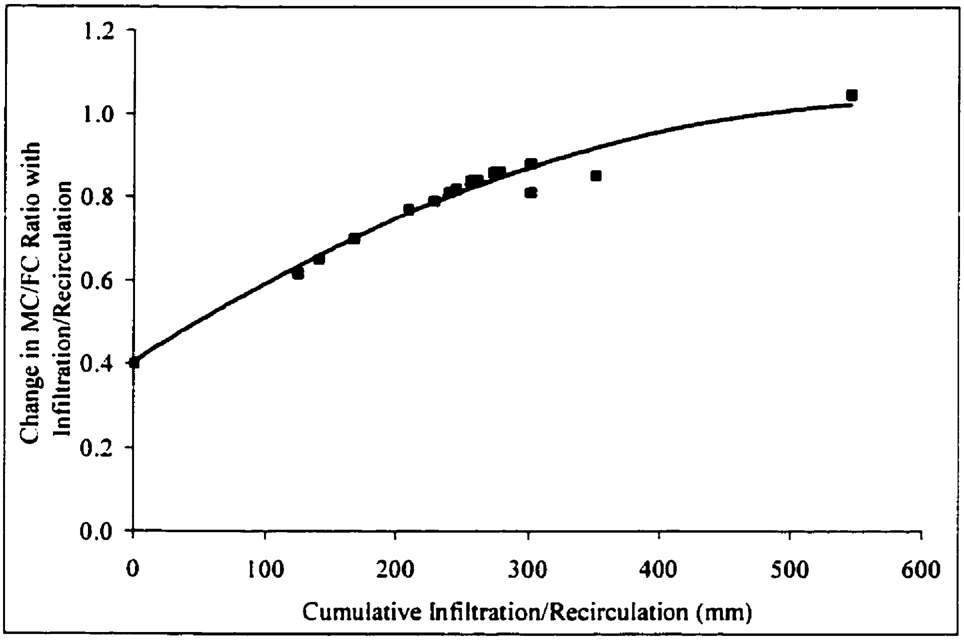


Figure 4.19: Cumulative Leachate Produced During the Rainfall/Leachate Re-circulation Simulations vs. Time

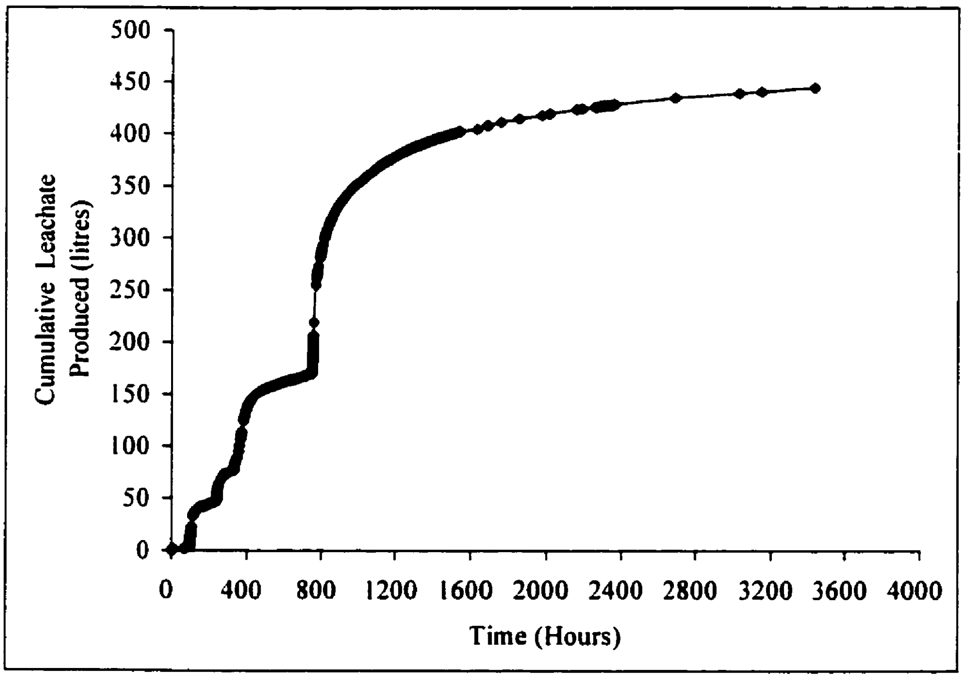
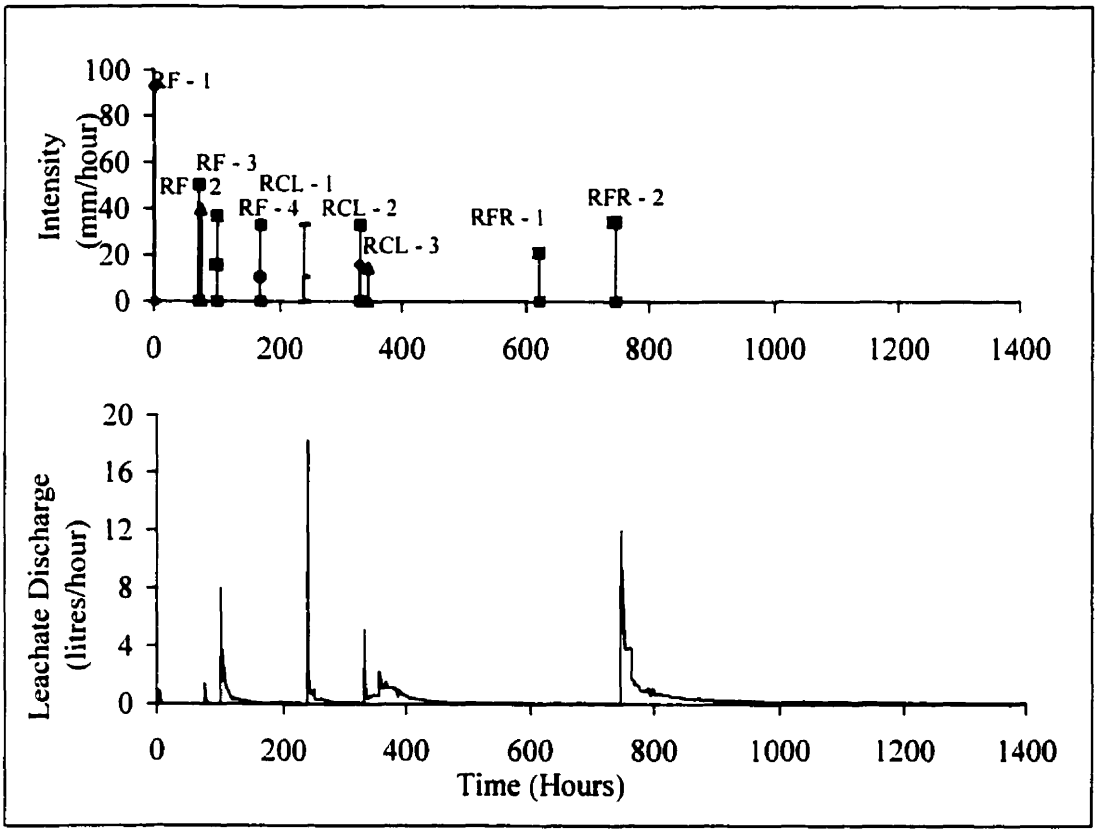


Figure 4.20: Infiltration Intensity and Leachate Production Rate for Infiltration/Re-circulation Simulations vs. Time



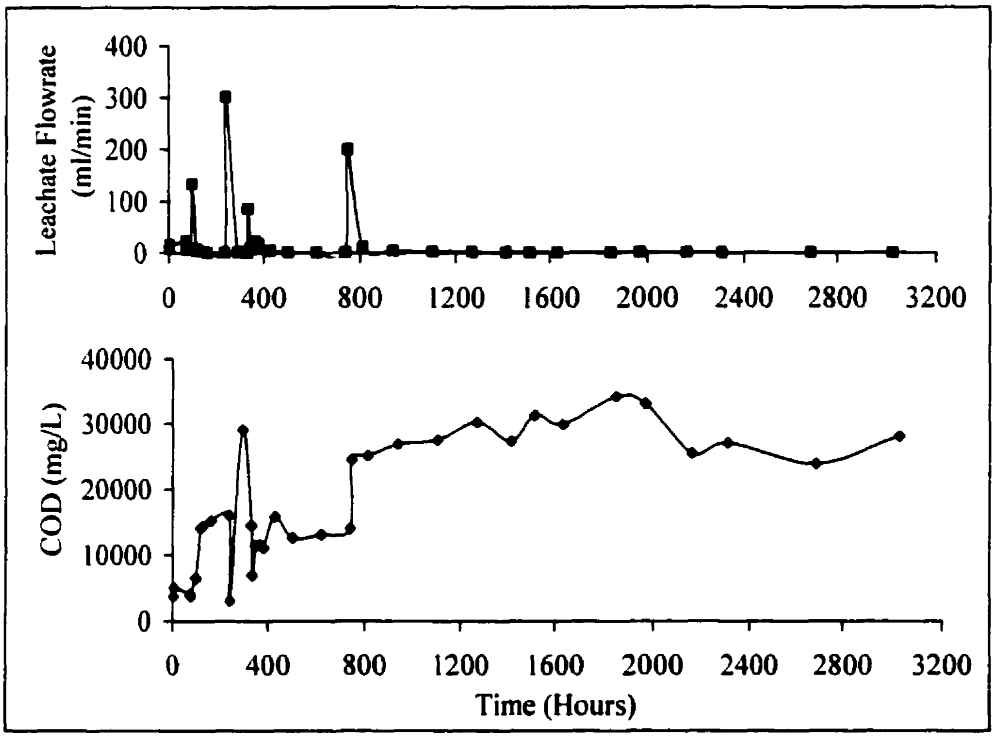
The waste absorbs moisture even after attaining PFC to reach the TFC. At TFC, the percentage of leachate produced may reach 100% of infiltration. TFC is an important design parameter for leachate re-circulation systems. In leachate re-circulation systems, moisture will be constantly re-circulated at low infiltration rates into the waste. The moisture is absorbed by the waste to reach TFC, after which leachate production will be equal to infiltration. Hence, the ratio of moisture content to TFC may govern the design of leachate re-circulation systems.

4.3 LEACHATE CHARACTERISTICS

Results from chemical characterization of leachate produced during rainfall and re-circulation simulations are presented in Figures 4.21 to 4.25 presents.

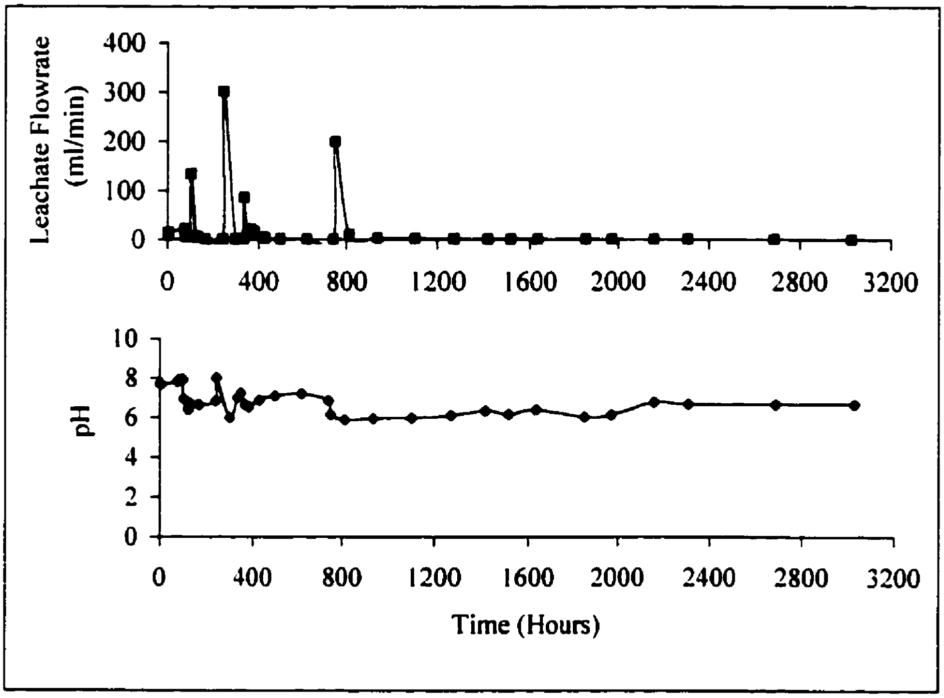
COD indicates the quantity of chemically degradable organics present in the leachate (Gau and Chow, 1998; Demetracopoulos et al., 1986). COD of leachate samples ranged from 3075 mg/L to 34225 mg/L (Figure 4.21).

Figure 4.21: Field Landfill Lysimeter : Leachate COD vs. Time



Initially, when the lysimeter was under aerobic conditions, due to low moisture content of the waste, the landfill lysimeter leachate had a low COD. As the moisture infiltrated into the waste, aerobic microrganisms initiated the decomposition process and produced leachable products. These products of decomposition were held in the waste and were leached by the migrating moisture front. Once oxygen was exhausted, facultative anaerobic microorganisms decomposed organic matter to gaseous and other products of decomposition, including organic acids (Ham and Bookter, 1982). This resulted in an increase in COD of the leachate and a decrease in pH, due to the presence of partially degraded organic matter. Figure 4.22 shows the decrease in pH corresponding to an increase in COD of the waste. The decrease in pH results in dissolution of inorganic metals and an increase in electrical conductivity (Figure 4.23).

Figure 4.22: Field Landfill Lysimeter : Leachate pH vs. Time



Biochemical Oxygen Demand (BOD) is an indicator of the presence of easily biodegradable organics in leachate. Figure 4.24 shows an increase in BOD with time. The BOD/COD ratio represents the proportion of easily biodegradable organics present in the waste sample and varies between 0.6 to 0.8 for young landfills (Chen, 1996). Figure 4.25 shows that the BOD/COD ratio stabilized between 0.7 to 0.8 indicating the presence of highly biodegradable organic matter. As the landfill ages, the increase in refractory long-chain carbohydrates, and/or humic substances, result in a decrease in BOD/COD ratio to

Figure 4.23: Field Landfill Lysimeter : Leachate Electrical Conductivity vs. Time

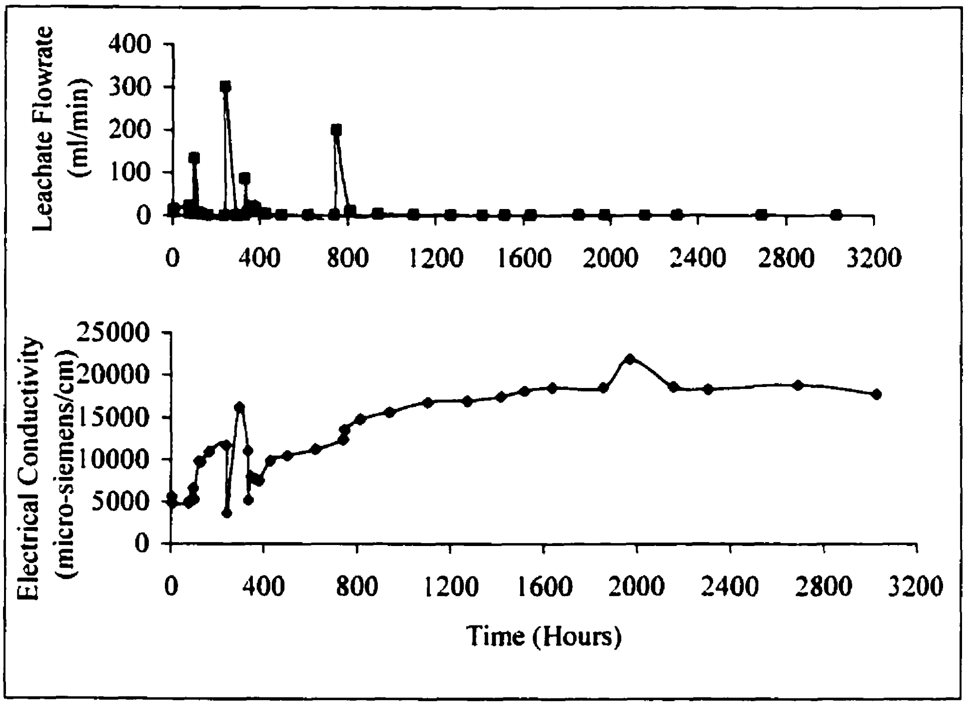


Figure 4.24: Field Landfill Lysimeter : Leachate BOD vs. Time

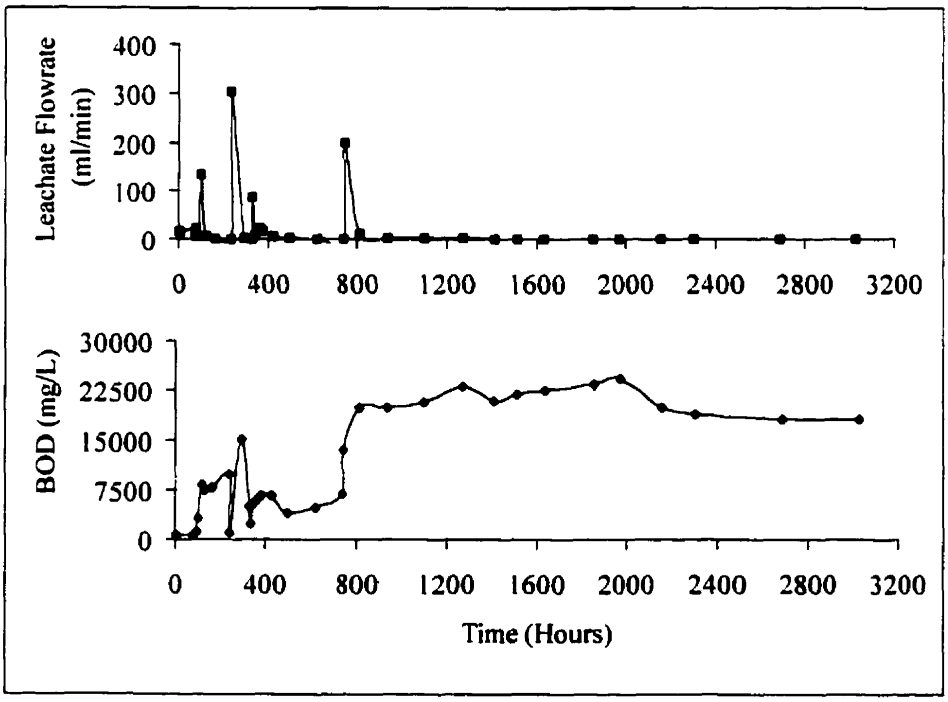
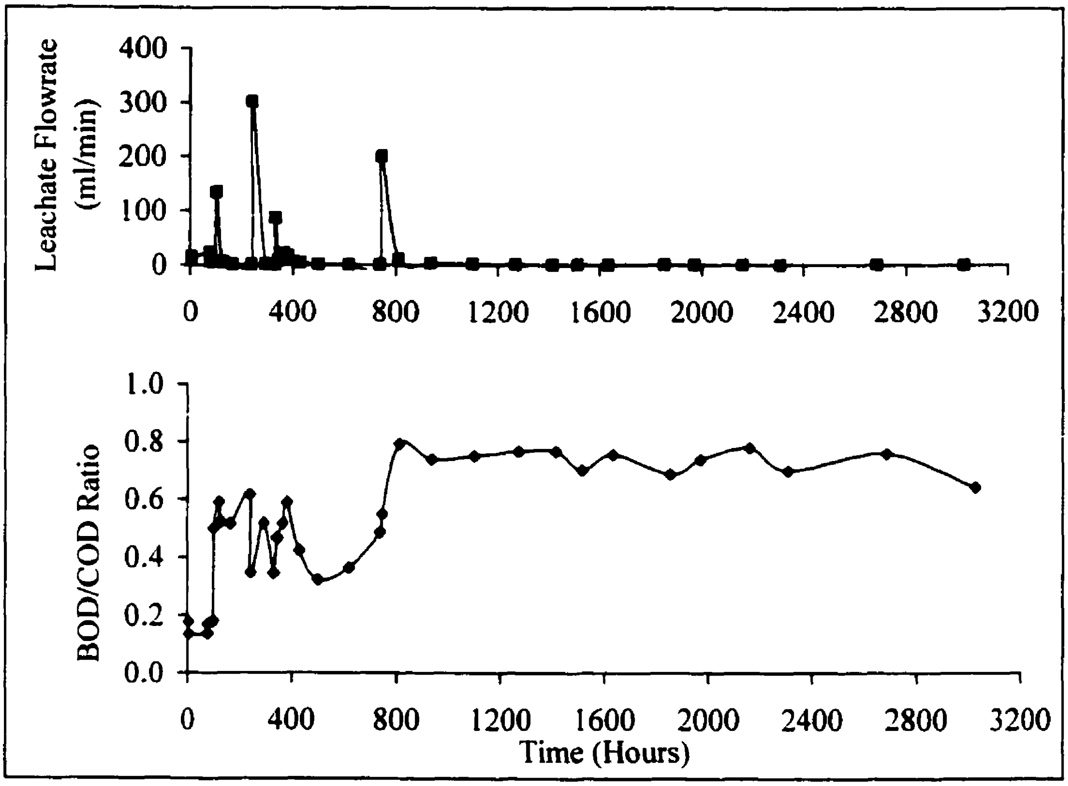


Figure 4.25: Field Landfill Lysimeter : Leachate BOD/COD Ratio vs. Time



0.2 to 0.4 (Chen, 1996). Further monitoring of leachate from the landfill lysimeter is required to verify this fact.

As evident from the graphs, the pH decreased over time and stabilized at around neutral conditions. COD, BOD, and the electrical conductivity increased over time. The BOD/COD ratio increased from a very low value of about 0.1 and stabilized between 0.6 to 0.8 indicating that the waste still had more of undecomposed organic matter.

At peak leachate flow rates, BOD, COD, and electrical conductivity decreased, and then again increased with the passage of time. This was due to the dilution effect of the infiltrated moisture.The chemical analysis of the leachate samples indicate that the artificial infiltration of moisture has increased the biological activity of the landfill lysimeter.

CHAPTER FIVE

HELP MODEL SIMULATIONS

The laboratory determined waste parameter values were used to perform the HELP model simulations and compare it with the field lysimeter leachate production data.

HELP model simulations were performed on:

- the closed landfill lysimeter – natural precipitation simulation
- the open landfill lysimeter rainfall/leachate re-circulation simulations.

5.1 HELP MODEL SIMULATIONS: CLOSED LYSIMETER

HELP model simulations were performed for the Phase-1 closed lysimeter conditions, using three sets of parameter values:

(1) HELP model default values

(2) HELP model default values modified for channeling

(3) Parameter values determined by laboratory experiments.

Table 5.1 presents the different MSW parameter values used for HELP model simulations. Table 5.2 presents the soil cover parameter values used for the HELP model simulations. The values were determined on the basis of the soil layer density and grain size distribution.

Table 5.1: MSW Parameter Values for the HELP Model Simulations: Closed Lysimeter

MSW Parameters	Total Porosity vol./vol.	Field Capacity vol./vol.	Wilting Point vol./vol.	Saturated Hydraulic Conductivity cm/sec.
HELP Model Default Values (600 kg/m^3)	0.671	0.292	0.077	1×10^{-3}
HELP Model Default Values Modified for Channeling	0.168	0.073	0.019	1×10^{-3}
Laboratory Determined Values (at density of 375 kg/m^3)	0.55	0.20	0.016	1.17×10^{-3}

Table 5.2: Soil Cover Parameter Values Used for HELP Model Simulations: Closed Lysimeter

Layer Type	Soil Parameter Values in HELP Model Simulations		
	Total Porosity vol./vol.	Field Capacity vol./vol.	Saturated Hydraulic Conductivity, cm/sec
Vegetative Layer	0.48	0.16	0.012
Drainage Layer	0.48	0.16	0.012
Barrier Layer	0.45	0.25	0.00005
Foundation Layer	0.48	0.16	0.012

5.1.1 HELP Model Simulations Using Default Parameter Values for MSW

The closed landfill lysimeter did not produce leachate during the 10-month monitoring period. A HELP model simulation was performed on the closed lysimeter, using the default parameter values for MSW (density = 600 kg/m^3) presented in Table 5.1 and final cover parameter values presented in Table 5.2. The HELP model predicted no leachate discharge for the 10-month period. The total precipitation during this period was 371.5 mm (1675 L) and the HELP model-predicted seepage through the barrier layer was 167.2 mm. The HELP model predicted a waste moisture content of 0.139 vol./vol. at the end of the simulation period. The moisture infiltration through the barrier layer into the waste predicted by the HELP model, was absorbed by the waste which reached a moisture content of 0.139 vol./vol. (which was less than the field capacity) from an initial moisture content of 0.08 vol./vol. Hence, no leachate was predicted, which is consistent with actual field results.

5.1.2 HELP Model Simulations Using Default Parameter Values Modified for Channeling Effects

A HELP model simulation was performed on the closed lysimeter using the default parameter values for MSW modified for channeling presented in Table 5.1 and the final cover parameter values presented in Table 5.2. The simulation predicted 835.8 L of leachate for the 10-month period (Figure 5.1). However, no leachate was produced from the lysimeter during this period.

The waste was placed at an initial moisture content of 0.08 vol./vol. Since this value was higher than the default field capacity for channeled flow (0.073 vol./vol), the HELP model estimated saturated flow through the waste resulting in desorption of moisture from the waste. According to the simulation, a total of 167.2 mm (756.4 L) of moisture infiltrated through the barrier layer. As the waste was already beyond field capacity on placement, the model predicted leachate production equal to the amount percolated across barrier layer and the amount desorped from the waste. The peak leachate discharge predicted by the HELP model was 58.9 L/day (Figure 5.2).

Figure 5.1: Phase-1 - Closed Lysimeter Cumulative Infiltration and HELP Model Prediction for Channeling Effects vs. Time

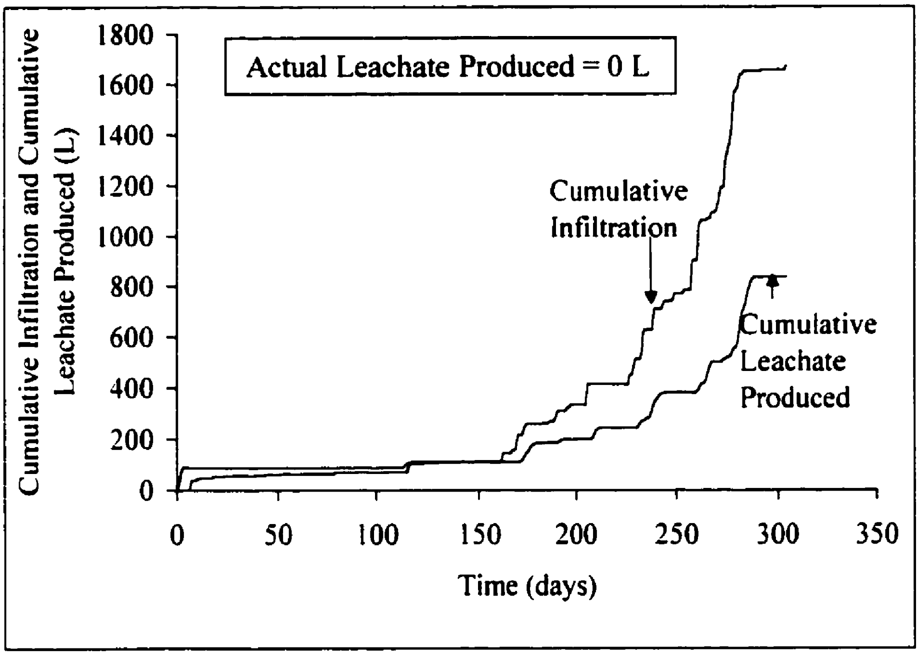
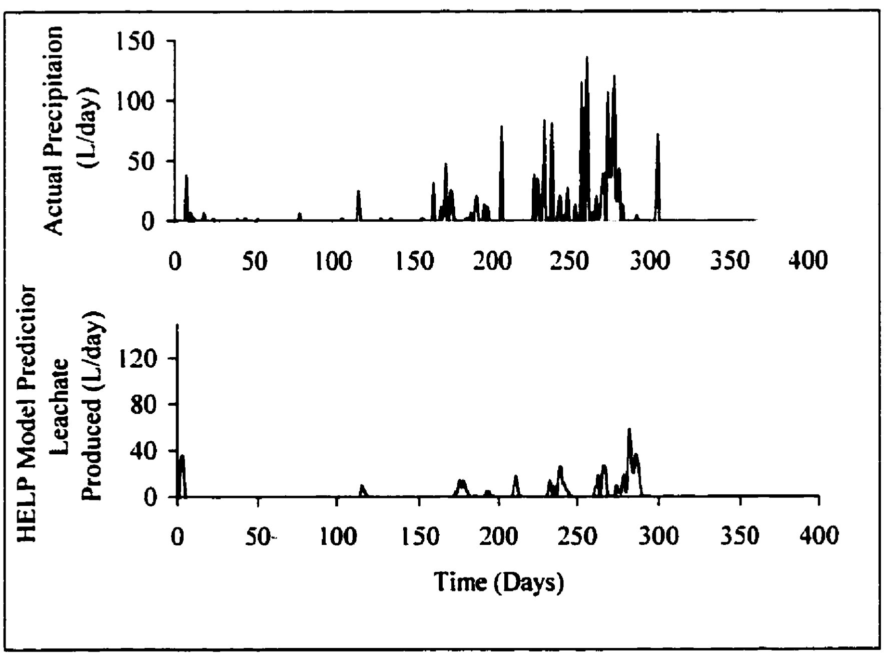


Figure 5.2: Phase-1 HELP Model Predicted Leachate Production Rate for Default Values for Channeled Flow



5.1.3 HELP Model Simulations Using Laboratory Determined Parameter Values for MSW

A HELP model simulation was undertaken using laboratory determined parameter values (refer Table 4.1 and Table 5.1). The simulation predicted no leachate discharge during this period. The HELP model simulation results, using the modified waste parameter values and cover parameter values, are presented in Table 5.3.

Table 5.3: HELP Model Simulation Results Using Laboratory Determined Waste Parameter Values: Closed Lysimeter

Model Input/Output	Values	
	mm	%
Precipitation	371.5	100
Runoff	31.5	8.5
Evapotranspiration	155.6	42.0
Sub-surface Runoff	22.24	6.0
Seepage into the Waste Layer	167.2	45.2
Leachate Produced	0	0

The model predicted 167.2 mm of seepage through the barrier layer and a waste moisture content at the end of the simulation of 0.139 vol.vol. The moisture was conducted from one layer to another as unsaturated flow and was stored by various layers including the waste. The HELP model predicted that 51.2% of the total precipitation, infiltrated into the drainage layer. Of the total infiltrated moisture, 12% (22.24/189.44) was predicted as sub-surface runoff and 88% was predicted as seepage through the barrier layer. These values are not consistent with laboratory determined values (15% seepage and 85% subsurface runoff), indicating problems with HELP model simulations. As the HELP model assumes the barrier layer to be saturated, it over-predicts the seepage from the barrier layer into the waste layer. The infiltrated moisture was absorbed by the waste and hence, no leachate was discharged.

5.1.4 Phase-1 HELP Model Simulations – Summary

The HELP model predicted no leachate generation when either the HELP model default parameter values were used (without channeling) or the laboratory determined parameter values were used. However, the HELP model predicted 835.8 L of leachate discharge with HELP model default values for channeled flow. Since the lysimeter did not generate any leachate in this case, the HELP model default values without channeling and the laboratory determined parameter values represented the field landfill lysimeter more accurately.

5.2 HELP MODEL SIMULATIONS: RAINFALL AND LEACHATE RE-CIRCULATION (PHASE-2 TO PHASE-4)

HELP model simulations were performed for the Phase-2, Phase-3, and Phase-4 open lysimeter conditions, using three different sets of parameter values:

(1) HELP model default values

(2) HELP model default values modified for channeling

(3) Laboratory determined values for MSW

The quantity of cumulative leachate predicted by the HELP model simulations on rainfall/ re-circulation field simulations, for three sets of parameter values are presented in Table 5.4. Details of HELP simulation results, including storage, evapotranspiration, are presented in Table 5.5.

Table 5.4: Phase-2 to Phase-4 Leachate Production: Results from HELP Simulations Using Different MSW Parameter Values

Source of MSW Parameter Values	Cumulative Leachate Volumes Predicted by the HELP Model (L)		
	Phase-2	Phase-2 & 3	Phase-2, 3, & 4
HELP Model Default Values	0	0	0
HELP Model Default Values with Channeling	1190	1437	2497
Laboratory Determined Parameter Values	0.93	173.2	1103.7

Table 5.5: Output from HELP Model Simulations: Phase-2 to Phase-4

Component	Phase-2		Phase-2 & 3		Phase-2,3, & 4	
	mm	%	mm	%	mm	%
Precipitation	245	100	301	100	546	100
Runoff	0	0	0	0	0	0
Evapotranspiration	2.23	0.91	3.57	1.19	3.57	0.65
Leachate	0.2	0.08	38.3	12.7	243.9	44.7
Storage	242.57	99.01	259.13	86.11	298.53	54.65

During the rainfall/re-circulation field simulations, water was added directly to the waste and the entire amount of infiltrated water was contained within the lysimeter. There was no runoff. Hence, during HELP simulations the parameter value for percentage of area contributing to runoff was specified as zero.

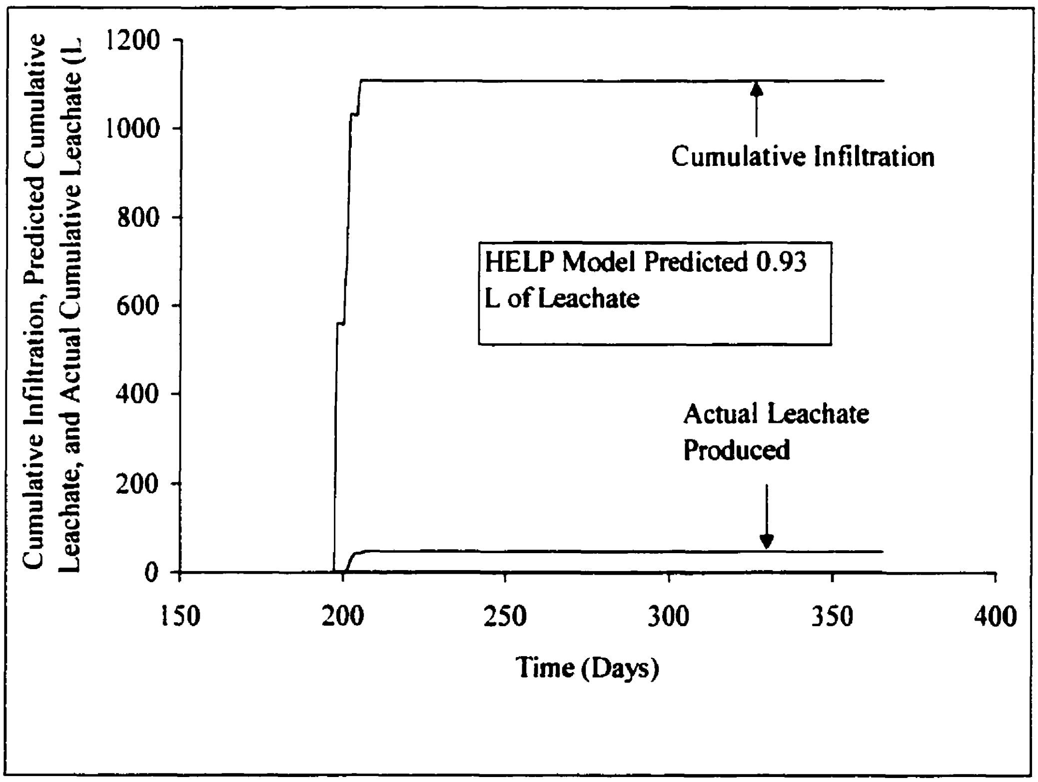
De Bruin (1985) identified evapotranspiration as the highest component of water loss from a landfill. A small change in the evapotranspiration value can have a significant impact on the final estimate of leachate generated. The daily potential evapotranspiration demand consists of radiative and aerodynamic component (Equation 14, Chapter 2) and is applied to any free water present on the surface. The radiative component is a function of solar radiations. The aerodynamic component is a function of wind speed and relative humidity at the landfill location. HELP model calculates the radiative component of evapotranspiration on the basis of available energy. However, under semi-arid climatic conditions, evapotranspiration is controlled by the availability of water and not the availability of energy (De Bruin, 1987). The HELP model may over-predict evapotranspiration in semi-arid climates (Khire et al., 1997).

The lysimeter was kept covered with the polyethylene sheets throughout the rainfall/re-circulation field simulations, to prevent the evaporation losses. Therefore, solar radiation was specified as zero during the HELP model simulations. The evapotranspirative demand due to the aerodynamic component was calculated by the HELP model. This demand was met by the available moisture in the waste layer. The model presumes that there is no available energy to meet the evapotranspirative demand, beyond the wilting point of the waste layer. Since the initial moisture content of the waste layer was 0.08 vol./vol. and the wilting point of the waste was 0.016 vol./vol., the available moisture for evaporative demand was 0.064 (difference between MC and wilting point) vol./vol.

5.2.1 Phase-2: HELP Model Simulations

HELP model simulations were performed for the rainfall field simulation studies RF-1 to RF-4. When HELP model default parameter values for MSW (at density of 600 kg/m^3) were used, leachate production was zero. HELP simulations using the parameter values for MSW with channeling, resulted in 1190 L of leachate. Since, the waste was at higher initial moisture content than the field capacity, when MSW channeled flow field capacity was used, desorption of moisture may occur. Next, laboratory modified parameter values were used for HELP simulations. This simulation resulted in a total of 0.93 L (0.2 mm) of leachate as against the actual amount of 48.08 L leachate. The HELP model simulation results, using laboratory modified parameter values, are shown in Figure 5.3. The HELP model predicted a total leachate discharge of 0.93L, occurring over one day. However, in the field 48.08 L of leachate was produced over the period of 10 days. The HELP model responded quickly to moisture loading, unlike the actual leachate discharge, and the leachate production stopped as soon as the moisture addition had ended. In the field, waste absorbs moisture and releases it over a longer duration of time, but the HELP model simulations are based on daily water balance calculations. The peak/average leachate discharge rate ratio predicted by the HELP model was 1, as against the actual peak/average leachate discharge rate ratio of 5.2.

Figure 5.3: Phase-2 Comparison of Actual Leachate Volumes and HELP Model Predictions (Using Laboratory Determined Parameter Values)



5.2.2 Phase-2 and Phase-3: HELP Model Simulations

HELP model simulations were performed for the cumulative phenomena of rainfall field simulation and re-circulation, RF-1 to RF-4, and RCL-1 to RCL-3. When HELP model default parameter values were used, leachate production was zero. HELP simulations using the parameter values modified for MSW with channeling produced 1437 L of leachate. Next, a HELP simulation was performed using the laboratory determined parameter values. This simulation produced 173.2 L (38.3 mm) of leachate, as against the actual production of 164.78 L. The HELP model simulation results using laboratory modified parameter values are presented in Figure 5.4. The figure shows that the HELP model predicted production of 173.2 L over four days. However, the lysimeter produced leachate continuously over the period of Phase-2 and Phase-3 field simulations. The HELP model predicted a sudden discharge of 173.2 L. According to Figure 5.5, the HELP model predicted a peak leachate discharge of 118.5 L/day, as against the actual peak discharge of 24.32 L/day. The HELP model predicted peak/average leachate discharge rate ratio of 8.9 as against the actual average peak/average leachate discharge rate ratio 10.

5.2.3 Phase-2 to Phase-4: HELP Model Simulations

HELP model simulations were performed for the cumulative phenomena of rainfall field simulations and re-circulation studies RF-1 to RF-4, RCL-1 to RCL-3, and RFR-1 and RFR-2. When HELP model default parameter values were used, leachate production was zero. The HELP model simulations using the parameter values modified for MSW with channeling produced 2497 L of leachate. Next, a HELP model simulation was also performed using the laboratory determined parameter values. This simulation produced 1103.7 L (243.9 mm) of leachate, as against the actual production of 442 L. The HELP model simulation results using laboratory modified parameter values are presented in Figure 5.6. The HELP model predicted that the waste had attained the field capacity at the end of Phase-3 simulation. Hence, the quantity of leachate predicted was equal to the

Figure 5.4:Phase -2 and Phase-3 Comparison of Actual Leachate Volumes and HELP Model Predictions (Using Laboratory Determined Parameter Values)

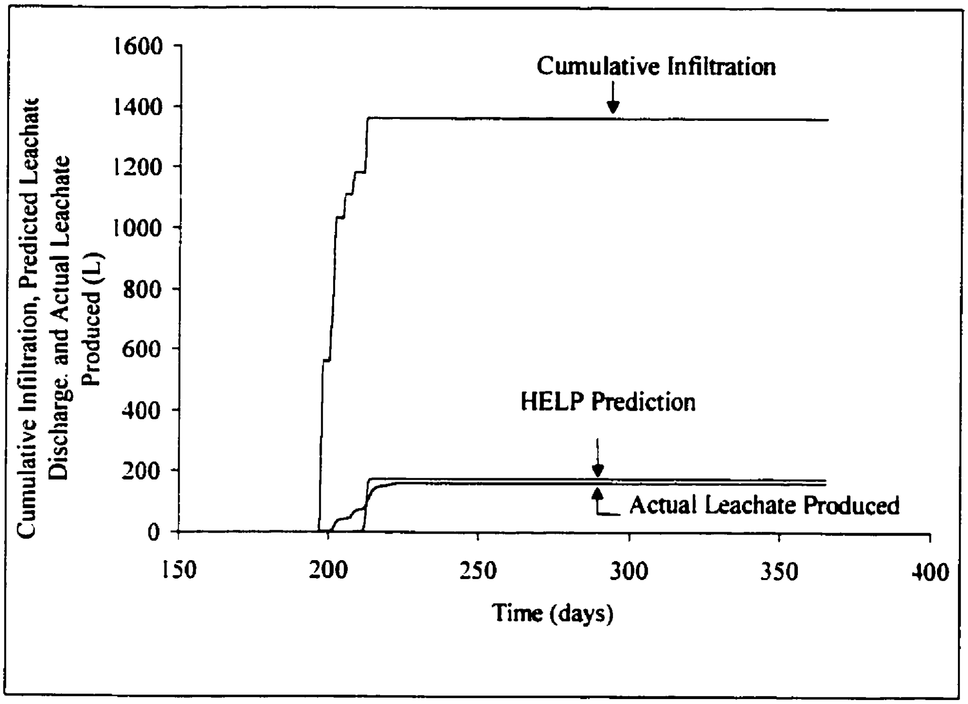


Figure 5.5: Actual Leachate Produced and HELP Model Predictions for the Rainfall/Leachate Re-circulation Simulations

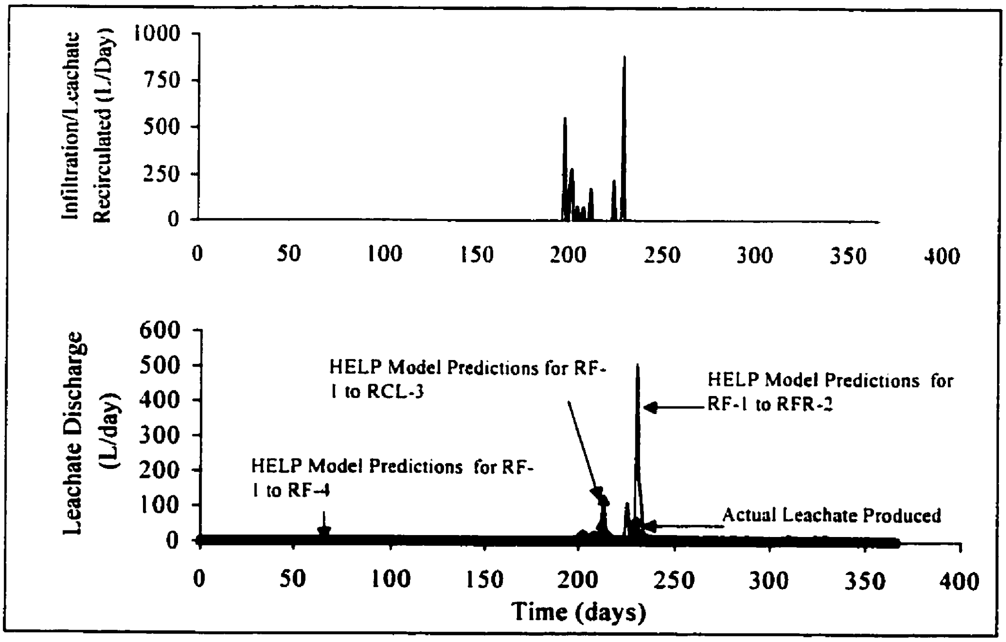
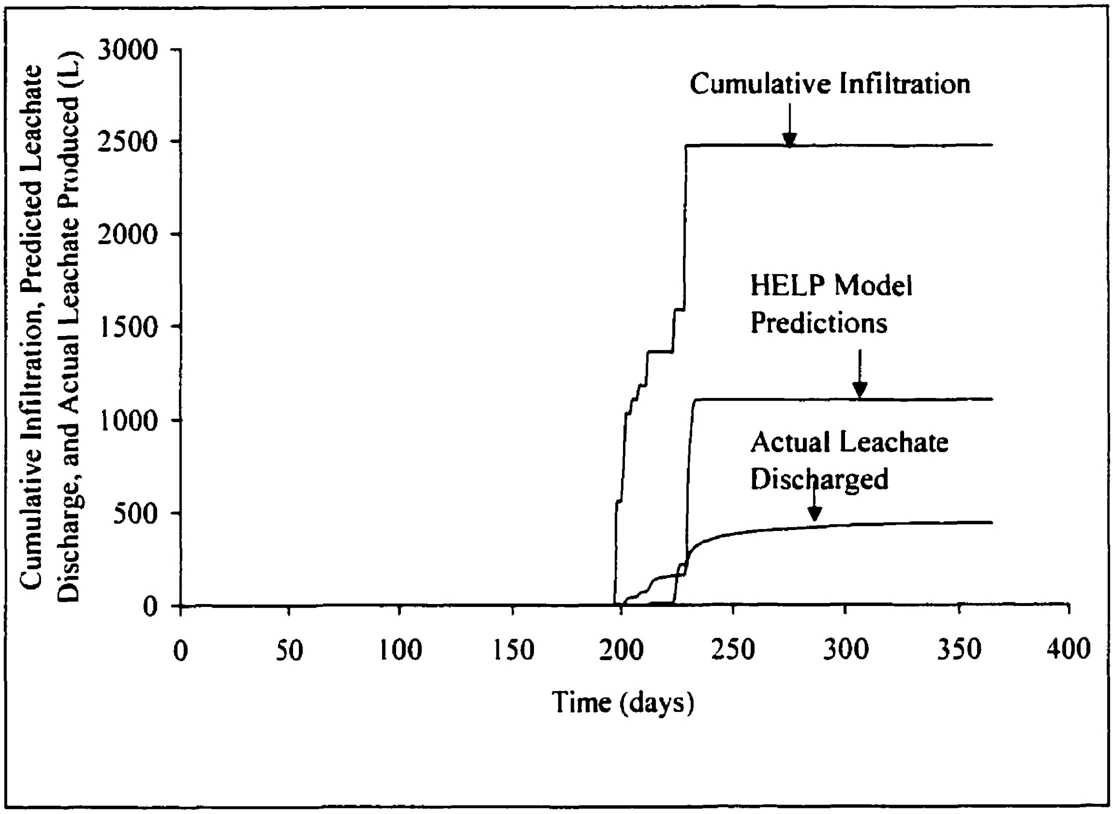


Figure 5.6: Phase-2 to Phase-4 Actual Leachate Produced and HELP Model Predictions (Using Laboratory Determined Parameter Values)



quantity of moisture infiltrated. Figure 5.5 shows that the HELP model predicted two peak leachate discharges. The first peak was predicted after the RFR-1 rainfall simulation and was predicted to be 109.5 L/day as against the actual peak discharge of 0.72 L/day. The HELP model predicted 212 L of leachate discharge over 3 days period as against the continuous leachate discharge of 2.2 L from the lysimeter. The model predicted the second peak after the RFR-2 rainfall simulation. This peak was predicted to be 505.4 L/day as against the actual peak of 54.53 L/day. The model predicted 884 L of leachate discharge from this simulation over a period of 5 days against the continuous leachate discharge of a total of 275 L over the period of three months. The over-prediction of peak leachate discharge limits the applicability of the model as a design tool. Moreover, the peak/average leachate discharge rate ratio predicted by the model was 18.9 as against the actual average peak/average leachate discharge rate ratio of 93.4. The actual average leachate discharge was very low as the leachate production was continuous over a simulation period as against the HELP model predicted sporadic leachate discharge. Thus, the HELP model provides a conservative design of LCRS.

Korfiatis et al., 1984 indicated that the field capacity continues to increase after drainage has started, indicating secondary absorption and redistribution of moisture within the waste. The lysimeter had secondary absorption of moisture even after reaching the practical field capacity. Hence, 275 L of leachate was produced during the RFR-1 and RFR-2 simulation against the HELP predicted leachate discharge of 1104 L.

5.3 SUMMARY: HELP MODEL SIMULATIONS AND ACTUAL OBSERVATIONS

The HELP model predictions in comparison to the actual observations are summarized below.

- The model assumes the barrier layer of the soil cover as saturated, and hence over-predicts the infiltration into the waste.
- A continuous flow of leachate was established in the field lysimeter at the moisture content of 0.175 vol./vol. The HELP model default field capacity is higher than the laboratory and field lysimeter practical field capacity. Hence, the model under-predicted the leachate discharge until field capacity was attained.
- The model predicted significantly higher peak leachate discharge as compared to the acutal landfill lysimeter peak leachate discharge.
- The model predicted significantly lower duration of leachate discharge as compared to the actual landfill lysimeter duration of leachate discharge.

- Since, the HELP model over-predicts the average leachate discharge rate, it under-predicts the peak/average leachate discharge rate ratio after the continuous leachate discharge was established.

5.4 HELP MODEL SENSITIVITY ANALYSIS

The HELP model uses weather data, parameter values for the cover layer, and for the waste layer. The relevant weather data for the simulations were obtained from the weather station located within the University of Calgary premises. The soil cover parameter values were determined on the basis of soil layer density and grain size distribution (Table 5.2). The HELP model has default moisture retention values for MSW at a 600 kg/m^3 compacted density and values modified for channeling (Table 5.1). The laboratory determined MSW parameter values (Table 5.1) were also used for the simulation.

A sensitivity analysis was performed by varying different soil cover and waste parameters to determine the parameter values of importance and specific to field simulation conditions. The following soil cover parameters were varied during the sensitivity analysis:

(1) Initial moisture content of the drainage layer
(2) Porosity of the drainage layer
(3) Saturated hydraulic conductivity of the drainage layer
(4) Drain slope of the drainage layer
(5) Field Capacity of the drainage layer
(6) Saturated hydraulic conductivity of the barrier layer

The waste parameters varied included:

(1) Field capacity of the waste
(2) Initial moisture content of the waste
(3) Wilting point of the waste

The sensitivity analysis results are presented in Tables 5.6 to 5.8. The results on the sensitivity of the HELP model outputs, to subsurface runoff and seepage, by varying drainage layer design parameter values are presented in Table 5.6. Appendix 5.1, Appendix 5.2, and Appendix 5.3 present the HELP model output results for sensitivity analysis for design parameter values, 25% increase in initial moisture content of the drainage layer from the design parameter values, and 25% decrease in the saturated hydraulic conductivity of the drainage layer from the design parameter values, respectively. Table 5.7 presents the results on the sensitivity of the HELP model outputs, to subsurface runoff and seepage, by varying barrier layer design parameter values.

The sensitivity analysis indicates that:

- the sub-surface runoff from the drainage layer was highly sensitive to porosity and initial moisture content of the drainage layer (refer Table 5.6). Furthermore, HELP model predictions are moderately sensitive to all other parameters. A decrease in porosity of the drainage layer by 25%, increased the sub-surface runoff by 49.5%, while a decrease in initial moisture content of the drainage layer by 25%, decreased the sub-surface runoff by 29.4%.
- The seepage from the drainage layer was sensitive to the field capacity of the drainage layer. A 25% decrease in the field capacity of the drainage layer, increased the seepage through the barrier layer by 9.7%.
- The barrier layer in the HELP model is assumed to be saturated. A decrease in saturated hydraulic conductivity by 25 %, increased the sub-surface runoff by 28.4% (refer Table 5.7).

Table 5.6: HELP Model Sensitivity Analysis on the Drainage Layer of the Soil Cover

Parameter Values and % Variation		Drainage Layer	
		% Change in Sub-surface Runoff	% Change in Seepage
Initial Moisture Content (vol./vol.)	0.15+25%	+24.3	+5.8
	0.15-25%	-29.4	-4.8
Porosity (vol./vol.)	0.48+25%	-25	+3.3
	0.48-25%	+49.5	-6.6
Saturated Hydraulic Conductivity (cm/sec)	0.012+25%	+19.7	-2.6
	0.012-25%	-21.5	+2.9
Drainage Slope (%)	4+25%	+17.8	-2.4
	4-25%	-18.6	+2.5
Field Capacity (vol./vol.)	0.16+25%	-12.2	-7.8
	0.16-25%	-1.1	+9.7

Table 5.7: HELP Model Sensitivity Analysis on the Barrier Layer of the Soil Cover

Parameter Values and % Variation		Barrier Layer	
		% Change in Sub-surface Runoff	% Change in Seepage
Saturated Hydraulic Conductivity(cm/sec)	0.00005+25%	-14.5	+1.5
	0.00005-25%	+28.4	-3.2

The results on the sensitivity analysis of the HELP model output, on leachate production, by varying the lysimeter waste parameter values determined in the laboratory for MSW are presented in Table 5.8. Appendix 5.4 and Appendix 5.5 present the HELP model output results for sensitivity analysis for design parameter values, and 25% decrease in field capacity of the waste layer from the design parameter values, respectively.

Table 5.8: HELP Model Sensitivity Analysis: Properties of Lysimeter Waste and Leachate Production

Parameter Values and % Variation		%Change in Leachate Produced
Practical Field Capacity of the Waste (vol.vol.)	0.2 + 25%	-49
	0.2 - 25%	+157
Initial Moisture Content of the Waste (vol./vol.)	0.08 + 25%	+149
	0.08 - 25%	-100
Wilting Point (vol./vol.)	0.016 –90%	3

The sensitivity analysis on the waste indicates that:

- the HELP model results are highly sensitive to the field capacity and initial moisture of the waste. The absorption/storage of moisture in the waste is one of the major processes affecting leachate production from a landfill (Blight et al., 1992). A decrease in field capacity of the waste reduces the moisture storage capacity of the waste. Once the field capacity is exceeded, the infiltrating moisture in excess of field capacity is discharged as leachate. An increase in initial moisture content of the waste, reduces the moisture absorption capacity of the waste, and therefore increases leachate production.
- the model output was less sensitive to the wilting point of the waste. Though practically, a "wilting point" of a compacted waste layer is an undefined parameter, the HELP model simulates the waste as a porous medium such as soil, and hence a value of the "wilting point" of the waste is necessary to run the model. An increase in wilting point of the waste, reduces the amount of moisture available to meet the evapotranspirative demand. Hence, it increases the quantity of leachate produced from a landfill by the amount of the difference of the initial moisture content and the wilting point moisture content.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 SUMMARY

The aims of this research were to study the leachate production patterns of landfills in semi-arid climates and to evaluate the applicability of the HELP model. A field landfill lysimeter was constructed to study the leachate production patterns. Laboratory studies were conducted to determine parameter values for incorporation in the HELP model. HELP model simulations were then performed to study the applicability of model in semi-arid climates.

6.1.1 Phase-1: Rainfall Simulations

- Phase-1 field simulations were performed to study the leachate production patterns of a closed landfill. The landfill lysimeter was immediately capped after the placement of MSW and was monitored for leachate production. The total precipitation recorded at the lysimeter site during the 10-month monitoring period was 371.5 mm. The landfill lysimeter did not produce leachate during this period.
- HELP model simulations, using the design parameter values for the cover and laboratory determined parameter values for the waste layer, predicted no leachate production.
- The laboratory soil column experimental results showed that under steady-state conditions, 85% of the moisture infiltrating into the drainage layer of the cover becomes sub-surface runoff and the balance 15% seeps through the barrier layer.

6.1.2 Phase-2 to Phase-4: Rainfall/Leachate Re-circulation Field Simulations

- Phase-2, Phase-3, and Phase-4 field simulations were performed to study the leachate production in open landfills during rainfall events and moisture re-circulation.
- The initial moisture breakthrough was observed from the waste layer only after the infiltration of about 124 mm of moisture into the waste layer, when the moisture content reached a value of 0.123 vol./vol.
- Based on a manual water balance calculation (using HELP model default field capacity), it may be estimated that the time to produce leachate from a Calgary landfill capped immediately after waste placement, will be about 31.5 years. It is estimated from the lysimeter studies that it may take about 5.5 years for initial breakthrough to occur from a Calgary landfill capped immediately after waste placement. However, both these conclusions need to be verified in actual landfill studies.
- A continuous flow of leachate was established only after 301 mm of infiltration/re-circulation of moisture into the waste layer, when the moisture content reached a value of 0.175 vol./vol. An extrapolation to Calgary conditions shows that, it may take at least 14 years for continuous flow to be established in a Calgary landfill. The waste had absorbed 0.3 L of moisture/kg of placed MSW when this continuous flow was established.
- The long-duration, low-intensity infiltration/recirculation simulations produced leachate at a higher peak/average leachate discharge ratio than all the other infiltration simulations.
- The peak/average leachate discharge rate ratio depends on the ratio of moisture content to the field capacity (MC/FC) of the waste. The MC/FC ratio is an important measure of propensity to produce leachate. As the MC/FC ratio approached 1, the quantity of leachate produced increased and leachate was discharged over longer duration of time.
- Waste absorbed moisture even after reaching the PFC. This indicated that waste will absorb moisture until it reaches the TFC. The TFC may govern the design of leachate re-circulation systems.

- The laboratory determined practical field capacity was 0.20 vol./vol. for waste compacted density of 375 kg/m^3 and 0.225 vol./vol. for waste compacted density of 525 kg/m^3.
- The HELP model under-predicted the quantity of leachate produced for Phase-2 rainfall simulations and over-predicted the quantity of leachate produced for Phase-2 to Phase-4 rainfall/re-circulation simulations.
- The HELP model over-predicted the peak leachate discharge rate and the average leachate discharge rate, and under-predicted the peak/average leachate discharge ratio, as it released the moisture over short duration of time. The moisture was released over longer period of time in the field simulations.
- The leachate characteristics indicated an increase in COD with the increase in moisture content due to decomposition by aerobic and anaerobic microorganisms. pH decreased due to the presence of organic acids from decomposed MSW. Electrical conductivity increased due to dissolution of metals with decrease in pH.
- BOD/COD ratio ranged from 0.6 to 0.8 indicating that the landfill was "young" and had highly biodegradable organic matter present.

6.1.3 Phase-5: Rainfall Simulations

- No leachate was produced during these field simulations as the landfill cover was unsaturated and it absorbed the infiltrated moisture.

6.2 CONCLUSIONS

The following conclusions were drawn from this study:

- The time of placement of final cover is critical in minimizing leachate production in landfills; the sooner the cover is placed, the less the leachate produced, and the larger is the breakthrough time. Under semi-arid climatic conditions in Calgary, immediate placement of the final cover could delay leachate production by several years.

- At low infiltration intensities, the waste absorbs moisture. However, leachate is produced over a longer duration of time, after a certain minimum quantity has infiltrated.
- Peak/average leachate ratio is as high as 20, for "point injection" of leachate re-circulation. For "area injection" the peak/average ratio can be up to 7.5. This indicates that LCRS for a landfill with "point injection" leachate re-circulation should be designed using different peak/average ratios than a landfill without re-circulation. The LCRS is designed based on peak/average leachate production rates.
- HELP model can be used to calculate the average leachate flow rate into the LCRS. However, landfill designers should calculate the peak leachate production rate for LCRS, based on the peak/average ratio.
- Since a high peak/average leachate discharge ratio is detrimental if the landfill is used as a treatment medium for leachate, "area injection" of leachate is preferred over "point injection".
- The density of compacted waste is an important factor governing leachate production from MSW landfills. As the field capacity varies with compacted waste density, the HELP model may have to incorporate waste properties as variables to accurately predict the leachate generation from a given landfill. Since waste density may change with time in a given landfill, time dependent variation in waste density needs to be considered.
- The leachate is produced before reaching the field capacity used in the HELP model. The HELP model under-predicts leachate production where default values are used.
- HELP model predictions can be improved by using a site-specific field capacity, instead of the default field capacity (including modification for channeling). This field capacity can be determined in the laboratory.
- The HELP model seems to over-predict the seepage through the barrier layer as it assumes the barrier layer to be always saturated. Under semi-arid climatic conditions, as precipitation is low, the infiltrated moisture is absorbed by the barrier layer before seeping through the barrier layer.

- The HELP model over-predicts the peak leachate discharge rate and the average leachate discharge rate, and under-predict the peak/average leachate discharge ratio, as once the field capacity is reached, it releases the moisture over short duration of time. The moisture is released over a longer period of time in the landfills.
- Waste parameters and landfill cover parameters used in the HELP model can be generated in the laboratory using well designed experiments. Accuracy of HELP model predictions can be increased by replacing default values by laboratory determined values.

6.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Based on this research, further studies on the following is recommended:

- The effect of moisture infiltration/re-circulation on leachate production patterns from landfills at higher initial moisture contents, i.e. waste at PFC.
- The ultimate storage capacity of the waste, or the TFC of the landfilled waste.
- The biodegradability and a decrease in BOD/COD ratio of "young" landfill at PFC moisture content, with time.
- The effect of various compacted waste densities on waste properties impacting leachate production.
- Develop better parameter values for field capacity as a function of the waste density, which can be used in the HELP model.

REFERENCES:

Ahmed, S., R.M. Khanbilvardi, J. Fillos, and P.J. Gleason (1992). Two-Dimensional Leachate Estimation Through Landfills. *Journal of Hydraulic Engineering.* 118(2): 306-322.

Bagchi, A. (1994). Design, Construction, and Monitoring of Landfills. Second Edition. Wiley-Interscience Publication: 35-36.

Blakey, N.C.(1982). Infiltration and Absorption of Water by Domestic Wastes in Landfills. *Harwell Landfill Leachate Symposium*, Harwell, Oxfordshire, U.K.: 1-13.

Blight, G.E., J.M. Ball, and J.J. Blight (1992). Moisture and Suction in Sanitary Landfills in Semiarid Areas. *Proceedings of ASCE, Journal of Environmental Engineering.* 118(6): 865-877.

Brooks, R.H. and A.T. Corey (1964). Hydraulic Properties of Porous Media. *Hydrology,* Paper No. 3, Colorado State University, Fort Collins, CO. pp. 27.

Brunner, P.R. and W.R. Ernst (1986). Alternative Methods for the Analysis of Municipal Solid Waste. *Waste Management and Research,* 4: 147.

Campbell, D.J.V.(1982). Absorptive Capactiy of Refuse. *Harwell Landfill Leachate Symposium*, Harwell, Oxfordshire, U.K.: 1-10.

Campbell, G.S.(1974). A Simple Method for Determining Unsaturated Conductivity from Moisture Retention Data. *Soil Science,* 117(6): 311-314.

Carpenter, P.J., R.S. Kaufmann, and B. Price (1990). Use of Resistivity Soundings to Determine Landfill Structure. *Ground Water*, 28(4): 569.

Chen, H.P. (1996). Assessment of Leachates from Sanitary Landfills: Impact of Age, Rainfall, and Treatment. *Environment International*, 22(2): 225-237.

Chen, T. and D.P. Chynoweth (1995). Hydraulic Conductivity of Compacted Municipal Solid Waste. *Bioresource Technology*, 51: 205-212.

Chen, C. and R.J. Wagenet (1992). Simulation of Water and Chemical in Macropore Soils. Part 1. Representation of the Equivalent Macropore Influence and its Effect on Soilwater Flow. *Journal of Hydrology*, 130: 105.

Chian, S.K., F.G. Pohland, K.C. Chang, and S.R. Harper (1985). Leachate Generation and Control at Landfill Disposal Sites. New Directions and Research in Waste Treatment and Residuals Management, University of British Columbia. Vancouver, B.C.

Christensen, T.H., R. Cossu, and R. Stegmann (1989). Sanitary Landfilling: Process, Technology and Environmental Impact. *Academic Press Limited*, London, Canada.

Daniel, D.E., and B.A. Gross (1996). "Caps", Section 6 in Workshop Proceedings on Containment of Solid Waste, R.Rumer, Ed., NTIS Publ. No. PB96-180583: 119-140.

Dass, P., G.R. Tamke, and C.M. Stoffel.(1977). Leachate Production at Sanitary Landfill Sites. *Proceedings of ASCE, Journal of Environmental Engineering*. 103(6): 981-988.

De Bruin, H.A.R. (1987). Evaporation in Arid and Semi-arid Regions. In Estimation of Natural Recharge, I. Simmers (ed). NATO ISI Series C, D. Reidel Publ. Co.

Demetracopoulos, A.C., G.P. Korfiatis, E.L. Bourodimos, and E.G. Nawy (1986). Unsaturated Flow Through Solid Waste Landfills: Model and Sensitivity Analysis. *Water Resources Bulletin, American Water Resources Association*: 601-609.

Dozier, T.S. (1992).Examination and Modification of Three Surface Hydrologic Processes in the HELP Model. *M.S. Thesis*, Mississippi State University, MS,USA.

El-Fadel, M., A.N. Findikakis, and J.O. Leckie (1997). Modeling Leachate Generation and Transport in Solid Waste Landfills. *Environmental Technology*. 18: 669-686.

Elsbury, B.R., D.E. Daniel, G.A. Sraders, and D.C. Anderson (1990). Lessons Learned from Compacted Clay Liner. *Journal of Geotechnical Engineering*, 116(1):

Etalla, M. (1987). Infiltration and Hydraulic Conductivity at a Sanitary Landfill. *Aqua Fennica*, 17(2): 231.

Fenn, D.G., K.J. Hanley, and T.V. DeGeare (1975). Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites, U.S. Environmental Protection Agency, EPA/530/SW-168, Washington, D.C

Fetter, C.W. (1993). Contaminant Hydrogeology. New York, MacMillan.

Fredlund, D.G. and H. Rahardjo (1993). Soil Mechanics for Unsaturated Soils. John Wiley & Sons, Inc., NY.

Freeze, R.A., and J.A. Cherry (1979). Groundwater. Prentice-Hall, Englewood Cliffs, NJ.

Fungaroli, A.A. and R.L. Steiner (1971). Laboratory Study of the Behavior of a Sanitary Landfill. *Journal WPCF.* 43(2): 252-267.

Gau, S. and Jing-Dong C. (1998). Landfill Leachate Characteristics and Modeling of Municipal Solid Wastes Combined with Incinerated Residuals. *Journal of Hazardous Materials.* 58: 249-259.

Guyonnet, D., B. Didier-Guelorget, G. Provost, and C. Feuillet (1998). Accounting for Water Storage Effects in Landfill Leachate Modelling. *Waste Management Research.* 16(3): 285-295.

Ham, R. K. and T. J. Bookter (1982). Decomposition of Solid Waste in Test Lysimeters. *Proceedings of the ASCE, Journal of the Environmental Engineering,* 108(6): 1147-1170.

Hamilton, (1996). Freezing Shrinkage in Compacted Clays. *Canadian Geotechnical Journal,* 111(1): 1-17.

Hillel, D. (1971). Soil and Water, Physical Principles and Processes. Academic Press, New York.

Huang, C.H. (1987). A Countermeasure on Leachate Treatment of Sanitary Landfill. *In: Proc. 2nd Conf. On Solid Waste Management Technology in Republic of China, Taiwan,* RCO: 207-219

Jasper, S.E., J.W. Atwater, and D.S. Mavinic (1985). Leachate Production and Characteristics as a Function of Water Input and Landfill Configuration. *Water Pollution Research Journal of Canada.* 20(3): 43-56.

Kao, C.F., T.E. Chang, and W.T. Kao (1986). Treatment of Landfill Leachate Using Improved Anaeration Filter Bed. *In: Proc. 16th Conf. On Wastewater Treatment Technology in Republic of China*, Taiwan, ROC: 477-490.

Khanbilvardi, R.M., S. Ahmed, and P.J. Gleason.(1995). Flow Investigation for Landfill Leachate (FILL). *Journal of Environmental Engineering,* 121(1): 45-57.

Khire, M.V., C.H. Benson, and P.J. Bosscher.(1997). Water Balance Modeling of Earthern Final Covers. *Journal of Geotechnical and Geoenvironmental Engineering* 123(8): 744-754.

Klee, A.J. (1993). New Approaches to Estimation of Solid-waste Quantity and Composition. *Proceedings of ASCE, Journal of Environmental Engineering.* 119(2): 248.

Knisel, W.G., ed. (1980). CREAMS, A Field Scale Model for Chemical Runoff and Evaporation from Agricultural Management Systems. Vols. I, II and III. Conservation Report 26, USDA-SEA

Koerner, R.M. and D.E. Daniel (1997). Final Covers for Solid Waste Landfills and Abandoned Dumps. American Society of Civil Engineers Press.

Korfiatis, G. P. and A.C. Demetracopoulos (1984). Moisture Transport in a Solid Waste Column. *Proceedings of ASCE, Journal of Environmental Engineering.* 110(4): 780-796.

Korfiatis, G.P. and A.C. Demetracopoulos (1986). Flow Characteristics of Landfill Leachate Collection Systems and Liners. *Proceedings of ASCE, Journal of Environmental Engineering.* 112(3): 538-550.

Lange, D.A., B.F. Cellier, and T. Dunchak (1997). A Case Study of the HELP Model: Actual Versus Predicted Leachate Production Rates at a Municipal Landfill in Northeastern Ohio. *Water Quality Index* 1997, Nov/Dec: 40-42.

Leskiw, E.J.(1992). Potential Leachate Production Due to Cold Weather Effects. *Canadian Journal of Civil Engineering.* 19: 660-667.

Macey, H.H. (1942) Clay-Water Relationships and the Internal Mechanism of Drying. *Transactions, British Ceramic Society.* 41:73-121

McEnroe, B.M.(1989). Steady Drainage of Landfill Covers and Bottom Liners. *Proceedings of ASCE, Journal of Environmental Engineering,* 115(6): 1114-1122.

Noble, J.J. and A. E. Arnold (1991). Experimental and Mathematical Modeling of Moisture Transport in Landfills. *Chemical Engineering Communications.* 100: 95-111.

Nyhan, J.W., T.G. Schofield, and R.H. Starmer (1997). A Water Balance Study of Four Landfill Cover Designs Varying in Slope for Semiarid Regions. *Journal of Environmental Quality,* 26: 1385-1392.

Othman, M.A., C.H. Benson, E.J. Chamberlain, and T.T. Zimmier (1994). Laboratory Testing to Evaluate Changes in Hydraulic Conductivity of Compacted Clays Caused by Freeze-Thaw: State-of-the-Art, Hydraulic Conductivity and Waste Containment Transport in Soil, ASTM STP 1142, American Society for Testing and Materials, Philadelphia, PA.: 227-251.

Oweis, I.S., D.A. Smith, R.B. Ellwood, and D.S. Greene (1990). Hydraulic Characteristics of Municipal Refuse. *Proceedings of ASCE, Journal of Geotechnical Engineering.* 116(4): 539-553.

Parsons, R.(1995). Water Balance Method to Predict Leachate Generation: Geohydrological Experiences. *Proceedings Sardinia 95. Fifth International Landfill Symposium,* Cagliari, Italy: 275-284.

Penman, H.L. (1963). Vegetation and Hydrology. Technical Comment No. 53, Commonwealth Bureau of Soils, Harpenden, England.

Perera M.D.N., J.P.A. Hettiaratchi, and V.S. Shroff (1998). An Improved Flux Chamber Methodology to Determine Gas Emissions from Lanfills, *Proceedings of the Fourteenth International Conference on Solid Waste Technology and Management*, Philadelphia, PA.

Peyton, L.R. and P.R. Schroeder (1988). Field Verification of HELP model for Landfills, *Proceedings of ASCE, Journal of Environmental Engineering.* 114(2): 247-269.

Ritchie, J. T.(1972). Model for Predicting Evaporation from a Row Crop with Incomplete Cover. *Water Resources Research,* 8(5): 1204-1213.

Rode, A.A.(1969). Theory of Soil Moisture, Vol. I: Moisture Properties of Soils and Movement of Soil Moisture. Israel Program for Scientific Translations, Jerusalem.

Rovers, F.A. and G.J. Farquhar (1973). Infiltration and Landfill Behavior. *Proceedings of ASCE, Journal of Environmental Engineering.* 99(5): 671-690

Schroeder, P.R., T.S. Dozier, P.A. Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton (1994). The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3, EPA/600/R-94/168b, U.S. Environmental Protection Agency Office of Research and Development, Washington, D.C.

Schroeder, P.R., N.M. Aziz, C.M. Lloyd, and P.A. Zappi (1994). "The Hydrologic Evaluation of Landfill Performance (HELP) Model: User's Guide for Version 3," EPA/600/R-94/168a, September 1994, U.S. Environmental Protection Agency Office of Research and Development, Washington, DC.

Serway, R.A. and J.S. Faughn (1985). College Physics, 3rd Edition. Saunders College Publishing.

Sharma, H.D. and S.P. Lewis (1994). Waste Containment Systems, Waste Stabilization, and Landfills: Design and Evaluation. Wiley-Interscience Publication, New York.

Shroff V.S., J.P.A. Hettiaratchi (1998). Importance of Field Capacity in Modeling Leachate Production from MSW Landfills. *Proceedings of the Fourteenth International Conference on Solid Waste Technology and Management*, Philadelphia, PA.

Standard Methods for the Examination of Water and Wastewater, 20th Edition (1998). Edited by: Lenore S. Clesceri, Arnold E. Greenberg, And Andrew D. Eaton. Prepared and Published by: American Public Health Association, American Water Works Association, and Water Environment Federation.

Sweeney, T.L., H.G. Bhatt, R.M. Sykes, O.J. Sproul (1982). Hazardous Waste Management for the 80's. Ann Arbor Science Publication.

Tchobanoglous, G., H. Theisen, and S. Vigil (1993). Integrated Solid Waste Management: Engineering Principles and Management Issues, Toronto, McGraw-Hill.

USDA, Soil Conservation Service (1985). National Engineering Handbook, Section 4: Hydrology, U.S. Government Printing Office, Washington, D.C.

U.S. EPA (United States Environmental Protection Agency) (1984).Office of Drinking Water. A Groundwater Protection Strategy for the Environmental Protection Agency

Uguccioni, M., A. (1995). Moisture Movement Through Municipal Solid Waste. *M.Sc. Thesis*, University of Alberta, Edmonton, Alberta.

Uguccioni, M., C. Zeiss (1996). Moisture Movement and Modelling Leachate Generation in Municipal Solid Waste. *CSCE, 4th Environmental Engineering Speciality Conference*, Edmonton, Alberta: 253-258.

Wall, D. K. (1993). The Use of Biological Enhancement to Expedite Landfill Stabilization and Beneficial Land Use. *MSc. Thesis*, University of Alberta, Alberta, Canada.

Wall, D. K. and C. Zeiss (1995). Municipal Landfill Biodegradation and Settlement. *Proceedings of ASCE, Journal of Environmental Engineering*. 121(3): 214-224.

Wong, J. (1977). The Design of a System for Collecting Leachate from a Lined Landfill Site. *Water Resources Research*, 13(2): 404-410.

Zeiss, C., and M. Uguccioni (1995). Mechanisms and Patterns of Leachate Flow in Municipal Solid Waste Landfills. *Journal of Environmental Systems*. 23(3): 247-270.

Zeiss, C., and M. Uguccioni (1997). Modified Flow Parameters for Leachate Generation. *Water Environment Research*. 69(3): 276-285.

Zeiss, C., and W. Major.(1993). Moisture Flow Through Municipal Solid Waste: Patterns and Characteristics. *Journal of Environmental Systems:* 22(3): 211-231.

Appendix 4.1: Field Landfill Lysimeter: Temperature at Various Depths

Date	Temperature in degree Celsius Measured at Different Depths from the Top of the Vegetative Layer							
	(a) 0.10m	(b) 0.60m	(c) 1.00m	(d) 2.00m	(e) 2.50m	(f) 3.50m	(g) 4.00m	(h) Average*
3-Oct-97	N.A.	14.3	41.3	50.8	54.1	51.3	34.7	46.4
7-Oct-97	N.A.	4.5	29.5	50.7	48.1	52.4	36.9	43.5
8-Oct-97	N.A.	1.3	30.0	47.9	52.4	35.4	35.1	40.2
9-Oct-97	N.A.	0.8	27.2	49.4	53.5	52.9	36.3	43.9
12-Oct-97	N.A.	6.4	38.2	48.0	52.1	52.9	38.0	45.8
14-Oct-97	N.A.	19.5	34.9	44.9	52.6	50.5	37.0	44.0
15-Oct-97	10.6	7.5	33.3	46.2	47.8	49.0	36.2	42.5
16-Oct-97	16.8	10.8	33.9	N.A.	46.8	47.5	35.8	41.0
20-Oct-97	9.8	13.8	33.1	43.0	43.5	43.2	33.7	39.3
22-Oct-97	7.1	14.5	33.1	40.6	40.1	42.9	33.0	37.9
26-Oct-97	16.1	12.2	30.5	37.4	38.1	39.4	31.0	35.3
27-Oct-97	7.8	13.9	32.8	39.0	39.7	41.0	32.9	37.1
29-Oct-97	7.8	13.0	30.6	36.6	37.4	38.8	31.1	34.9
31-Oct-97	7.0	11.6	25.5	34.4	35.9	36.8	28.8	32.3
3-Nov-97	6.6	12.2	28.7	34.5	35.1	37.0	29.6	33.0
5-Nov-97	13.0	10.2	24.3	30.3	30.5	32.4	25.0	28.5
7-Nov-97	1.9	11.6	27.1	24.5	32.9	26.1	22.1	26.5
10-Nov-97	4.3	10.4	27.9	33.3	34.4	35.4	29.3	32.1
12-Nov-97	11.3	7.5	26.3	30.8	32.2	33.8	26.9	30.0
14-Nov-97	-3.2	7.8	26.6	32.5	32.9	34.6	27.3	30.8
17-Nov-97	1.0	7.7	26.8	33.0	33.4	34.6	28.9	31.3
19-Nov-97	0.7	8.4	26.8	32.5	32.4	34.8	28.3	31.0
26-Nov-97	-1.7	3.7	19.5	24.0	24.8	26.9	22.7	23.6
28-Nov-97	0.2	4.1	17.9	22.7	23.1	25.0	20.6	21.9
1-Dec-97	1.0	6.6	19.3	24.0	24.0	25.4	22.7	23.1
3-Dec-97	2.4	7.0	19.3	24.0	23.9	26.6	23.6	23.5
5-Dec-97	2.2	9.0	18.5	24.6	25.6	28.2	24.3	24.2
8-Dec-97	2.2	6.2	17.0	23.5	24.8	27.5	25.1	23.6
12-Dec-97	0.9	5.5	15.6	22.9	23.9	26.1	23.2	22.3
17-Dec-97	0.6	3.5	14.6	20.6	21.5	24.3	21.1	20.4
23-Dec-97	2.7	5.7	16.0	23.7	24.2	26.1	22.6	22.5

Appendix 4.1: Field Landfill Lysimeter: Temperature at Various Depths

Date	Temperature in degree Celsius Measured at Different Depths from the Top of the Vegetative Layer							
	(a) 0.10m	(b) 0.60m	(c) 1.00m	(d) 2.00m	(e) 2.50m	(f) 3.50m	(g) 4.00m	(h) Average*
27-Jan-98	-1.0	N.A.	15.2	21.0	21.7	23.3	19.5	20.1
30-Jan-98	-3.2	3.6	13.4	19.7	20.1	20.7	17.5	18.3
4-Feb-98	-1.3	4.0	12.8	17.6	19.1	20.4	17.6	17.5
9-Feb-98	-1.4	2.3	10.4	14.9	14.9	16.4	14.3	14.2
10-Feb-98	-0.8	1.3	8.2	12.6	12.4	14.6	12.4	12.0
20-Feb-98	-0.5	1.5	8.3	11.8	11.2	13.6	12.4	11.5
23-Feb-98	-0.9	1.3	9.0	12.6	12.1	13.8	12.6	12.0
27-Feb-98	-0.5	2.3	8.9	11.9	12.0	13.2	12.7	11.7
11-Mar-98	-1.5	4.7	8.2	12.3	12.6	14.3	13.5	12.2
18-Mar-98	0.7	3.9	10.5	12.3	14.4	16.5	14.3	13.6
24-Mar-98	-0.2	4.4	8.0	11.0	10.9	13.7	11.5	11.0
27-Mar-98	0.2	2.4	8.5	10.2	10.4	12.0	10.9	10.4
9-Apr-98	3.0	3.9	8.5	10.5	10.4	10.3	11.3	10.2
15-Apr-98	2.1	4.4	8.5	9.3	9.6	10.8	10.2	9.7
24-Apr-98	8.1	4.8	7.0	8.0	7.8	8.1	7.6	7.7
28-Apr-98	8.6	5.8	9.0	9.4	9.0	8.6	8.2	8.8
1-May-98	9.7	6.7	8.4	7.7	7.3	7.8	6.4	7.5
5-May-98	11.6	7.9	10.6	8.8	8.6	7.5	6.5	8.4
11-May-98	11.3	8.6	11.9	9.1	8.9	7.6	6.0	8.7
13-May-98	13.4	11..7	13.1	10.2	10.6	8.4	7.2	9.9
19-May-98	12.4	12.1	13.0	10.9	10.2	8.5	6.5	9.8
22-May-98	15.2	N.A.	16.3	12.4	12.7	9.6	7.8	11.8
27-May-98	14.6	12.2	15.8	11.9	11.9	8.3	6.2	10.8
3-Jun-98	13.6	11.5	15.2	12.9	12.4	9.8	7.8	11.6
11-Jun-98	15.2	12.4	16.0	13.4	13.5	9.7	7.0	11.9
19-Jun-98	16.8	14.4	18.2	15.4	14.7	11.4	8.4	13.6
24-Jun-98	18.1	14.8	19.6	15.9	16.0	11.6	9.2	14.5
3-Jul-98	18.0	14.9	18.7	16.8	16.9	13.1	9.4	15.0
8-Jul-98	19.2	16.5	18.9	17.5	17.1	13.3	9.9	15.3
15-Jul-98	20.3	N.A.	20.2	17.6	17.6	13.7	9.5	15.7
18-Jul-98	N.A.	N.A.	25.0	21.6	21.5	18.0	11.9	19.6

Appendix 4.1: Field Landfill Lysimeter: Temperature at Various Depths

Date	Temperature in degree Celsius Measured at Different Depths from the Top of the Vegetative Layer							
	(a) 0.10m	(b) 0.60m	(c) 1.00m	(d) 2.00m	(e) 2.50m	(f) 3.50m	(g) 4.00m	(h) Average*
20-Jul-98	N.A.	N.A.	23.5	21.9	21.4	18.5	13.5	19.8
21-Jul-98	N.A.	N.A.	24.0	21.8	22.3	19.3	12.8	20.0
31-Jul-98	N.A.	N.A.	25.0	26.5	26.3	24.6	22.8	25.0
2-Aug-98	N.A.	N.A.	26.1	24.8	25.3	23.4	19.2	23.8
12-Aug-98	N.A.	N.A.	29.3	25.2	23.9	19.3	12.5	22.0
20-Aug-98	N.A.	N.A.	29.0	27.3	27.1	21.4	15.5	24.1
25-Aug-98	N.A.	N.A.	26.0	25.6	26.1	21.5	15.1	22.9
27-Aug-98	N.A.	N.A.	26.8	25.4	26.1	21.1	15.3	22.9
28-Aug-98	N.A.	N.A.	26.1	25.3	25.5	21.0	14.8	22.5
30-Aug-98	N.A.	N.A.	25.6	25.3	25.5	21.4	15.0	22.6
1-Sep-98	N.A.	N.A.	24.7	24.2	24.9	20.6	14.7	21.8
2-Sep-98	N.A.	N.A.	24.1	23.3	24.1	20.4	15.2	21.4
3-Sep-98	N.A.	N.A.	25.0	24.0	25.5	20.3	15.7	22.1
4-Sep-98	N.A.	N.A.	24.7	24.2	24.3	20.6	14.5	21.7
8-Sep-98	N.A.	N.A.	23.0	22.6	23.2	21.2	14.3	20.9
14-Sep-98	N.A.	N.A.	24.6	22.8	23.6	20.9	15.8	21.5
15-Sep-98	N.A.	N.A.	22.5	21.6	21.8	18.6	14.2	19.7
17-Sep-98	N.A.	N.A.	23.5	22.4	22.4	20.2	14.7	20.6
20-Sep-98	N.A.	N.A.	23.6	22.9	23.0	20.2	16.0	21.1
23-Sep-98	N.A.	N.A.	22.1	21.1	21.8	19.2	14.7	19.8
7-Oct-98	N.A.	N.A.	20.0	20.0	18.1	18.7	15.1	18.4
14-Nov-98	N.A.	N.A.	13.3	14.7	14.8	15.8	15.3	14.8
20-Nov-98	N.A.	N.A.	11.4	13.7	13.4	14.0	13.9	13.3
25-Nov-98	N.A.	N.A.	10.8	12.5	12.1	14.2	13.7	12.7
7-Dec-98	N.A.	N.A.	10.2	12.1	11.3	13.4	13.7	12.1
15-Dec-98	N.A.	N.A.	9.0	11.8	10.6	12.9	13.1	11.5

Notes:

N.A. = Not Available

* Average value of the probes in the lysimeter waste layer, i.e. average of columns (c), (d), (e), (f), (g).

APPENDIX 5.1: HELP Model Output for the Sensitivity Analysis for Drainage Layer: Design Parameter Values

```
******************************************************************************
******************************************************************************

            HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
             HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)
               DEVELOPED BY ENVIRONMENTAL LABORATORY
                  USAE WATERWAYS EXPERIMENT STATION
            FOR USEPA RISK REDUCTION ENGINEERING LABORATORY
******************************************************************************
******************************************************************************
******************************************************************************

     TITLE:  HELP Model Simulations Using the Design Parameter Values
             for the Drainage Layer

******************************************************************************

     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.

                                        LAYER  1
                                        --------

                      TYPE 1 - VERTICAL PERCOLATION LAYER
                          MATERIAL TEXTURE NUMBER   0
           THICKNESS                    =     10.00   CM
           POROSITY                     =      0.4800 VOL/VOL
           FIELD CAPACITY               =      0.1600 VOL/VOL
           WILTING POINT                =      0.0600 VOL/VOL
           INITIAL SOIL WATER CONTENT   =      0.1650 VOL/VOL
           EFFECTIVE SAT. HYD. COND.    =  0.115970001000E-01 CM/SEC

                                        LAYER  2
                                        --------

                        TYPE 2 - LATERAL DRAINAGE LAYER
                          MATERIAL TEXTURE NUMBER   0
           THICKNESS                    =     40.00   CM
           POROSITY                     =      0.4800 VOL/VOL
           FIELD CAPACITY               =      0.1600 VOL/VOL
           WILTING POINT                =      0.0600 VOL/VOL
           INITIAL SOIL WATER CONTENT   =      0.1500 VOL/VOL
           EFFECTIVE SAT. HYD. COND.    =  0.120000001000E-01 CM/SEC
           SLOPE                        =      4.00   PERCENT
           DRAINAGE LENGTH              =      1.2    METERS
```

```
                    LAYER  3
                    --------

          TYPE 3 - BARRIER SOIL LINER
          MATERIAL TEXTURE NUMBER   0
THICKNESS                    =     30.00   CM
POROSITY                     =      0.4500 VOL/VOL
FIELD CAPACITY               =      0.2500 VOL/VOL
WILTING POINT                =      0.1300 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.4500 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.499999987000E-04 CM/SEC

                    LAYER  4
                    --------

      TYPE 1 - VERTICAL PERCOLATION LAYER
          MATERIAL TEXTURE NUMBER   0
THICKNESS                    =     20.00   CM
POROSITY                     =      0.4800 VOL/VOL
FIELD CAPACITY               =      0.1600 VOL/VOL
WILTING POINT                =      0.0600 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.1500 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.115970001000E-01 CM/SEC

                    LAYER  5
                    --------

      TYPE 1 - VERTICAL PERCOLATION LAYER
          MATERIAL TEXTURE NUMBER   0
THICKNESS                    =    285.00   CM
POROSITY                     =      0.5500 VOL/VOL
FIELD CAPACITY               =      0.2000 VOL/VOL
WILTING POINT                =      0.0160 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.0800 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.116999997000E-01 CM/SEC

                    LAYER  6
                    --------

        TYPE 2 - LATERAL DRAINAGE LAYER
          MATERIAL TEXTURE NUMBER  21
THICKNESS                    =     20.00   CM
POROSITY                     =      0.3970 VOL/VOL
FIELD CAPACITY               =      0.0320 VOL/VOL
WILTING POINT                =      0.0130 VOL/VOL
INITIAL SOIL WATER CONTENT   =      0.0300 VOL/VOL
EFFECTIVE SAT. HYD. COND.    =  0.300000012000       CM/SEC
SLOPE                        =      4.00   PERCENT
DRAINAGE LENGTH              =      1.2    METERS
```

LAYER 7

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 36

THICKNESS	=	0.00	CM
POROSITY	=	0.0000	VOL/VOL
FIELD CAPACITY	=	0.0000	VOL/VOL
WILTING POINT	=	0.0000	VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000	VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.399999993000E-12	CM/SEC
FML PINHOLE DENSITY	=	0.00	HOLES/HECTARE
FML INSTALLATION DEFECTS	=	0.00	HOLES/HECTARE
FML PLACEMENT QUALITY	=	4 - POOR	

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE # 9 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 4.% AND A SLOPE LENGTH OF 4. METERS.

SCS RUNOFF CURVE NUMBER	=	93.00	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	0.0010	HECTARES
EVAPORATIVE ZONE DEPTH	=	10.0	CM
INITIAL WATER IN EVAPORATIVE ZONE	=	1.650	CM
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.800	CM
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.600	CM
INITIAL SNOW WATER	=	0.000	CM
INITIAL WATER IN LAYER MATERIALS	=	47.550	CM
TOTAL INITIAL WATER	=	47.550	CM
TOTAL SUBSURFACE INFLOW	=	0.00	MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Calgary Alberta

STATION LATITUDE	=	51.17	DEGREES
MAXIMUM LEAF AREA INDEX	=	1.00	
START OF GROWING SEASON (JULIAN DATE)	=	125	
END OF GROWING SEASON (JULIAN DATE)	=	278	
EVAPORATIVE ZONE DEPTH	=	10.0	CM
AVERAGE ANNUAL WIND SPEED	=	4.59	KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	64.23	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	76.95	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	68.11	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	68.01	%

NOTE: PRECIPITATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: TEMPERATURE DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: SOLAR RADIATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

MONTHLY TOTALS (MM) FOR YEAR 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION	12.5	1.5	1.5	8.0	1.0	33.0
	34.0	69.0	105.0	106.0	0.0	0.0
RUNOFF	2.36	0.00	0.04	0.00	0.00	0.12
	1.10	3.59	10.11	14.20	0.00	0.00
EVAPOTRANSPIRATION	2.69	1.50	0.09	15.37	1.70	8.82
	25.78	29.45	46.72	20.28	3.17	0.00
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.480	0.000	0.821
FROM LAYER 2	0.939	2.876	6.643	10.479	0.000	0.000
PERCOLATION/LEAKAGE	0.000	0.000	0.000	6.772	0.000	16.383
THROUGH LAYER 3	13.044	30.509	34.273	66.204	0.000	0.000
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.000	0.000	0.000
FROM LAYER 6	0.000	0.000	0.000	0.000	0.000	0.000
PERCOLATION/LEAKAGE	0.000	0.000	0.000	0.000	0.000	0.000
THROUGH LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000

MONTHLY SUMMARIES FOR DAILY HEADS (CM)

AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.004	0.000	0.016
TOP OF LAYER 3	0.013	0.041	0.062	0.101	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.021	0.000	0.040
HEAD ON TOP OF LAYER 3	0.065	0.110	0.174	0.240	0.000	0.000
AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.000	0.000	0.000
TOP OF LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.000	0.000	0.000
HEAD ON TOP OF LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000

ANNUAL TOTALS FOR YEAR 1998

	MM	CU. METERS	PERCENT
PRECIPITATION	371.50	3.700	100.00
RUNOFF	31.514	0.315	8.52
EVAPOTRANSPIRATION	155.565	1.556	42.04
DRAINAGE COLLECTED FROM LAYER 2	22.2371	0.222	6.01
PERC./LEAKAGE THROUGH LAYER 3	167.184082	1.672	45.18
AVG. HEAD ON TOP OF LAYER 3	0.1976		
DRAINAGE COLLECTED FROM LAYER 6	0.0000	0.000	0.00
PERC./LEAKAGE THROUGH LAYER 7	0.000000	0.000	0.00
AVG. HEAD ON TOP OF LAYER 7	0.0000		
CHANGE IN WATER STORAGE	160.684	1.607	43.43
SOIL WATER AT START OF YEAR	481.499	4.815	
SOIL WATER AT END OF YEAR	642.183	6.422	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0001	0.000	0.00

AVERAGE MONTHLY VALUES (MM) FOR YEARS 1998 THROUGH 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	12.50	1.50	1.50	8.00	1.00	33.00
	34.00	69.00	105.00	106.00	0.00	0.00
STD. DEVIATIONS	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00

RUNOFF

TOTALS	2.362	0.000	0.040	0.000	0.000	0.119
	1.098	3.590	10.106	14.199	0.000	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000

EVAPOTRANSPIRATION

TOTALS	2.687	1.500	0.094	15.368	1.698	8.820
	25.776	29.449	46.721	20.277	3.174	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000

LATERAL DRAINAGE COLLECTED FROM LAYER 2

TOTALS	0.0000	0.0000	0.0000	0.4800	0.0000	0.8207
	0.9389	2.8758	6.6431	10.4787	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

PERCOLATION/LEAKAGE THROUGH LAYER 3

TOTALS	0.0000	0.0000	0.0000	6.7716	0.0000	16.3827
	13.0437	30.5087	34.2734	66.2041	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

LATERAL DRAINAGE COLLECTED FROM LAYER 6

TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

PERCOLATION/LEAKAGE THROUGH LAYER 7

TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (CM)

DAILY AVERAGE HEAD ON TOP OF LAYER 3

AVERAGES	0.0000	0.0000	0.0000	0.0038	0.0000	0.0157
	0.0132	0.0412	0.0623	0.1009	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

DAILY AVERAGE HEAD ON TOP OF LAYER 7

AVERAGES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

****
****

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1998 THROUGH 1998

	MM	CU. METERS	PERCENT
PRECIPITATION	371.50 (0.000)	3.7	100.00
RUNOFF	31.514 (0.0000)	0.32	8.517
EVAPOTRANSPIRATION	155.565 (0.0000)	1.56	42.044
LATERAL DRAINAGE COLLECTED FROM LAYER 2	22.23712 (0.00000)	0.222	6.01003
PERCOLATION/LEAKAGE THROUGH LAYER 3	167.18408 (0.00000)	1.672	45.18489
AVERAGE HEAD ON TOP OF LAYER 3	0.198 (0.000)		
LATERAL DRAINAGE COLLECTED FROM LAYER 6	0.00000 (0.00000)	0.000	0.00000
PERCOLATION/LEAKAGE THROUGH LAYER 7	0.00000 (0.00000)	0.000	0.00000
AVERAGE HEAD ON TOP OF LAYER 7	0.000 (0.000)		
CHANGE IN WATER STORAGE	160.684 (0.0000)	1.61	43.428

****
****

PEAK DAILY VALUES FOR YEARS 1998 THROUGH 1998

	(MM)	(CU. METERS)
PRECIPITATION	30.00	0.300
RUNOFF	8.380	0.0838
DRAINAGE COLLECTED FROM LAYER 2	4.82436	0.04824
PERCOLATION/LEAKAGE THROUGH LAYER 3	15.349300	0.15349

AVERAGE HEAD ON TOP OF LAYER 3	11.312	
MAXIMUM HEAD ON TOP OF LAYER 3	10.024	
LOCATION OF MAXIMUM HEAD IN LAYER 2 (DISTANCE FROM DRAIN)	0.3 METERS	
DRAINAGE COLLECTED FROM LAYER 6	0.00000	0.00000
PERCOLATION/LEAKAGE THROUGH LAYER 7	0.000000	0.00000
AVERAGE HEAD ON TOP OF LAYER 7	0.000	
MAXIMUM HEAD ON TOP OF LAYER 7	0.000	
LOCATION OF MAXIMUM HEAD IN LAYER 6 (DISTANCE FROM DRAIN)	0.0 METERS	
SNOW WATER	5.90	0.0590
MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.2834	
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0600	

*** Maximum heads are computed using McEnroe's equations. ***

Reference: Maximum Saturated Depth over Landfill Liner
by Bruce M. McEnroe, University of Kansas
ASCE Journal of Environmental Engineering
Vol. 119, No. 2, March 1993, pp. 262-270.

****
****

FINAL WATER STORAGE AT END OF YEAR 1998

LAYER	(CM)	(VOL/VOL)
1	0.6000	0.0600
2	6.3999	0.1600
3	13.5000	0.4500
4	2.9848	0.1492
5	39.5336	0.1387
6	0.6000	0.0300
7	0.0000	0.0000
SNOW WATER	0.000	

****
****

APPENDIX 5.2: HELP Model Output the Sensitivity Analysis for Drainage Layer- Design Parameter Values + 25% Initial Moisture Content of the Drainage Layer

```
******************************************************************************
******************************************************************************

              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)
                 DEVELOPED BY ENVIRONMENTAL LABORATORY
                   USAE WATERWAYS EXPERIMENT STATION
             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY

******************************************************************************
******************************************************************************
******************************************************************************
      TITLE:  HELP Model Simulations Using the Design Parameter Values
              and +25% Initial Moisture Content of the Drainage Layer
******************************************************************************

      NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
               WERE SPECIFIED BY THE USER.

                                   LAYER  1
                                   --------

                  TYPE 1 - VERTICAL PERCOLATION LAYER
                       MATERIAL TEXTURE NUMBER   0
            THICKNESS                  =     10.00   CM
            POROSITY                   =      0.4800 VOL/VOL
            FIELD CAPACITY             =      0.1600 VOL/VOL
            WILTING POINT              =      0.0600 VOL/VOL
            INITIAL SOIL WATER CONTENT =      0.1650 VOL/VOL
            EFFECTIVE SAT. HYD. COND.  =  0.115970001000E-01 CM/SEC

                                   LAYER  2
                                   --------
                    TYPE 2 - LATERAL DRAINAGE LAYER
                       MATERIAL TEXTURE NUMBER   0
            THICKNESS                  =     40.00   CM
            POROSITY                   =      0.4800 VOL/VOL
            FIELD CAPACITY             =      0.1600 VOL/VOL
            WILTING POINT              =      0.0600 VOL/VOL
            INITIAL SOIL WATER CONTENT =      0.1880 VOL/VOL
            EFFECTIVE SAT. HYD. COND.  =  0.120000001000E-01 CM/SEC
            SLOPE                      =      4.00   PERCENT
            DRAINAGE LENGTH            =      1.2    METERS
```

LAYER 3

TYPE 3 - BARRIER SOIL LINER
MATERIAL TEXTURE NUMBER 0

THICKNESS	=	30.00 CM
POROSITY	=	0.4500 VOL/VOL
FIELD CAPACITY	=	0.2500 VOL/VOL
WILTING POINT	=	0.1300 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.4500 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.499999987000E-04 CM/SEC

LAYER 4

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 0

THICKNESS	=	20.00 CM
POROSITY	=	0.4800 VOL/VOL
FIELD CAPACITY	=	0.1600 VOL/VOL
WILTING POINT	=	0.0600 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.1500 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.115970001000E-01 CM/SEC

LAYER 5

TYPE 1 - VERTICAL PERCOLATION LAYER
MATERIAL TEXTURE NUMBER 0

THICKNESS	=	285.00 CM
POROSITY	=	0.5500 VOL/VOL
FIELD CAPACITY	=	0.2000 VOL/VOL
WILTING POINT	=	0.0160 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0800 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.116999997000E-01 CM/SEC

LAYER 6

TYPE 2 - LATERAL DRAINAGE LAYER
MATERIAL TEXTURE NUMBER 21

THICKNESS	=	20.00 CM
POROSITY	=	0.3970 VOL/VOL
FIELD CAPACITY	=	0.0320 VOL/VOL
WILTING POINT	=	0.0130 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0300 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.300000012000 CM/SEC
SLOPE	=	4.00 PERCENT
DRAINAGE LENGTH	=	1.2 METERS

LAYER 7

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 36

THICKNESS	=	0.00 CM
POROSITY	=	0.0000 VOL/VOL
FIELD CAPACITY	=	0.0000 VOL/VOL
WILTING POINT	=	0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY	=	0.00 HOLES/HECTARE
FML INSTALLATION DEFECTS	=	0.00 HOLES/HECTARE
FML PLACEMENT QUALITY	=	4 - POOR

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE # 9 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 4.% AND A SLOPE LENGTH OF 4. METERS.

SCS RUNOFF CURVE NUMBER	=	93.00
FRACTION OF AREA ALLOWING RUNOFF	=	100.0 PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	0.0010 HECTARES
EVAPORATIVE ZONE DEPTH	=	10.0 CM
INITIAL WATER IN EVAPORATIVE ZONE	=	1.650 CM
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.800 CM
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.600 CM
INITIAL SNOW WATER	=	0.000 CM
INITIAL WATER IN LAYER MATERIALS	=	49.070 CM
TOTAL INITIAL WATER	=	49.070 CM
TOTAL SUBSURFACE INFLOW	=	0.00 MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Calgary Alberta

STATION LATITUDE	=	51.17 DEGREES
MAXIMUM LEAF AREA INDEX	=	1.00
START OF GROWING SEASON (JULIAN DATE)	=	125
END OF GROWING SEASON (JULIAN DATE)	=	278
EVAPORATIVE ZONE DEPTH	=	10.0 CM
AVERAGE ANNUAL WIND SPEED	=	4.59 KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	64.23 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	76.95 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	68.11 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	68.01 %

NOTE: PRECIPITATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: TEMPERATURE DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: SOLAR RADIATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

****

MONTHLY TOTALS (MM) FOR YEAR 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION	12.5	1.5	1.5	8.0	1.0	33.0
	34.0	69.0	105.0	106.0	0.0	0.0
RUNOFF	2.36	0.00	0.04	0.00	0.00	0.12
	1.10	3.59	10.11	14.20	0.00	0.00
EVAPOTRANSPIRATION	2.69	1.50	0.09	15.37	1.70	8.82
	25.78	29.45	46.72	20.28	3.17	0.00
LATERAL DRAINAGE COLLECTED	4.378	0.000	0.000	1.676	0.000	0.821
FROM LAYER 2	0.939	2.876	6.643	10.479	0.000	0.000
PERCOLATION/LEAKAGE	6.822	0.000	0.000	9.575	0.000	16.383
THROUGH LAYER 3	13.044	30.509	34.273	66.204	0.000	0.000
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.000	0.000	0.000
FROM LAYER 6	0.000	0.000	0.000	0.000	0.000	0.000
PERCOLATION/LEAKAGE	0.000	0.000	0.000	0.000	0.000	0.000
THROUGH LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000

MONTHLY SUMMARIES FOR DAILY HEADS (CM)

AVERAGE DAILY HEAD ON	0.028	0.000	0.000	0.019	0.000	0.016
TOP OF LAYER 3	0.013	0.041	0.062	0.101	0.000	0.000
STD. DEVIATION OF DAILY	0.157	0.000	0.000	0.104	0.000	0.040
HEAD ON TOP OF LAYER 3	0.065	0.110	0.174	0.240	0.000	0.000
AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.000	0.000	0.000
TOP OF LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.000	0.000	0.000
HEAD ON TOP OF LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000

****

ANNUAL TOTALS FOR YEAR 1998

	MM	CU. METERS	PERCENT
PRECIPITATION	371.50	3.700	100.00
RUNOFF	31.514	0.315	8.52
EVAPOTRANSPIRATION	155.565	1.556	42.04
DRAINAGE COLLECTED FROM LAYER 2	27.8112	0.278	7.52
PERC./LEAKAGE THROUGH LAYER 3	176.809860	1.768	47.79
AVG. HEAD ON TOP OF LAYER 3	0.2338		
DRAINAGE COLLECTED FROM LAYER 6	0.0000	0.000	0.00
PERC./LEAKAGE THROUGH LAYER 7	0.000000	0.000	0.00
AVG. HEAD ON TOP OF LAYER 7	0.0000		
CHANGE IN WATER STORAGE	155.110	1.551	41.92
SOIL WATER AT START OF YEAR	496.699	4.967	
SOIL WATER AT END OF YEAR	651.809	6.518	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0000	0.000	0.00

AVERAGE MONTHLY VALUES (MM) FOR YEARS 1998 THROUGH 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	12.50	1.50	1.50	8.00	1.00	33.00
	34.00	69.00	105.00	106.00	0.00	0.00
STD. DEVIATIONS	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
RUNOFF						
TOTALS	2.362	0.000	0.040	0.000	0.000	0.119
	1.098	3.590	10.106	14.199	0.000	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000

	0.000	0.000	0.000	0.000	0.000	0.000

EVAPOTRANSPIRATION

TOTALS	2.687	1.500	0.094	15.368	1.698	8.820
	25.776	29.449	46.721	20.277	3.174	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000

LATERAL DRAINAGE COLLECTED FROM LAYER 2

TOTALS	4.3778	0.0000	0.0000	1.6763	0.0000	0.8207
	0.9389	2.8758	6.6431	10.4787	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

PERCOLATION/LEAKAGE THROUGH LAYER 3

TOTALS	6.8221	0.0000	0.0000	9.5753	0.0000	16.3827
	13.0437	30.5087	34.2734	66.2041	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

LATERAL DRAINAGE COLLECTED FROM LAYER 6

TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

PERCOLATION/LEAKAGE THROUGH LAYER 7

TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (CM)

DAILY AVERAGE HEAD ON TOP OF LAYER 3

AVERAGES	0.0282	0.0000	0.0000	0.0190	0.0000	0.0157
	0.0132	0.0412	0.0623	0.1009	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

DAILY AVERAGE HEAD ON TOP OF LAYER 7

AVERAGES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

****
****

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1998 THROUGH 1998

	MM		CU. METERS	PERCENT
PRECIPITATION	371.50	(0.000)	3.7	100.00
RUNOFF	31.514	(0.0000)	0.32	8.517
EVAPOTRANSPIRATION	155.565	(0.0000)	1.56	42.044
LATERAL DRAINAGE COLLECTED FROM LAYER 2	27.81116	(0.00000)	0.278	7.51653
PERCOLATION/LEAKAGE THROUGH LAYER 3	176.80986	(0.00000)	1.768	47.78645
AVERAGE HEAD ON TOP OF LAYER 3	0.234	(0.000)		
LATERAL DRAINAGE COLLECTED FROM LAYER 6	0.00000	(0.00000)	0.000	0.00000
PERCOLATION/LEAKAGE THROUGH LAYER 7	0.00000	(0.00000)	0.000	0.00000
AVERAGE HEAD ON TOP OF LAYER 7	0.000	(0.000)		
CHANGE IN WATER STORAGE	155.110	(0.0000)	1.55	41.922

****
****

PEAK DAILY VALUES FOR YEARS 1998 THROUGH 1998

	(MM)	(CU. METERS)
PRECIPITATION	30.00	0.300
RUNOFF	8.380	0.0838
DRAINAGE COLLECTED FROM LAYER 2	4.82436	0.04824
PERCOLATION/LEAKAGE THROUGH LAYER 3	15.349300	0.15349
AVERAGE HEAD ON TOP OF LAYER 3	11.312	
MAXIMUM HEAD ON TOP OF LAYER 3	10.024	
LOCATION OF MAXIMUM HEAD IN LAYER 2 (DISTANCE FROM DRAIN)	0.3 METERS	
DRAINAGE COLLECTED FROM LAYER 6	0.00000	0.00000

PERCOLATION/LEAKAGE THROUGH LAYER 7	0.000000	0.00000
AVERAGE HEAD ON TOP OF LAYER 7	0.000	
MAXIMUM HEAD ON TOP OF LAYER 7	0.000	
LOCATION OF MAXIMUM HEAD IN LAYER 6 (DISTANCE FROM DRAIN)	0.0 METERS	
SNOW WATER	5.90	0.0590

MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.2834
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0600

*** Maximum heads are computed using McEnroe's equations. ***

Reference: Maximum Saturated Depth over Landfill Liner
by Bruce M. McEnroe, University of Kansas
ASCE Journal of Environmental Engineering
Vol. 119, No. 2, March 1993, pp. 262-270.

****
****

FINAL WATER STORAGE AT END OF YEAR 1998

LAYER	(CM)	(VOL/VOL)
1	0.6000	0.0600
2	6.3999	0.1600
3	13.5000	0.4500
4	3.0082	0.1504
5	40.4728	0.1420
6	0.6000	0.0300
7	0.0000	0.0000
SNOW WATER	0.000	

****
****

APPENDIX 5.3: HELP Model Output for Sensitivity Analysis for Drainage Layer- Design Parameter Values -25% Saturated Hydraulic Conductivity

```
******************************************************************************
******************************************************************************

               HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
                 HELP MODEL VERSION 3.07   (1 NOVEMBER 1997)
                  DEVELOPED BY ENVIRONMENTAL LABORATORY
                    USAE WATERWAYS EXPERIMENT STATION
              FOR USEPA RISK REDUCTION ENGINEERING LABORATORY

******************************************************************************
******************************************************************************
******************************************************************************
     TITLE:  HELP Model Simulations for Design Parameters with -25%
             Saturated Hydraulic Conductivity of the Drainage Layer
******************************************************************************

     NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
              WERE SPECIFIED BY THE USER.

                                    LAYER  1
                                    --------

                      TYPE 1 - VERTICAL PERCOLATION LAYER
                          MATERIAL TEXTURE NUMBER   0
           THICKNESS                  =     10.00   CM
           POROSITY                   =      0.4800 VOL/VOL
           FIELD CAPACITY             =      0.1600 VOL/VOL
           WILTING POINT              =      0.0600 VOL/VOL
           INITIAL SOIL WATER CONTENT =      0.1650 VOL/VOL
           EFFECTIVE SAT. HYD. COND.  =  0.115970001000E-01 CM/SEC

                                    LAYER  2
                                    --------

                        TYPE 2 - LATERAL DRAINAGE LAYER
                          MATERIAL TEXTURE NUMBER   0
           THICKNESS                  =     40.00   CM
           POROSITY                   =      0.4800 VOL/VOL
           FIELD CAPACITY             =      0.1600 VOL/VOL
           WILTING POINT              =      0.0600 VOL/VOL
           INITIAL SOIL WATER CONTENT =      0.1500 VOL/VOL
           EFFECTIVE SAT. HYD. COND.  =  0.899999961000E-02 CM/SEC
           SLOPE                      =      4.00   PERCENT
           DRAINAGE LENGTH            =      1.2    METERS
```

```
                    LAYER  3
                    --------

          TYPE 3 - BARRIER SOIL LINER
          MATERIAL TEXTURE NUMBER   0
THICKNESS                  =     30.00   CM
POROSITY                   =       0.4500 VOL/VOL
FIELD CAPACITY             =       0.2500 VOL/VOL
WILTING POINT              =       0.1300 VOL/VOL
INITIAL SOIL WATER CONTENT =       0.4500 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.499999987000E-04 CM/SEC

                    LAYER  4
                    --------

       TYPE 1 - VERTICAL PERCOLATION LAYER
          MATERIAL TEXTURE NUMBER   0
THICKNESS                  =     20.00   CM
POROSITY                   =       0.4800 VOL/VOL
FIELD CAPACITY             =       0.1600 VOL/VOL
WILTING POINT              =       0.0600 VOL/VOL
INITIAL SOIL WATER CONTENT =       0.1500 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.115970001000E-01 CM/SEC

                    LAYER  5
                    --------

       TYPE 1 - VERTICAL PERCOLATION LAYER
          MATERIAL TEXTURE NUMBER   0
THICKNESS                  =    285.00   CM
POROSITY                   =       0.5500 VOL/VOL
FIELD CAPACITY             =       0.2000 VOL/VOL
WILTING POINT              =       0.0160 VOL/VOL
INITIAL SOIL WATER CONTENT =       0.0800 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.116999997000E-01 CM/SEC


                    LAYER  6
                    --------

         TYPE 2 - LATERAL DRAINAGE LAYER
          MATERIAL TEXTURE NUMBER  21
THICKNESS                  =     20.00   CM
POROSITY                   =       0.3970 VOL/VOL
FIELD CAPACITY             =       0.0320 VOL/VOL
WILTING POINT              =       0.0130 VOL/VOL
INITIAL SOIL WATER CONTENT =       0.0300 VOL/VOL
EFFECTIVE SAT. HYD. COND.  =  0.300000012000      CM/SEC
SLOPE                      =       4.00   PERCENT
DRAINAGE LENGTH            =       1.2    METERS
```

LAYER 7

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 36

THICKNESS	=	0.00 CM
POROSITY	=	0.0000 VOL/VOL
FIELD CAPACITY	=	0.0000 VOL/VOL
WILTING POINT	=	0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY	=	0.00 HOLES/HECTARE
FML INSTALLATION DEFECTS	=	0.00 HOLES/HECTARE
FML PLACEMENT QUALITY	=	4 - POOR

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE # 9 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 4.% AND A SLOPE LENGTH OF 4. METERS.

SCS RUNOFF CURVE NUMBER	=	93.00	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	0.0010	HECTARES
EVAPORATIVE ZONE DEPTH	=	10.0	CM
INITIAL WATER IN EVAPORATIVE ZONE	=	1.650	CM
UPPER LIMIT OF EVAPORATIVE STORAGE	=	4.800	CM
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.600	CM
INITIAL SNOW WATER	=	0.000	CM
INITIAL WATER IN LAYER MATERIALS	=	47.550	CM
TOTAL INITIAL WATER	=	47.550	CM
TOTAL SUBSURFACE INFLOW	=	0.00	MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Calgary Alberta

STATION LATITUDE	=	51.17	DEGREES
MAXIMUM LEAF AREA INDEX	=	1.00	
START OF GROWING SEASON (JULIAN DATE)	=	125	
END OF GROWING SEASON (JULIAN DATE)	=	278	
EVAPORATIVE ZONE DEPTH	=	10.0	CM
AVERAGE ANNUAL WIND SPEED	=	4.59	KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	64.23	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	76.95	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	68.11	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	68.01	%

NOTE: PRECIPITATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: TEMPERATURE DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: SOLAR RADIATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

****

MONTHLY TOTALS (MM) FOR YEAR 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION	12.5	1.5	1.5	8.0	1.0	33.0
	34.0	69.0	105.0	106.0	0.0	0.0
RUNOFF	2.36	0.00	0.04	0.00	0.00	0.12
	1.10	3.59	10.11	14.20	0.00	0.00
EVAPOTRANSPIRATION	2.69	1.50	0.09	15.37	1.70	8.82
	25.78	29.45	46.72	20.28	3.17	0.00
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.366	0.000	0.627
FROM LAYER 2	0.724	2.232	5.235	8.272	0.000	0.000
PERCOLATION/LEAKAGE	0.000	0.000	0.000	6.885	0.000	16.576
THROUGH LAYER 3	13.258	31.153	35.681	68.410	0.000	0.000
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.000	0.000	0.000
FROM LAYER 6	0.000	0.000	0.000	0.000	0.000	0.000
PERCOLATION/LEAKAGE THROUGH	0.000	0.000	0.000	0.000	0.000	0.000
LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000

MONTHLY SUMMARIES FOR DAILY HEADS (CM)

AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.004	0.000	0.016
TOP OF LAYER 3	0.013	0.041	0.062	0.101	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.021	0.000	0.040
HEAD ON TOP OF LAYER 3	0.065	0.110	0.174	0.240	0.000	0.000
AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.000	0.000	0.000
TOP OF LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.000	0.000	0.000
HEAD ON TOP OF LAYER 7	0.000	0.000	0.000	0.000	0.000	0.000

****

****

ANNUAL TOTALS FOR YEAR 1998

	MM	CU. METERS	PERCENT
PRECIPITATION	371.50	3.700	100.00
RUNOFF	31.514	0.315	8.52
EVAPOTRANSPIRATION	155.565	1.556	42.04
DRAINAGE COLLECTED FROM LAYER 2	17.4573	0.175	4.72
PERC./LEAKAGE THROUGH LAYER 3	171.963882	1.720	46.48
AVG. HEAD ON TOP OF LAYER 3	0.1976		
DRAINAGE COLLECTED FROM LAYER 6	0.0000	0.000	0.00
PERC./LEAKAGE THROUGH LAYER 7	0.000000	0.000	0.00
AVG. HEAD ON TOP OF LAYER 7	0.0000		
CHANGE IN WATER STORAGE	165.464	1.655	44.72
SOIL WATER AT START OF YEAR	481.499	4.815	
SOIL WATER AT END OF YEAR	646.963	6.470	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0001	0.000	0.00

****

****

AVERAGE MONTHLY VALUES (MM) FOR YEARS 1998 THROUGH 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	12.50	1.50	1.50	8.00	1.00	33.00
	34.00	69.00	105.00	106.00	0.00	0.00
STD. DEVIATIONS	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
RUNOFF						
TOTALS	2.362	0.000	0.040	0.000	0.000	0.119
	1.098	3.590	10.106	14.199	0.000	0.000

```
STD. DEVIATIONS          0.000     0.000     0.000     0.000     0.000     0.000
                         0.000     0.000     0.000     0.000     0.000     0.000

EVAPOTRANSPIRATION
------------------
TOTALS                   2.687     1.500     0.094    15.368     1.698     8.820
                        25.776    29.449    46.721    20.277     3.174     0.000

STD. DEVIATIONS          0.000     0.000     0.000     0.000     0.000     0.000
                         0.000     0.000     0.000     0.000     0.000     0.000

LATERAL DRAINAGE COLLECTED FROM LAYER  2
----------------------------------------
TOTALS                  0.0000    0.0000    0.0000    0.3662    0.0000    0.6273
                        0.7245    2.2318    5.2351    8.2724    0.0000    0.0000

STD. DEVIATIONS         0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

PERCOLATION/LEAKAGE THROUGH LAYER  3
------------------------------------
TOTALS                  0.0000    0.0000    0.0000    6.8855    0.0000   16.5761
                       13.2581   31.1527   35.6813   68.4103    0.0000    0.0000

STD. DEVIATIONS         0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

LATERAL DRAINAGE COLLECTED FROM LAYER  6
----------------------------------------
TOTALS                  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

STD. DEVIATIONS         0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

PERCOLATION/LEAKAGE THROUGH LAYER  7
------------------------------------
TOTALS                  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000

STD. DEVIATIONS         0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
--------------------------------------------------------------------------------
                  AVERAGES OF MONTHLY AVERAGED DAILY HEADS (CM)
--------------------------------------------------------------------------------
   DAILY AVERAGE HEAD ON TOP OF LAYER  3
   -------------------------------------
AVERAGES                0.0000    0.0000    0.0000    0.0038    0.0000    0.0157
                        0.0132    0.0412    0.0623    0.1009    0.0000    0.0000

STD. DEVIATIONS         0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                        0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
```

DAILY AVERAGE HEAD ON TOP OF LAYER 7

AVERAGES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1998 THROUGH 1998

	MM		CU. METERS	PERCENT
PRECIPITATION	371.50	(0.000)	3.7	100.00
RUNOFF	31.514	(0.0000)	0.32	8.517
EVAPOTRANSPIRATION	155.565	(0.0000)	1.56	42.044
LATERAL DRAINAGE COLLECTED FROM LAYER 2	17.45730	(0.00000)	0.175	4.71819
PERCOLATION/LEAKAGE THROUGH LAYER 3	171.96388	(0.00000)	1.720	46.47673
AVERAGE HEAD ON TOP OF LAYER 3	0.198	(0.000)		
LATERAL DRAINAGE COLLECTED FROM LAYER 6	0.00000	(0.00000)	0.000	0.00000
PERCOLATION/LEAKAGE THROUGH LAYER 7	0.00000	(0.00000)	0.000	0.00000
AVERAGE HEAD ON TOP OF LAYER 7	0.000	(0.000)		
CHANGE IN WATER STORAGE	165.464	(0.0000)	1.65	44.720

PEAK DAILY VALUES FOR YEARS 1998 THROUGH 1998

	(MM)	(CU. METERS)
PRECIPITATION	30.00	0.300
RUNOFF	8.380	0.0838
DRAINAGE COLLECTED FROM LAYER 2	3.88301	0.03883
PERCOLATION/LEAKAGE THROUGH LAYER 3	16.084158	0.16084
AVERAGE HEAD ON TOP OF LAYER 3	11.312	

MAXIMUM HEAD ON TOP OF LAYER 3	10.622	
LOCATION OF MAXIMUM HEAD IN LAYER 2 (DISTANCE FROM DRAIN)	0.3 METERS	
DRAINAGE COLLECTED FROM LAYER 6	0.00000	0.00000
PERCOLATION/LEAKAGE THROUGH LAYER 7	0.000000	0.00000
AVERAGE HEAD ON TOP OF LAYER 7	0.000	
MAXIMUM HEAD ON TOP OF LAYER 7	0.000	
LOCATION OF MAXIMUM HEAD IN LAYER 6 (DISTANCE FROM DRAIN)	0.0 METERS	
SNOW WATER	5.90	0.0590
MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.2834	
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0600	

*** Maximum heads are computed using McEnroe's equations. ***

Reference: Maximum Saturated Depth over Landfill Liner
by Bruce M. McEnroe, University of Kansas
ASCE Journal of Environmental Engineering
Vol. 119, No. 2, March 1993, pp. 262-270.

****

****

FINAL WATER STORAGE AT END OF YEAR 1998

LAYER	(CM)	(VOL/VOL)
1	0.6000	0.0600
2	6.3999	0.1600
3	13.5000	0.4500
4	2.9961	0.1498
5	40.0003	0.1404
6	0.6000	0.0300
7	0.0000	0.0000
SNOW WATER	0.000	

****

APPENDIX 5.4: HELP Model Output for Sensitivity Analysis for Waste Layer: Design Parameter Values

```
******************************************************************************
******************************************************************************

          HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
           HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)
             DEVELOPED BY ENVIRONMENTAL LABORATORY
                 USAE WATERWAYS EXPERIMENT STATION
          FOR USEPA RISK REDUCTION ENGINEERING LABORATORY

******************************************************************************
******************************************************************************
******************************************************************************
TITLE: HELP Model Simulations for the Waste Layer Design Parameter Values
******************************************************************************

      NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
               WERE SPECIFIED BY THE USER.


                              LAYER  1
                              --------

                  TYPE 1 - VERTICAL PERCOLATION LAYER
                     MATERIAL TEXTURE NUMBER   0
        THICKNESS                  =    285.00   CM
        POROSITY                   =      0.5500 VOL/VOL
        FIELD CAPACITY             =      0.2000 VOL/VOL
        WILTING POINT              =      0.0160 VOL/VOL
        INITIAL SOIL WATER CONTENT =      0.0800 VOL/VOL
        EFFECTIVE SAT. HYD. COND.  =  0.116999997000E-01 CM/SEC


                              LAYER  2
                              --------

                   TYPE 2 - LATERAL DRAINAGE LAYER
                     MATERIAL TEXTURE NUMBER  21
        THICKNESS                  =     20.00   CM
        POROSITY                   =      0.3970 VOL/VOL
        FIELD CAPACITY             =      0.0320 VOL/VOL
        WILTING POINT              =      0.0130 VOL/VOL
        INITIAL SOIL WATER CONTENT =      0.0300 VOL/VOL
        EFFECTIVE SAT. HYD. COND.  =  0.300000012000      CM/SEC
        SLOPE                      =      4.00   PERCENT
        DRAINAGE LENGTH            =      4.0    METERS
```

LAYER 3

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 36

THICKNESS	=	0.00 CM
POROSITY	=	0.0000 VOL/VOL
FIELD CAPACITY	=	0.0000 VOL/VOL
WILTING POINT	=	0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY	=	0.00 HOLES/HECTARE
FML INSTALLATION DEFECTS	=	0.00 HOLES/HECTARE
FML PLACEMENT QUALITY	=	4 - POOR

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE # 9 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 4.% AND A SLOPE LENGTH OF 4. METERS.

SCS RUNOFF CURVE NUMBER	=	93.00
FRACTION OF AREA ALLOWING RUNOFF	=	0.0 PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	0.0010 HECTARES
EVAPORATIVE ZONE DEPTH	=	1.0 CM
INITIAL WATER IN EVAPORATIVE ZONE	=	0.080 CM
UPPER LIMIT OF EVAPORATIVE STORAGE	=	0.550 CM
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.016 CM
INITIAL SNOW WATER	=	0.000 CM
INITIAL WATER IN LAYER MATERIALS	=	23.400 CM
TOTAL INITIAL WATER	=	23.400 CM
TOTAL SUBSURFACE INFLOW	=	0.00 MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Calgary Alberta

STATION LATITUDE	=	51.17 DEGREES
MAXIMUM LEAF AREA INDEX	=	0.00
START OF GROWING SEASON (JULIAN DATE)	=	125
END OF GROWING SEASON (JULIAN DATE)	=	278
EVAPORATIVE ZONE DEPTH	=	1.0 CM
AVERAGE ANNUAL WIND SPEED	=	4.93 KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	90.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	90.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	90.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	90.00 %

NOTE: PRECIPITATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: TEMPERATURE DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: SOLAR RADIATION DATA FOR Calgary Alberta
WAS ENTERED BY THE USER.

MONTHLY TOTALS (MM) FOR YEAR 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION	0.0	0.0	0.0	0.0	0.0	0.0
	300.6	0.0	0.0	0.0	0.0	0.0
RUNOFF	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
EVAPOTRANSPIRATION	0.64	0.00	0.00	0.00	0.00	0.00
	2.64	0.29	0.00	0.00	0.00	0.00
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.000	0.000	0.000
FROM LAYER 2	10.894	27.379	0.000	0.000	0.000	0.000
PERCOLATION/LEAKAGE	0.000	0.000	0.000	0.000	0.000	0.000
THROUGH LAYER 3	0.001	0.002	0.000	0.000	0.000	0.000

MONTHLY SUMMARIES FOR DAILY HEADS (CM)

AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.000	0.000	0.000
TOP OF LAYER 3	0.008	0.020	0.000	0.000	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.000	0.000	0.000
HEAD ON TOP OF LAYER 3	0.043	0.107	0.000	0.000	0.000	0.000

ANNUAL TOTALS FOR YEAR 1998

	MM	CU. METERS	PERCENT
PRECIPITATION	300.60	3.006	100.00
RUNOFF	0.000	0.000	0.00
EVAPOTRANSPIRATION	3.570	0.036	1.19
DRAINAGE COLLECTED FROM LAYER 2	38.2728	0.383	12.73
PERC./LEAKAGE THROUGH LAYER 3	0.002556	0.000	0.00

AVG. HEAD ON TOP OF LAYER 3	0.0235		
CHANGE IN WATER STORAGE	258.755	2.588	86.08
SOIL WATER AT START OF YEAR	240.000	2.400	
SOIL WATER AT END OF YEAR	498.754	4.988	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0000	0.000	0.00

****
****

AVERAGE MONTHLY VALUES (MM) FOR YEARS 1998 THROUGH 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	0.00	0.00	0.00	0.00	0.00	0.00
	300.60	0.00	0.00	0.00	0.00	0.00
STD. DEVIATIONS	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
RUNOFF						
TOTALS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000
EVAPOTRANSPIRATION						
TOTALS	0.640	0.000	0.000	0.000	0.000	0.000
	2.639	0.291	0.000	0.000	0.000	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000
LATERAL DRAINAGE COLLECTED FROM LAYER 2						
TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	10.8942	27.3786	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

PERCOLATION/LEAKAGE THROUGH LAYER 3

TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0007	0.0018	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (CM)

DAILY AVERAGE HEAD ON TOP OF LAYER 3

AVERAGES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0080	0.0202	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1998 THROUGH 1998

	MM		CU. METERS	PERCENT
PRECIPITATION	300.60	(0.000)	3.0	100.00
RUNOFF	0.000	(0.0000)	0.00	0.000
EVAPOTRANSPIRATION	3.570	(0.0000)	0.04	1.188
LATERAL DRAINAGE COLLECTED FROM LAYER 2	38.27282	(0.00000)	0.383	12.73214
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.00256	(0.00000)	0.000	0.00085
AVERAGE HEAD ON TOP OF LAYER 3	0.023	(0.000)		
CHANGE IN WATER STORAGE	258.755	(0.0000)	2.59	86.079

PEAK DAILY VALUES FOR YEARS 1998 THROUGH 1998

	(MM)	(CU. METERS)
PRECIPITATION	123.70	1.237
RUNOFF	0.000	0.0000
DRAINAGE COLLECTED FROM LAYER 2	26.19035	0.26190
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.001749	0.00002
AVERAGE HEAD ON TOP OF LAYER 3	5.980	

MAXIMUM HEAD ON TOP OF LAYER 3	8.840	
LOCATION OF MAXIMUM HEAD IN LAYER 2 (DISTANCE FROM DRAIN)	0.5 METERS	
SNOW WATER	0.00	0.0000
MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.2933	
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0160	

*** Maximum heads are computed using McEnroe's equations. ***

Reference: Maximum Saturated Depth over Landfill Liner
by Bruce M. McEnroe, University of Kansas
ASCE Journal of Environmental Engineering
Vol. 119, No. 2, March 1993, pp. 262-270.

****

FINAL WATER STORAGE AT END OF YEAR 1998

LAYER	(CM)	(VOL/VOL)
1	48.6354	0.1707
2	0.6400	0.0320
3	0.0000	0.0000
SNOW WATER	0.000	

****

APPENDIX 5.5: HELP Model Output for Sensitivity Analysis for Waste Layer: Design Parameter Values - 25% Field Capacity

```
******************************************************************************
            HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE
             HELP MODEL VERSION 3.07   (1 NOVEMBER 1997)
               DEVELOPED BY ENVIRONMENTAL LABORATORY
                 USAE WATERWAYS EXPERIMENT STATION
            FOR USEPA RISK REDUCTION ENGINEERING LABORATORY

******************************************************************************
******************************************************************************
******************************************************************************
   TITLE:  HELP Model Simulations for the Waste Layer for Design
            Parameter Values with -25% Field Capacity
******************************************************************************

    NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER
            WERE SPECIFIED BY THE USER.


                              LAYER  1
                              --------
                 TYPE 1 - VERTICAL PERCOLATION LAYER
                     MATERIAL TEXTURE NUMBER   0
      THICKNESS                  =    285.00   CM
      POROSITY                   =      0.5500 VOL/VOL
      FIELD CAPACITY             =      0.1500 VOL/VOL
      WILTING POINT              =      0.0160 VOL/VOL
      INITIAL SOIL WATER CONTENT =      0.0800 VOL/VOL
      EFFECTIVE SAT. HYD. COND.  =  0.116999997000E-01 CM/SEC


                              LAYER  2
                              --------

                   TYPE 2 - LATERAL DRAINAGE LAYER
                     MATERIAL TEXTURE NUMBER  21
      THICKNESS                  =     20.00   CM
      POROSITY                   =      0.3970 VOL/VOL
      FIELD CAPACITY             =      0.0320 VOL/VOL
      WILTING POINT              =      0.0130 VOL/VOL
      INITIAL SOIL WATER CONTENT =      0.0300 VOL/VOL
      EFFECTIVE SAT. HYD. COND.  =  0.300000012000      CM/SEC
      SLOPE                      =      4.00   PERCENT
      DRAINAGE LENGTH            =      4.0    METERS
```

LAYER 3

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 36

THICKNESS	=	0.00 CM
POROSITY	=	0.0000 VOL/VOL
FIELD CAPACITY	=	0.0000 VOL/VOL
WILTING POINT	=	0.0000 VOL/VOL
INITIAL SOIL WATER CONTENT	=	0.0000 VOL/VOL
EFFECTIVE SAT. HYD. COND.	=	0.399999993000E-12 CM/SEC
FML PINHOLE DENSITY	=	0.00 HOLES/HECTARE
FML INSTALLATION DEFECTS	=	0.00 HOLES/HECTARE
FML PLACEMENT QUALITY	=	4 - POOR

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE # 9 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 4.% AND A SLOPE LENGTH OF 4. METERS.

SCS RUNOFF CURVE NUMBER	=	93.00
FRACTION OF AREA ALLOWING RUNOFF	=	0.0 PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	0.0010 HECTARES
EVAPORATIVE ZONE DEPTH	=	1.0 CM
INITIAL WATER IN EVAPORATIVE ZONE	=	0.080 CM
UPPER LIMIT OF EVAPORATIVE STORAGE	=	0.550 CM
LOWER LIMIT OF EVAPORATIVE STORAGE	=	0.016 CM
INITIAL SNOW WATER	=	0.000 CM
INITIAL WATER IN LAYER MATERIALS	=	23.400 CM
TOTAL INITIAL WATER	=	23.400 CM
TOTAL SUBSURFACE INFLOW	=	0.00 MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
Calgary Alberta

STATION LATITUDE	=	51.17 DEGREES
MAXIMUM LEAF AREA INDEX	=	0.00
START OF GROWING SEASON (JULIAN DATE)	=	125
END OF GROWING SEASON (JULIAN DATE)	=	278
EVAPORATIVE ZONE DEPTH	=	1.0 CM
AVERAGE ANNUAL WIND SPEED	=	4.93 KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	90.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	90.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	90.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	90.00 %

NOTE: PRECIPITATION DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: TEMPERATURE DATA FOR CALGARY ALBERTA
WAS ENTERED FROM AN ASCII DATA FILE.

NOTE: SOLAR RADIATION DATA FOR Calgary Alberta
WAS ENTERED BY THE USER.

****

MONTHLY TOTALS (MM) FOR YEAR 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION	0.0	0.0	0.0	0.0	0.0	0.0
	300.6	0.0	0.0	0.0	0.0	0.0
RUNOFF	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
EVAPOTRANSPIRATION	0.64	0.00	0.00	0.00	0.00	0.00
	2.82	0.24	0.00	0.00	0.00	0.00
LATERAL DRAINAGE COLLECTED	0.000	0.000	0.000	0.000	0.000	0.000
FROM LAYER 2	60.695	37.641	0.000	0.000	0.000	0.000
PERCOLATION/LEAKAGE	0.000	0.000	0.000	0.000	0.000	0.000
THROUGH LAYER 3	0.004	0.003	0.000	0.000	0.000	0.000

MONTHLY SUMMARIES FOR DAILY HEADS (CM)

AVERAGE DAILY HEAD ON	0.000	0.000	0.000	0.000	0.000	0.000
TOP OF LAYER 3	0.038	0.024	0.000	0.000	0.000	0.000
STD. DEVIATION OF DAILY	0.000	0.000	0.000	0.000	0.000	0.000
HEAD ON TOP OF LAYER 3	0.090	0.090	0.000	0.000	0.000	0.000

****
****

ANNUAL TOTALS FOR YEAR 1998

	MM	CU. METERS	PERCENT
PRECIPITATION	300.60	3.006	100.00
RUNOFF	0.000	0.000	0.00
EVAPOTRANSPIRATION	3.697	0.037	1.23
DRAINAGE COLLECTED FROM LAYER 2	98.3363	0.983	32.71

PERC./LEAKAGE THROUGH LAYER 3	0.006567	0.000	0.00
AVG. HEAD ON TOP OF LAYER 3	0.0515		
CHANGE IN WATER STORAGE	198.560	1.986	66.05
SOIL WATER AT START OF YEAR	240.000	2.400	
SOIL WATER AT END OF YEAR	438.559	4.386	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0000	0.000	0.00

AVERAGE MONTHLY VALUES (MM) FOR YEARS 1998 THROUGH 1998

	JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
PRECIPITATION						
TOTALS	0.00	0.00	0.00	0.00	0.00	0.00
	300.60	0.00	0.00	0.00	0.00	0.00
STD. DEVIATIONS	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00
RUNOFF						
TOTALS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000
EVAPOTRANSPIRATION						
TOTALS	0.640	0.000	0.000	0.000	0.000	0.000
	2.820	0.237	0.000	0.000	0.000	0.000
STD. DEVIATIONS	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000
LATERAL DRAINAGE COLLECTED FROM LAYER 2						
TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	60.6954	37.6409	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

PERCOLATION/LEAKAGE THROUGH LAYER 3

TOTALS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0041	0.0025	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

AVERAGES OF MONTHLY AVERAGED DAILY HEADS (CM)

DAILY AVERAGE HEAD ON TOP OF LAYER 3

AVERAGES	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0383	0.0235	0.0000	0.0000	0.0000	0.0000
STD. DEVIATIONS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

****
****

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1998 THROUGH 1998

	MM		CU. METERS	PERCENT
PRECIPITATION	300.60	(0.000)	3.0	100.00
RUNOFF	0.000	(0.0000)	0.00	0.000
EVAPOTRANSPIRATION	3.697	(0.0000)	0.04	1.230
LATERAL DRAINAGE COLLECTED FROM LAYER 2	98.33630	(0.00000)	0.983	32.71334
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.00657	(0.00000)	0.000	0.00218
AVERAGE HEAD ON TOP OF LAYER 3	0.052	(0.000)		
CHANGE IN WATER STORAGE	198.560	(0.0000)	1.99	66.054

****

****

PEAK DAILY VALUES FOR YEARS 1998 THROUGH 1998

	(MM)	(CU. METERS)
PRECIPITATION	123.70	1.237
RUNOFF	0.000	0.0000
DRAINAGE COLLECTED FROM LAYER 2	24.67901	0.24679
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.001648	0.00002
AVERAGE HEAD ON TOP OF LAYER 3	4.769	
MAXIMUM HEAD ON TOP OF LAYER 3	8.372	
LOCATION OF MAXIMUM HEAD IN LAYER 2 (DISTANCE FROM DRAIN)	0.5 METERS	
SNOW WATER	0.00	0.0000
MAXIMUM VEG. SOIL WATER (VOL/VOL)	0.2933	
MINIMUM VEG. SOIL WATER (VOL/VOL)	0.0160	

*** Maximum heads are computed using McEnroe's equations. ***

Reference: Maximum Saturated Depth over Landfill Liner
by Bruce M. McEnroe, University of Kansas
ASCE Journal of Environmental Engineering
Vol. 119, No. 2, March 1993, pp. 262-270.

****

FINAL WATER STORAGE AT END OF YEAR 1998

LAYER	(CM)	(VOL/VOL)
1	42.6159	0.1495
2	0.6400	0.0320
3	0.0000	0.0000
SNOW WATER	0.000	

****

****