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Infiltration Rates Through Landfill Liners

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List of Abbreviations

AMC	Antecedent Moisture Condition
BPNL	Battelle, Pacific Northwest Laboratories
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFR	Code of Federal Registry
cm	Centimeters
CN	Curve Number
CO	Epichlorohydrin Rubber
CPE	Chlorinated Polyethylene
CPE-A	Chlorinated Polyethylene-Alloy
CR	Ethylene-Propylene Polychloroprene
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
CSPE	Chlorosulfonated Polyethylene
d	Day
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EIA	Ethylene Interpolymer Alloy
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ET	Evapotranspiration
F.A.C.	Florida Administrative Code
FDEP	Florida Department Environmental Protection
FILL	The Flow Investigation for Landfill Leachate
FML	Flexible Membrane Liner
ft	Feet
GPH	Gallons Per Hour
GPM	Gallons Per Minute
GSA	General Services Administration
HC	Hydraulic Conductivity
HDPE	High-Density Polyethylene
HDPE-A	High Density Polyethylene-Alloy
HELP	Hydrologic Evaluation of Landfill Performance
HEW	Health, Education, and Welfare
hr	Hour
HSSWDS	Hydrologic Simulation on Solid Waste Disposal Sites
I	Infiltration
ID	Storm Intensity
IIR	Isobutylene Rubber
in	Inches
kg	Kilogram

List of Abbreviations

l	Liter
lpm	Liter Per Minute
L	Leakage
LAI	Leaf Area Index
LDPE	Low Density Polyethylene
LLDPE	Linear Low Density Polyethylene
m	Meter
mm	Millimeters
MILL	Model Investigation of Landfill Leachate
min	Minute
MSW	Municipal Solid Waste
NEPA	National Environment Policy Act
NITS	National Technical Information Service
NPL	National Priority List
P	Precipitation
PL	Public Law
PNL	Pacific Northwest Laboratories
PSI	Pounds Per Square Inch
PVC	Polyvinyl Chloride
PVC-OR	Oil Resistant Polyvinyl Chloride
R	Runoff
RCRA	Resource Conservation and Recovery Act
S	Slope
SCS	Soil Conservation Service
s	Seconds
SWRRB	Simulator for Water Resource in Rural Basins
T-EPDM	Thermoplastic Ethylene-Proylene Diene Monomer
TN-PVC	Thermoplastic Nitride Polyvinyl Chloride
TOT	Time of Travel
TR-55	Technical Release 55
UNSAT1D	Unsaturated Groundwater Flow Model
UNSAT-H	Unsaturated Soil Water and Heat Flow Model, Version 2
U.S.	United States
USC	Unified Soil Classification System
USF	University of South Florida
USDA	United States Department of Agriculture
vol	Volume
%	Percent
□ S	Soil Moisture Storage

Key Words

Municipal Solid Waste
Landfill
Runoff
Infiltration
Leakage
Regression Modeling

Abstract

Predictive modeling involved with landfills requires an understanding of moisture movement through final surface covers. An experimental study was undertaken to evaluate the runoff, infiltration, and leakage through a final surface cover liner system with a geomembrane and present predictive models The project's objectives included: assessment of applications of current liner technology and regulations, presentation of existing landfill flow models, identification of surface cover and geomembrane leakage mechanisms, presentation of results of experimental testing of a landfill topliner system, development of mathematical models tailored to landfill final cover applications, and statistical evaluation of the models with the experimental data.

A total of 61 experimental runs were run from February to June 1997. The infiltration and leakage parameters were monitored although the primary interest was to evaluate the runoff. The objective of this experiment was to measure the moisture movement through the final cover system when the liner is at field capacity. The average mass water balance for the experimental simulations ranged from 93.3% to 96.7%. The experimental data was converted from a mass parameter to flux values, gallons per minute-acre, for a more descriptive output. Modeling the runoff flux was the principal result of the evaluation. The analysis used storm intensity, slope, and hydraulic conductivity parameters to predict the runoff flux values. A linear relationship was clearly seen from the experimental data. The correlation coefficients for the two runoff models are .983 and .984, respectively, indicating an excellent data fit. A geomembrane leakage trend is apparent from the data analysis; as the slope increases the average leakage flux decrease.

The experimental runoff flux data was compared with default runoff predictions from the Hydrologic Evaluation of Landfill Performance (HELP) model. The HELP model tends to underpredict runoff for all simulations run on the experimental cell, which ultimately results in an overprediction of infiltration. Underprediction of the runoff flux ranged from 8% to 24% for the simulations. The HELP model runoff flux output is highly dependent on the soils hydraulic conductivity and moisture storage capacity. Predictions made with the HELP model are not necessarily accurate, even when the input parameters have a high degree of precision.

Executive Summary

Landfilling has been the most economical and environmentally accepted method of solid waste disposal in the United States (US) and in the world. Implementation of waste reduction, recycling, and transformation technologies has decreased landfill burdens, but landfills remain an important component of an integrated solid waste management strategy. A good final cover system should be designed to reduce infiltration and ultimate leachate generation. Reduction of infiltration in a landfill is achieved through surface drainage and runoff with minimal erosion, transpiration, and restriction of percolation.

With the implementation of the Resource Conservation and Recovery Act (RCRA) 40 CFR Part 258 or 'Subtitle D' regulations, maintenance, design, and final closure of landfills changed. The regulations require the final cover be equal or better than the bottom liner system. This regulation has propelled synthetic materials to the forefront of liner systems.

Presently, the means to combat leachate migration to the surrounding subsurface and ground water is to have an impermeable geomembrane liner encompassing the landfill. A liner system using geomembrane material typically encloses the solid waste matrix in a single or double geomembrane liner. Geomembranes are engineered polymeric materials produced to be virtually impermeable. Studies have shown that high-density polyethylene (HDPE) is the material of choice for a wide range of wastes typically encountered in landfill disposal facilities. Most double liner systems installed to date have developed a loss of integrity and are expected to produce some leakage through the liner material. Consequently, liner systems have been designed to counteract the inability to construct a perfect liner. The objective is to design a combination of various liner components into a liner system that will reduce the leakage rate into and from landfills.

Regulations require that post-closure care be conducted for 30 years or for a period approved by the state if the owner can demonstrate the reduced period is sufficient. Leachate treatment and disposal are an inherent part of post-closure care. Currently, several models are used to predict moisture movement at solid waste disposal sites. A common deficiency in research on liner mechanisms has been the focus on the evaluation of the bottom liners. As a result, there may be a lack of pertinent data on the final surface cover liner systems and how percolation is affected by liner types. Most of the existing models have not been specifically designed to project infiltration of the caps and sideslopes of landfills, and most lack sufficient experimental field data to support them.

This project advances the methods for determining runoff and infiltration rates generated through final surface cover systems at landfills. The results of this project have led to a better projection of runoff and infiltration through final cover systems at landfills with synthetic liner systems. The project's objectives included:

- Assessment of applications of current liner technology and regulations;
- Presentation of existing landfill flow models;
- Identification of surface cover and geomembrane leakage mechanisms;
- Presentation of results of experimental testing of a landfill topliner system;
- Development of mathematical models tailored to landfill final cover applications;
- Statistical evaluation of the mathematical models with experimental data.

Landfill literature has shown many landfill failures are attributed to insufficient surface barriers. Even in arid regions, over time, buried waste is vulnerable to transport via rainwater percolation, gas diffusion, erosion, and intrusion by plant roots, burring animals, and humans. Standard models and field tests of engineering covers designed to impede these pathways implicitly and erroneously assume that surface barrier technology is well developed and works as expected.

Landfill liner systems consist of a top and bottom liner. The top liner is designed to prevent or reduce the migration of precipitation into the waste. The bottom liner is designed to collect and remove leachate that may make its way through the system. Generally, bottom liners consist of a leachate collection system and liner. Leachate collected is drained from the liner to reduce fluid pressure on the liner. Many research efforts have been devoted to predicting landfill moisture flow. Several methods and computer models have been developed to deal with the unique conditions of a landfill. These numeric models fall into the general categories of deterministic water balance methods and finite-difference methods. Landfill flow modeling consists of predicting the runoff, infiltration, and leakage rate of a system.

The water balance methods are based on procedures developed by C.W. Thorthwaite in the soil and water conservation field. Since his work many research efforts have developed the water balance equations in the last 40 years. These qualitative water balance models consider the landfill a "black box," requiring a material balance of water flow into and out of the system. The water balance models have been used extensively in predicting leachate quantity and aiding design of landfills.

The most widely used predictive water balance landfill infiltration model is the Hydrologic Evaluation of Landfill Performance (HELP) model. HELP is a quasi-two-dimensional, deterministic water balance model that estimates daily water movement through landfills. Water migrating through landfill barrier layers may stress liner systems and possibly lead to a breach. Although HELP is used extensively by regulatory agencies there are few verifications or investigations of the predictive abilities of the model. HELP estimates runoff, infiltration, evapotranspiration, drainage, leachate collection, and liner leakage. The HELP model has been shown to provide reasonable predictions of infiltration of moisture movement through landfills. However, the model's theoretically based algorithms and limited verification studies present several limitations: the Soil Conservation Service (SCS) equations with the HELP infiltration approach may carry the method beyond the data on which it was based and produce erroneous results, the dominant flow mechanism is assumed to be porous media flow, where the lateral moisture movement is only allowed in drainage layers, and the effects of alternative slopes an sideslopes cannot be modeled.

Surface water infiltration is perhaps the largest contributing factor of leachate production in sanitary landfills. It may directly affect moisture content of the landfill system. Runoff begins when the rainfall intensity exceeds the infiltration capacity of the soil matrix. Factors affecting surface runoff are surface topography, cover material, vegetation, permeability, moisture condition, and precipitation. The SCS method can be summarized as a relationship of soil depth and runoff depth. Many factors influence infiltration including rainfall patterns, initial soil moisture, tillage practice, physical soil properties, and influences of vegetation roots and stems. Factors that influence overland flow attenuation include surface roughness, storage, slope, size of watershed, and rate of precipitation.

The principal application of the SCS method is estimating runoff in flood hydrographs. Rainfall data used in the development generally is from ungauged watersheds. The relationship excludes time as a variable. Runoff amounts for specific time increments of a storm may be estimated. The method was intended as a design procedure for SCS personnel in evaluating watershed response for SCS projects, and it has since been adopted for use by various government agencies including the Environmental Protection Agency.

Currently, geomembranes are a widely used material in final surface cover design. Many factors contribute to leakage, including the geometry, configuration, and cross-sections of the landfill. The primary mechanisms of leakage through landfill geomembrane liners are fluid permeation through the undamaged geomembrane cover, and fluid flow through geomembrane defects and holes. Leakage through a geomembrane hole is primarily dependent on three factors: (1) area of hole; (2) hydraulic conductivity of layer above and/or below the geomembrane, and (3) liquid head over the liner. Even with the best quality control during installation of geomembrane liners one can expect 1 to 2 defects per acre (3 to 5 defects per hectare).

The ability of a final cover system to prevent infiltration into underlying material is largely determined by the effectiveness of the final cover system. The surface layer is the upper soil layer that intercepts rainfall and removes a segment as surface runoff. Part of the rainfall that infiltrates the upper soil layer then penetrates the infiltration layer. A large part of the water that migrates from the upper soil layer is expected to drain by gravity, moving along the geomembrane to a drainage collection point. Finally, some amount of the water will flow through the geomembrane liner as leakage, but this will be much less than runoff and infiltration.

An experimental cell was designed to simulate a landfill cover for a variety of short-term high-intensity storm events. The cell consisted of a base structure built of pressure-treated wood, a geomembrane liner system, a simulated rainfall system, soil cover material, and recording devices. The cell was built approximately eight feet (2.44 m) in length, two feet (0.61 m) in width, and three feet (0.92 m) in height. The liner system was designed to simulate a final cover system constructed with 60-mil high density polyethylene geomembrane that complies with the State of Florida landfill design standards. A total of 61 experimental runs were made from February to June 1997. The infiltration and leakage parameters were monitored, although the primary interest was to evaluate the runoff. The experimental results are presented as follows: water mass balance across the experimental apparatus;

factorial analysis of the main effects and interactions of the principal variables; statistical modeling of the system using regression analysis; and comparison of data to the HELP model.

The water balance of the landfill cover may be segregated into six components: precipitation (P), runoff (R), infiltration (I), evapotranspiration (ET), soil moisture storage (ΔS), and Leakage (L). These parameters must be properly estimated to balance the water in the cover system. The water balance methods are used to perform a mass balance on the experimental system. These parameters were addressed in the experiment as follows: precipitation is known, runoff, infiltration, and leakage was collected and measured, evapotranspiration is insignificant due to the short duration of the storm event, and soil moisture storage is known by using a soil matrix at field capacity.

As was noted from the literature review of landfill surface runoff modeling, predicting short-duration, high-intensity storm events needed a more thorough assessment. A 30-minute duration storm event was developed to assess runoff in storm simulations. The time increment is extensive enough to produce runoff, infiltration, and leakage with the exposed soil at field capacity moisture content. The primary parameters chosen for evaluation were landfill slope, storm intensity, and hydraulic conductivity of the soil matrix. An experimental statistical factorial design was developed to evaluate these parameters and potential interactions.

Factorial designs facilitate the evaluation of the interactions of variables and thus assist the process of model building. These experimental designs provide estimates of the "effects" of the interactions, while assuring that such interactions are not experimental errors. In statistical factorial designs, high and low values of the parameters maybe used to set up a matrix. In this experiment the storm events were a 2-year frequency event and a 10-year event, slopes were evaluated at 2%, 5%, and 10%, and the hydraulic conductivity of the upper soil layers used were 6.5×10^{-5} inch/sec (1.6×10^{-4} cm/s) and 7.5×10^{-6} inch/sec (1.9×10^{-5} cm/s). Simulations were performed on all combinations of the primary variables.

The purpose of the factorial design matrix was to statistically test as many parameters as possible simultaneously. A matrix was used to analyze the runoff data using Yates algorithm calculations. The high estimates of the effects storm intensity and hydraulic conductivity indicated they are the major factors affecting the system and, since the interaction between the two was low, were acting independently of each other. The slope parameter appears to have minimal affect on the runoff flux. Consequently, it was concluded that the main independent variables that affect runoff are storm intensity and soil hydraulic conductivity, whereas the slope of the soil surface was not a significant factor within the range of 2% to 10%.

The average mass balance for the experimental final cover system ranged from 93.3% to 96.7%. The low standard deviations for average runoff flux and the high closure rate indicated good reliability of the data. The experimental data was converted from a mass parameter to flux values, gallons per minute-acre, for a more descriptive output. Modeling the runoff was the principal concern and used storm intensity, slope, and hydraulic conductivity to predict runoff flux values. A linear relationship was clearly seen from the experimental data. The correlation coefficients for the two runoff models are .983 and .984, respectively, indicating and excellent data fit. Storm intensity and hydraulic conductivity clearly have a good linear fit, but the slope parameter obviously has no significant impact. The hydraulic conductivity evaluation may be limited due to the constricted range of this variable (2 levels) in this study. Although two soil hydraulic conductivities were explored in the study, the second soil matrix was possibly too impermeable to provide reliable data. Two leakage models were presented: a 3-variable model and a 2-variable model. Data trends for the leakage models were difficult to predict due to the second soil profile producing minimal leakage, which effectively gave only two parameters to evaluate. A leakage trend appears to exit; as the slope increased the leakage flux decreased.

The results of this study serve to identify an alternative approach to predicting surface runoff from closed landfills. Consequently, the design of surface runoff collection/storage requirements can be more simply projected within the range of the variables evaluated in this study. Generally, the scenario for such predictions is encompassed in the experiments and the resultant regression model's have been developed. Further, the experimental results confirm previous evaluations of the HELP models underprediction of surface runoff from landfills. It is also significant that the experimental results demonstrated that, at a surface slope of 10%, the effects of leachate leakage through holes in the underlying surface geomembrane liner are minimized. Obviously, such a slope mitigates the creation of sufficient static head in the soil above the liner to facilitate leachate through the geomembrane liner. These results may also be translated into the effects of slope on the bottom liner leakage rates in landfills (i.e., a slope of 10% on the bottom liner may inhibit leakage in the bottom liner system).

The experimental runoff flux data was compared with default runoff predictions from the HELP model. The HELP model tends to underpredict runoff for all simulations run on the experimental cell, which ultimately results in an overprediction of infiltration. Underprediction of the runoff flux ranged from 8% to 24% for the simulations. The HELP model runoff flux output is highly dependent on the soils hydraulic conductivity and moisture storage capacity. Prediction made with the HELP model are not necessarily accurate, even when the input parameters have a high degree of precision.

Follow-up research should be performed using other ranges of the parameters selected for this study. This is especially significant for additional soil material with a broad range of hydraulic conductivity, which would enhance the leakage models. A single or a set of regression models should be developed specifically designed for landfill use. Further, based on the literature review, capillary barriers need to be evaluated for their ability to impede infiltration. Reduction of leakage with these capillary systems may be possible, but current experimental field data is not sufficient to substantiate.

1. INTRODUCTION

Landfilling has been the most economical and environmentally accepted method of solid waste disposal in the U.S. and in the world (Tchobanoglous et al., 1993). Implementation of waste reduction, recycling, and transformation technologies has decreased landfill burdens but landfills remain an important component of an integrated solid waste management strategy. In Florida, an estimated 69% of municipal solid waste (MSW) generated is landfilled (Murphy and Batiste, 1991). Leachate produced in these landfills are the result of moisture acting as a solvent seeping through the landfill cells and enhancing solid waste decomposition. Depending on the type of material deposited in the landfill, this leachate may be considered contaminated. A good final cover system should be designed to reduce infiltration and ultimate leachate generation.

Generally the best approach to impede leachate generation is the use of an impermeable geosynthetic in the final surface cover. The purposes of final cover systems in landfills are to reduce the infiltration of water from precipitation, limit the uncontrollable release of landfill gasses, reduce the proliferation of vectors, reduce potential fires, provide surface revegetation, and serve as a primary element in reclamation of the site (Tchobanoglous et al., 1993) Reduction of infiltration in a landfill is achieved through surface drainage and runoff with minimal erosion, transpiration, and restriction of percolation (EPA, 1992).

With the implementation of the Resource Conservation and Recovery Act (RCRA) 40 CFR Part 258 or 'Subtitle D' regulations in 1993, maintenance, design, and final closure of landfills changed. No longer was it acceptable to merely put MSW in a large excavation. The regulations require the final cover be equal or better than the bottom liner system. This regulation has propelled synthetic materials to the forefront of liner systems. Specifically, the post-closure criteria require a maintenance and monitor period of 30 years and give guidelines for hydraulic barrier layers, vegetative layers, and hydrologic surface conditions. These liner systems need to be evaluated for the long term risk of infiltration.

Presently, the means to combat leachate migration to the surrounding subsurface and ground water is to have an impermeable geomembrane liner encompassing the landfill. A liner system using geomembrane material typically, a single or double geomembrane liner, encloses the solid waste matrix. Geomembranes are engineered polymeric materials produced to be nearly impermeable. Studies have shown that high-density polyethylene (HDPE) is the material of choice for a wide range of wastes encountered in landfill disposal facilities (LaGrega et al., 1994). Most double liner systems installed to date have developed a loss of integrity. This is verified with the detection of leachate in the secondary leakage detection liner system. A study by Southeast Research Institute on 28 geomembrane-lined storage facilities showed only two liner systems had no leaks. An average of 26.2 leaks per 10,000 square meters was reported (Murphy and Borgmeyer, 1992).

Current knowledge concedes that the absolute leak-proof liner is improbable to accomplish. Accordingly, systems have been designed to compensate for the failure to produce an impermeable liner system. The objective is to design a liner system with a combination of various components that reduce the leakage rate into and from landfills (Tedder, 1992). The leakage rate may be a result of imperfect seaming, rips, punctures during installation, and failures that result from soil failures after installation. The U.S. Office of Technical Assessment reported the three most common geomembrane liner failures are deficient seam welds, deformation due to poor liner subbase, and tears and punctures often caused by vehicles (Jayawickrama et al., 1988).

Whatever the cause, liners leak and require management. The cost of leachate management is estimated at $1.36/ton-year of the landfilled waste (Murphy and Batiste, 1991) and is incurred for the post-closure period and possibly longer. There is a potential for continual leachate generation in landfills. Cost and methods of treatment alternatives vary depending on quality and quantities of the leachate. It is important that leachate generation rates are correctly determined to design and project the cost of the treatment system.

Regulations require that post-closure care be conducted for 30 years or for a period approved by the state if the owner can demonstrate the reduced period is sufficient (EPA, 1992). Leachate treatment and disposal are an inherent part of post-closure care. Currently, several models are used to predict quantity of leachate generation at solid waste disposal sites as a function of water infiltration and number of cells. Perhaps the best known is the water balance model, Hydrologic Evaluation of Landfill Performance (HELP) (Schroeder et al., 1984a, 1984b). HELP was intended as a tool for designing new landfills, but is also used in estimating leachate generation. The HELP model may be limited in the application. For example, HELP may yield a zero result when given a proper mix of landfill surface layers and their characteristics (Nixon, 1995). As noted earlier, this ideal result is not attainable in actual construction. To date, surface water hydrologic models and models designed to determine leakage from the bottom liner have been used to calculate infiltration into the top liner.

A common deficiency in research on liner mechanisms has been the focus on the evaluation of the bottom liners. As a result, there may be a lack of pertinent data on the final surface cover liner systems and how percolation is affected by liner types. Most of the existing models have not been specifically designed to project infiltration of the caps and sideslopes of landfills, and most lack sufficient experimental field data to support them.

This project advances the methods for determining runoff and infiltration rates generated through final cover systems at landfills. The study at the University of South Florida (USF) included:

- Assessment of applications of current liner technology and regulations;
- Evaluation of existing landfill flow models;
- Identification of surface cover and geomembrane leakage mechanisms;
- Presentation of results of experimental testing of a landfill topliner pilot scale system;
- Development of experimental mathematical models specifically tailored to landfill final cover applications;
- Statistical evaluation of the mathematical models with experimental data.

The results of this project may lead to a better predictions of runoff, infiltration, and leakage flux through caps and side slopes of landfills with synthetic liner systems.

2. LANDFILL LINER REGULATIONS AND REQUIREMENTS

The solid waste burden on landfills will continue for years to come. Although legislation has been enacted to direct a good portion of solid waste to recycling and reuse, landfills are still needed. Solid waste management is primarily affected by the federal legislative process. Most state governments adopt federal regulations as a minimum standard to their solid waste management programs. This chapter explains the major legislation of solid waste and federal and states guidelines pertinent to landfill final cover designs.

2.1 MAJOR LEGISLATION FOR SOLID WASTE MANAGEMENT

The federal government has provided impetus for solid waste management legislation that began approximately 30 years ago. The first major legislation enacted was the Solid Waste Disposal Act, PL 89-272, of 1965. The law was intended to (Tchobanoglous et al., 1993):

- Promote solid waste management and resource recovery systems;
- Provide technical and financial assistance in solid waste programs;
- Promote research and development programs for improved solid waste management;
- Provide guidelines for collection, transport, separation, recovery, and disposal systems;
- Provide training grants for occupations involving solid waste management.

The National Environment Policy Act (NEPA) is a congressional law enacted in 1969. It gave the public an opportunity to participate in the process by creating the Council of Environmental Quality in the Office of the President. The council has the authority to force every federal agency to submit an Environmental Impact Statement (EIS) on every project. An EIS statement evaluates all possible detrimental effects on the environment and must be prepared for solid waste facilities.

The Resource Recovery Act of 1970 changed the emphasis of management from disposal to recycling and reuse. Progress under the Resource Recovery Act prompted congress to pass the Resource Conservation and Recovery Act (RCRA), in 1976. RCRA was the legal basis for implementation of guidelines for solid waste storage, treatment, and disposal. The legislation included both hazardous and solid waste, later separated by the Environmental Protection Agency (EPA). RCRA has been amended often since its inception by various laws and currently major regulations concerning MSW landfills.

The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), PL 96-510, was enacted in 1980. CERCLA established a trust fund called "Superfund" that allowed an immediate response to problems at uncontrollable hazardous waste disposal sites. Uncontrollable MSW landfills are facilities that have not operated or are not operating under RCRA permits. Uncontrolled landfills are subject to CERCLA. Reauthorization in 1986 extended the nation's commitment to resolving past problems of mismanagement of hazardous waste. Over 32,000 sites have been identified as potential hazardous waste sites, and 1183 sites are currently on the National Priority List (NPL) (Peters, 1992).

The Public Utility Regulation and Policy Act was enacted in 1981. This law directs public and private utilities to purchase power from waste-to-energy facilities and the manner in which utilities set prices.

MSW landfills today are subject to EPA regulations pursuant to 40 CFR Part 258, Subtitle D of RCRA, released as final on October 9, 1991. The regulations strengthened the design requirements for new MSW landfills to nearly reflecting those of hazardous waste landfills. Under subtitle D, cover requirements are based primarily on the hydraulic conductivity of the bottom liner (EPA, 1993). Existing MSW landfills were forced to make modifications to meet the new standards. The regulations economically impacted almost every MSW landfill in the United States except those already operating under strict regulations.

Many other laws apply to the control of solid waste management. These include the Noise Pollution and Abatement Act of 1970, which regulates the noise exposure to workers employed at solid waste facilities. The Clean Air Act of 1970, PL 91-604, pertaining to dust, smoke, and gas discharge from solid waste operations. Many states have adopted their own laws and have established agencies for the control of solid waste management.

2.2 FEDERAL AGENCIES INVOLVED WITH SOLID WASTE MANAGEMENT

Solid waste management has become a responsibility of many federal agencies due to the various laws, regulations, and executive orders in the past 30 years. Federal agencies interpret laws and apply the minimum standards to be followed by all states. Some significant agencies and their impacts are presented in Table 1.

Table 1 Federal Agencies with Impacts on Solid Waste Management (Tchobanoglous, 1993).

Agencies	Impact
Environmental Protection Agency (EPA)	-sets performance standards for landfills
Health, Education, and Welfare (HEW)	-sets health standards for solid waste storage
Department of Defense (DOD)	-protects navigable waterways
Department of Commerce (DOC)	-decision regarding interstate commerce and tariffs
Department of Transportation (DOT)	-load restrictions on solid waste transports
General Services Administration (GSA)	-material specifications for federal purchasing
Department of Energy (DOE)	-development of alternative fuels
Department of Interior	-siting of landfills

2.3 FEDERAL LANDFILL FINAL COVER REQUIREMENTS

In accordance with RCRA on October 9, 1991, the EPA promulgated revised criteria for MSW landfills. These federal regulations are contained in 40 CFR Part 258 and provide the minimal requirements for all facets of solid waste landfills. The new requirements were implemented on October 9, 1993 (FDEP, 1995). The criteria for landfill closures focus on establishment of a low-maintenance cover system, and its design to minimize infiltration from precipitation. Technical issues that must be addressed in landfill design are:

- Amount and rate of settlement of the surface cover barriers;
- Long-term durability of the surface cover system;
- Long-term waste decomposition and management of leachate and gasses;
- Environmental performance of the combined bottom liner system and surface barrier.

The final cover system required to close a landfill unit must have an infiltration layer that is a minimum of 18 inches (450 mm) thick, overlain by an erosion layer that is a minimum of six inches (150 mm) thick. The infiltration layer must have a hydraulic conductivity less than or equal to any bottom liner or natural subsoils present to prevent the bathtub effect. The infiltration layer may not have a hydraulic conductivity greater than $4x10^{-7}$ inch/sec ($1x10^{-5}$ cm/sec) regardless of permeability of underlying liners or natural subsoils. If a synthetic membrane is in the bottom liner, there must be a synthetic membrane in the final top cover. The final cover must be designed to have a permeability less than or equal to the permeability of the bottom liner system of natural subsoil present, or a permeability no greater than $3.94x10^{-6}$ inch/sec ($1x10^{-5}$ cm/sec).

Installation of the final cover must be completed within six months of the last received waste (EPA, 1993). The erosion layer is used typically to support vegetation. The infiltration barrier should have a slope of 3% but no more than 5% after allowance of settlement (Daniel, 1994). Figure 1 shows the recommended EPA final cover barrier for MSW landfills.

2.4 FLORIDA LANDFILL FINAL COVER REQUIREMENTS

Florida began requiring landfill liners as early as 1985 and has incorporated extensive technical regulations for design, operation, and closure of landfills into Chapter 62-701, Florida Administrative Code (F.A.C.). EPA reviewed and issued a full approval to Florida guidelines effective July 11, 1994. After the Federal amendment to the Subtitle D closure criteria (57 FR 28626 dealing with 40 CFR Part 258.60) in June of 1992, the Florida requirements had to be amended also. Florida revised chapter 62-701, F.A.C., to include additional permeability requirements and required the use of geomembrane in the final cover if it is used as part of the bottom liner system. These revisions became effective on January 2, 1994. Florida's alternative barrier layer designs are linked to water infiltration rates through final covers. To achieve a successful alternative design, an applicant must have as a minimum the following design standards (FDEP, 1995):

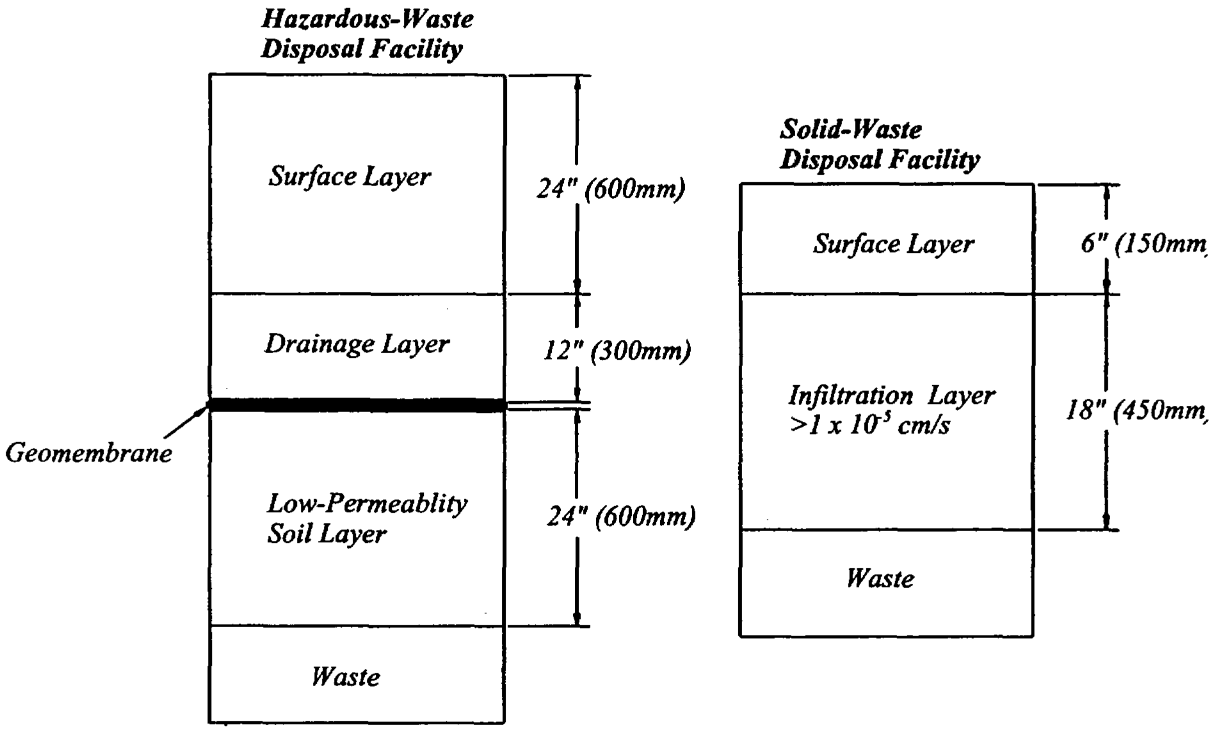


Figure 1 Recommended Surface Barrier Cross-Section for Hazardous-Waste and Solid-Waste Landfills (Daniel, 1994).

- Landfills will have a soil layer, a geomembrane, or combination of a geomembrane with low permeability material. For MSW landfills, barrier layer will be equivalent to or less than the permeability of the bottom liner. For MSW landfills without geomembranes, the barrier layer will have a permeability of $1x10^{-7}$ cm/sec or less.

- If the top liner consist of only soil, it will be 18-inch thick, placed in 6-inch lifts. The 18-inch thick layer will be capable of sustaining vegetation.

- If a geomembrane is used in the barrier layer, it will be a semi-crystalline thermoplastic at least 40 mils thick or non-crystalline thermoplastic at least 30 mils thick with a maximum water vapor transmission rate of 2.4 g/m^2/day. A protective soil layer at least 24-inch thick will be put on top of the geomembrane.

- An alternative design for the barrier layer, or parts of the barrier layer may be used upon a demonstration that the alternate design will result in a substantially equivalent rate of storm water infiltration as the minimum design standard.

Using these criteria, minimum final cover designs for closing various types of landfills have been determined. A summary of minimum closure designs corresponding to common types of bottom liners in Florida MSW landfills are as follows (FDEP, 1995):

- Unlined MSW landfills - An 18-inch thick soil barrier emplaced in 6-inch thick lifts with maximum permeability of 1×10^{-7} cm/sec.

- MSW landfills lined with single soil liner - An 18-inch thick soil barrier layer with permeability less than or equal to the permeability of bottom liner covered with 18-inch thick protective soil layer.

- MSW landfills lined with a slurry wall keyed into in-situ bottom soils - an 18-inch thick soil barrier layer with permeability less than or equal to the permeability of the bottom liner with and 18-inch thick protective cover.

- MSW landfills lined with a single geomembrane - A geomembrane covered with a 24-inch protective soil layer.

- MSW landfills lined with a composite liner - A geomembrane covered with a 24-inch protective soil layer.

- MSW landfills lined with a composite double geomembrane liner - A geomembrane covered with a 24-inch protective soil layer.

2.5 LANDFILL FINAL COVERS

Two options to consider for landfill leachate management are entombment and recirculation. Entombing is to design, construct, and maintain to prevent moisture infiltration. The solid waste will eventually remain in a state of mummification until the cover system is breached and moisture enters. A recirculation concept results in the rapid physical, chemical, and biological stabilization of the waste. To accomplish this, a moisture balance within the landfill will accelerate this stabilization process. Recirculation needs a leachate collection system and a leachate injection system. The benefit of this approach is that after stabilization the facility should not require further maintenance. A more important advantage is that the decomposed and stabilized waste may be removed and used like compost, the plastics and metals could be recycled, and the site used again (EPA, 1991).

Most engineering surface barriers in the United States consist of multiple components. The components of a surface barrier may be grouped into five layers; surface layer, protective layer, drainage layer, barrier layer, and gas collection or a foundation layer. Not all components are needed for all surface barriers (Daniel, 1994).

- Surface Layer - Topsoil, geosynthetic erosion control layer, cobbles, or gravel
- Protective Layer - Soil, recycled or reused waste material, or cobbles
- Drainage Layer - Sand or gravel, or geonet or geocomposite
- Barrier Layer - Compacted clay, geomembrane, geosynthetic clay liner, waste material, or asphalt
- Gas Collection/or Foundation Layer - Sand or gravel, soil, geonet or geotextile, or recycled and reused waste material

The design of final covers is complicated by (Daniel, 1995):

- Temperature extremes;
- Cyclic wetting and drying of soils;
- Plant roots, burrowing animals, and insect in soil;
- Differential settlement;
- Down slope slippage or creep;
- Vehicular movement on roads;
- Wind and water erosion;
- Deformation caused by earthquakes.

Landfill literature has shown many landfill failures are attributed to insufficient surface barriers (Daniel, 1994). Even in arid regions, over time, buried waste is vulnerable to transport via rainwater percolation, gas diffusion, erosion, and intrusion by plant roots, burrowing animals, and humans. Standard models and field tests of engineering covers designed to impede these pathways implicitly and erroneously assume that surface barrier technology is well developed and works as expected.

Melchior et al., (1994) has monitored the water balance and long term performance of different landfill covers of Georgswerder landfill in Hamburg since 1988. The compacted soil liners have lost their efficiency due to desiccation and shrinkage. The geomembrane liners and the extended capillary barriers performed well. Water movement through a capillary barrier is governed by the difference in unsaturated hydraulic properties that exist between the cover layers. When the soils are unsaturated the hydraulic conductivity of the top surface layer is higher then the underlying soil layer. Suction is produced between the soil layers which drives water flow upward. As a result, if the upper layer has enough storage capacity, there is little percolation from the liner system. A slight periodic desiccation due to thermally induced water transport was observed within the soil liners below the geomembranes. Melchior et al., (1994) concluded that a further detailed study of capillary barriers may render improvements in these systems. The combination of a geomembrane liner above a capillary liner may be a promising concept.

3. LANDFILL SYSTEMS FLOW MODELS

Landfill barrier systems consist of a cover and bottom liner. The cover liner is designed to prevent or reduce the migration of precipitation into the waste. The bottom liner is designed to collect and remove leachate that may make its way through the system. Generally, bottom liners consist of a leachate collection system and liner. Leachate collected is drained from the liner to reduce fluid pressure on the liner. Many research efforts have been devoted to predicting landfill moisture flow. Several methods and computer models have been developed to deal with the unique conditions of a landfill. These numeric models fall into the general categories of deterministic water balance methods and finite-difference/finite-element methods. Landfill flow modeling consists of predicting the runoff, infiltration, and leakage rate of a system.

The water balance methods are based on procedures developed by C.W. Thorthwaite (1955, 1957, 1964) in the soil and water conservation field. Since his work, many research efforts have developed the water balance equations in the last 40 years (Fenn et al., 1975; Perrier and Gibson, 1980; Knisel and Nicks, 1980; Skaggs, 1980; Schroeder et al, 1984a, 1984b; Mack, 1991). These water balance models consider the landfill a "black box," requiring only a material balance of water flow into and out of the system. The basic water balance equation used to develop the model is:

$$L = P - ET - R - \Delta S \qquad (3.1)$$

where:

- L = the leakage volume produced
- P = precipitation falling on the surface
- ET = water lost due to evapotranspiration
- R = water lost due to runoff
- ΔS = the change in moisture storage volume

The water balance models have been used extensively in predicting leachate quantity and aiding design of landfills. Water balance model predictions may be suspect due to the questionable accuracy of the input parameters, such as, rainfall, evapotranspiration, permeability, and refuse moisture storage estimates (Bagchi, 1990). For a detailed review of flow models designed primarily to determine the leachate generation see El-Fadel et al., (1997).

The second approach to predicting landfill flow is using finite-difference/finite-element solution techniques. Many investigators have taken this more complex approach of using the unsaturated flow theory through porous media to predict landfill flow (Korfiatis, 1984; SOILINER, 1986; Staub and Lynch, 1982). This method has been primarily used to predict flow rates through soil media in the past (Nobel and Arnold, 1991). Current flow models are presented in the following sections.

3.1 CHEMICALS, RUNOFF, AND EROSION FROM AGRICULTURAL MANAGEMENT SYSTEMS (CREAMS) (1980)

The CREAMS (Knisel and Nicks, 1980) model was developed for the Department of Agriculture (USDA) to evaluate nonpoint source pollution for agricultural land. The model is based on the water balance and may estimate runoff, erosion/sediment transport, plant nutrient, and pesticide yields. The general logic of the model is that hydrologic processes provide the transport medium for sediment and agricultural chemicals. CREAMS was developed for modeling agricultural systems but has been used in waste management research including erosion studies, water balance research, and landfill cover design (Nyhan, 1990).

Nyhan (1989, 1990) studied calibrations of the model for two shallow land burial cover configurations at the Los Alamos National Laboratory. Field data from the arid/semiarid region were used for the calibrations. The predicted results of water movement in the experimental landfill cells were acceptable, but extreme failure events are beyond the model capability. Devaurs and Spriner (1988) evaluated various trench cover designs in a semiarid region. The model can predict soil moisture in the various controlled cover designs, but overpredicted soil moisture when vegetation was most active. Limitations of the model include simulating moisture movement as gravity flow, assuming a linear relationship for hydraulic conductivity, and simulating one-dimensional vertical moisture movement. CREAMS has also been tested for accuracy in runoff and erosion studies. The model can predict average runoff, but has a tendency to underestimate sedimentation yield for large storms (Binger et al., 1992; Wu et al., 1993).

3.2 HYDROLOGIC SIMULATION ON SOLID WASTE DISPOSAL SITES (HSSWDS) (1980)

Perrier and Gibson (1980) modified the CREAMS model and the USDA Soil Conservation Service (1993) runoff curves to develop the Hydrologic Simulation on Solid Waste Disposal Sites (HSSWDS) computer model. The model was designed to simulate the hydrologic flow characteristics of solid and hazardous waste landfills using a deterministic water balance approach to predicting landfill moisture flow. Input parameters such as geographical locations, site area, hydrologic characteristics, final soil and vegetative cover, and default overrides are provided by the user. Gee (1981) evaluated HSSWDS in predicting leachate production from laboratory and field tests. Predicted values for HSSWDS model produced a 107% error. The later published HELP model is primarily a refinement of the HSSWDS concept (Nixon, 1995).

3.3 UNSATURATED GROUNDWATER FLOW MODEL (UNSAT1D) (1981)

UNSAT1D (1981) was developed by the Battelle, Pacific Northwest Laboratories (BPNL) for the Electric Power Research Institute to study flow applications for cover designs of fly ash landfills. UNSAT1D is a one-dimensional, finite-difference model that solves a form of the Richards equation. UNSAT1D algorithms account for both gravity and capillary forces in calculating flow through the profiles. In a comparative study to the HELP version 1, UNSAT1D produced similar results in the humid conditions and proved more representative under arid and semiarid conditions (Thompson and Tyler, 1984).

3.4 HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL (1984, 1988, 1994)

The most widely used predictive water balance landfill infiltration model is the Hydrologic Evaluation of Landfill Performance (HELP)(Schroeder et al., 1984a, 1984b; Schroeder et al., 1994) model. It was developed to "facilitate rapid, economical estimation of the amount of surface runoff, surface drainage, and leachate that may be expected to result from the operation of a variety of possible landfill designs" (Schroeder et al., 1984b). HELP is a quasi-two-dimensional, deterministic water balance model that estimates daily water movement through landfills. Water migrating through landfill barrier layers may stress liner systems and possibly lead to a breach. Although HELP is used extensively by regulatory agencies, there are few verifications or investigations of the predictive abilities of the model. Version 1 was published in June 1984 with the preliminary evaluation based on 22 months of data. HELP estimates runoff, infiltration, evapotranspiration, drainage, leachate collection, and liner leakage. The model requires daily climatologic data, soil characteristics, and design specifications to do an analysis. The HELP model is extensively reviewed in Section 4.

3.5 SOILINER (1986)

SOILINER (1986) was developed by GCA Technology Division, Inc., for the EPA's Office of Solid Waste. The model predicts the rate of leachate flow through clay liners, given the liner's saturated hydraulic conductivity, hydraulic gradient, and effective porosity. SOILINER is a one-dimensional, finite-difference approximation method that solves an unsaturated flow equation in the vertical direction. A centered node grid system is used to evaluate the potential over time. The features of the model include the ability to simulate multilayered systems, variable initial moisture content, and changing conditions on the boundaries. Output is a contaminant time of travel (TOT) over a 100-foot horizontal distance.

Daniel et al. (1991) studied inorganic solutes through laboratory clay liner columns in an attempt to validate the model, but found it overpredicted time of travel (TOT) in some cases by a factor as high as 52. They concluded the error may be the model's assumption that the liner's actual and effective porosities are equal, while in fact the effective porosity of a compacted clay may vary with hydraulic gradient. Coates (1987) studied the hydrologic components of experimental multilayer landfill covers and found the major limitations of the model are that it does not account for dispersion and breakthrough time for migration contaminants. Al-Jobeh (1994), in a comparison study of several models, also concluded that the model does not take into consideration gas-phase flow or pressure, and flow is only considered in the vertical direction.

3.6 UNSATURATED SOIL WATER AND HEAT FLOW MODEL (UNSAT-H) VERSION 2.0 (1990)

In 1990, UNSAT-H, Version 2.0 (1990) was published by Pacific Northwest Laboratories (PNL) for the U.S. Department of Energy. UNSAT-H is a one-dimensional unsaturated soil-water and heat-flow model. Fayer and Jones (1990) conducted a field study to simulate the water balance without calibrations in eight non-vegetative lysimeters over 1.5 years. Heat flow components were not sufficiently tested and were not considered in the analysis. The moisture flow is calculated using a form of the Richards equation for moisture flow response to gravitational and suction-head gradients, and using Frick's law for diffusion vapor flow. The data shows overprediction of evaporation in the winter and underprediction in the summer. The study concluded that drainage results may become applicable in a semiarid climate with additional testing, calibration, and model enhancements (Fayer et al., 1992).

3.7 FULFILL (1991)

The FULFILL model is a one-dimensional, finite-difference computer model using a form of the Richards equation developed by the Center for Environmental Management at Tufts University. Documentation of the model is presented in research by Arnold (1989). Noble and Arnold (1991) tested the theory of unsaturated flow through porous media in simulated laboratory-scale landfill models or the vertical infiltration and the effects of a capillary rise. Results were compared with the FULFILL model. Laboratory scale landfills have shown the FULFILL model to provide some reasonable predictions of moisture transport with the capillary rise a significant factor. The FULFILL model is still in the developmental stage.

3.8 MODEL INVESTIGATION OF LANDFILL LEACHATE (MILL) (1991)

MILL (Mack, 1991) is an interactive computer model that calculates leachate production volume for solid and hazardous waste landfills using minimal climatic and environmental data. The model uses a deterministic water balanced method with landfill sectioning to simulate landfill moisture movement and application of moisture. MILL may be used to evaluate landfill cells when in construction, open or closed. Simulation results of MILL on several test cells were consistently very close to the HELP model output.

3.9 THE FLOW INVESTIGATION FOR LANDFILL LEACHATE (FILL) (1992)

FILL is a two-dimensional, unsteady-state moisture flow model that predicts the leachate flow through landfills. A kinematic wave equation is used to calculate runoff by taking into account the slope and the roughness of the surface. The model's infiltration analysis is based on Philip's methods of solution (1969). Various papers by Demtracopoulos and Korfiatis (Demtracopoulos et al., 1984; Korfiatis and Demtracopoulos, 1986; Demtracopoulos et al., 1986; Demtracopoulos, 1988) describe techniques used to compute the leachate-mound head in the saturated zone of a landfill. FILL's primary equation is based on the mass-conservation principle and uses the movement of the leachate-mound head to compute the leachate flow rate. Khanbilvardi, et al., (1995) compared the FILL model with leachate flow rate data from section 6/7 of Fresh Kills Landfill in Stanton Island. They surmised the model gave better estimates of leachate flow by representing the field conditions more realistically than the HELP model.

3.10 LANDFILL LINING SYSTEM FLOW MODEL (1993)

The model is a numerical finite difference model to simulate flow conditions and predict performance. The model can simulate complex configurations under transient flow conditions and is one of a few models to incorporate geomembrane liner effects. The model was calibrated based on sixteen case studies of landfill lining systems (Gilbert, 1993). The model consistently overestimated the actual leakage rate and the primary liner leakage was through single geomembrane liners on the cell sideslopes. To account for the model bias Gilbert recommended that the expected value of the leakage rate should be multiplied by a factor of 0.180. Compared with current finite difference models using simple geometries and/or steady state cases, this model is an advancement of predicting moisture transport.

3.11 FINITE-ELEMENT MODEL (1994)

Al-Jobeh (1994) presented a two-dimensional transient finite-element model that combines flow of liquid and gas with the deformation of porous media under unsaturated flow conditions. The model simulated realistic geometry and boundary conditions. When compared to HELP and SOILINER, the model is more representative of the physical situation that takes place in hydraulic barriers underlying disposal facilities under large loading condition. However, this model lacks an infiltration algorithm.

4. HELP MODEL EVALUATION

The most widely used predictive landfill infiltration model is the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al., 1984a, 1984b; Schroeder et al., 1994). It was developed to "facilitate rapid, economical estimating of the amount of surface runoff, surface drainage, and leachate that may be expected to result from the operation of a variety of possible landfill designs" (Schroeder et al., 1984b). Percolation through landfills is perhaps the most important parameter for design of cover systems because water pressure on the barrier layers may stress a system and possibly lead to a breach in the system. Although HELP is extensively used by regulatory agencies there are few verifying investigations of the predictive abilities of the model. Version 1 was published in June 1984 with the preliminary evaluation based on 22 months of data.

4.1 HELP MODEL, VERSION 1

Version 1 is a quasi-two-dimensional, deterministic water balance model developed to estimate daily water movement through landfill systems. The model is called quasi-two-dimensional because it does not consider vertical and lateral components of flow in each layer. The model is called "quasi steady state" because the vertical flow is simulated by an unsteady-state moisture-routine equation and the lateral flow component is calculated from a steady-state solution of the Boussinesq equation (Khanbiluabi et al., 1995) Version 1 is a refinement of the U.S. EPA Hydrological Simulation Model for Estimating Percolation at Solid Waste Disposal Sites (HSSWDS)(Perrier and Gibson, 1980) and the U.S. Department of Agriculture Management Systems (CREAMS)(Knisel and Nicks, 1980) hydrologic model. The model predicts runoff, evapotranspiration, soil moisture storage, lateral drainage, and percolation through barrier layers for multi-layered landfills. Version 1 and HSSWDS were developed by the Waterways Experimental Station, for the U.S. Environmental Protection Agency. The model incorporates most runoff evaporation and transpiration routines of the CREAMS model.

Version 1 computes daily runoff by the Soil Conservation Service (SCS) runoff curve number (CN) method, modified using an algorithm from CREAMS. Daily infiltration into the soil matrix is the net daily precipitation minus runoff and evapotranspiration. Vertical moisture movement is calculated by Darcys law through vegetative, drainage, waste, and barrier layers. Barrier layers are assumed saturated for calculating percolation. The migration through a barrier layer is directly proportional to the saturated hydraulic conductivity and the hydraulic gradient. For vertical percolation layers and drainage layers above the barrier layers, free gravity flow is assumed with and the hydraulic gradient is equal to one. Ponded water at the surface is assumed negligible and hydraulic conductivities of the layer are assumed homogenous. The vertical moisture movement flow rate is assumed equal to the unsaturated hydraulic conductivity. Lateral drainage is calculated using an analytical, linear form of the Boussinesq equation and is allowed only in drainage layers.

Version 1 calculates evapotranspiration (ET) using a modified Penman method developed by Richie (1972) adapted for limited soil moisture conditions. CREAMS uses the method to calculate potential ET on a particular day given the mean solar radiation and mean temperature. Surface evaporation, potential soil evaporation, and potential plant transpiration are calculated separately to estimate total ET for the day, where the addition of the three is not allowed to exceed the potential ET.

Fourier analysis is used to calculate the daily mean temperatures and solar radiation values that fit a monthly value to a simple harmonic curve with an annual period (Sudar et al., 1981).

Version 1 simulates moisture movement through a vertical section of a landfill. The evaporative zone is divided into seven segments with each layer beneath the evaporative zone representing an additional segment. Moisture movement between segments is calculated using a storage routing procedure based on the continuity equation. The total ET is produced from the soil profile by extracting a portion from each segment in the evaporative zone. The amount extracted from each segment is determined by weighing factors taken from CREAMS.

Potential soil evaporation and plant respiration is calculated by the leaf area index (LAI). The concept LAI is important because potential soil evaporation and plant transpiration depend only on the LAI value for each day. The measure of the leaf area is "the total projected leaf area of vegetation per unit area or the sum of the areas of all the leaf per unit area ground" (Sudar et al., 1981). The LAI can be classified as excellent grass, good grass, fair grass, and poor grass in the model. Each set of LAIs includes 13 values for dates throughout the year, which are typical values for a normal year (Schroeder and Peyton, 1988b). Daily LAI is used to calculate the monthly LAI by linear interpolation.

4.1.1 Version 1 Studies

Version 1 is limited in its application to existing landfills because it assumes homogeneity and isotropy within layers, idealized barrier-layer compaction, and assumes waste is placed above the water table. These conditions preclude the irregularities in landfill systems most identified with liner system failures. The model will yield a theoretical zero-leakage result when given a proper mix of layers and conditions that are improbable in actual landfill situations (Nixon and Murphy, 1995). Most studies on the model's performance involve evaluation of a specific algorithm of the program. Version 1 model assumes the clay liner to be a homogenous mass of clay with uniform hydraulic properties. It has been shown that the actual hydraulic conductivity of clay test liners was 10 to 10,000 times larger than values obtained from laboratory testing (Lee, 1994).

Schroeder and Peyton (1988b) did long-term verification studies with existing field data for 20 landfill cells. Measured runoff data existed only for six of thirteen cells at the University of Wisconsin and Sonoma County. No lateral drainage and barrier soil percolation data was collected so the evaluation used only leachate collection data. Measurements of percolation were available from only one cell and there was no data on evapotranspiration. The model overpredicted runoff by 30% for five cells and underpredicted by 20% for six; percolation was overpredicted by 35%, and lateral drainage was overpredicted by 19% in two cells. The study concluded that a considerable amount of engineering judgement is necessary for developing a simulation (Schroeder and Peyton, 1988a; Peyton and Schroeder, 1988). Later they used two large-scale physical models to verify the models' lateral drainage subroutine. The study compared drainage data with Version 1 and a numerical solution of the Boussinesq equation for saturated flow. Neither the Version 1 model nor the Boussinesq equation solution agreed completely with the drainage results due to problems in evaluation of air entrapments, compaction, drainage media, hydraulic conductivity, and depths of saturation (Schroeder and Peyton, 1988b).

Coates (1987) studied Versions 1 ability to predict hydrologic performance of multi-layered landfill covers. The model consistently overpredicted evapotranspiration and runoff and underpredicted drainage annually using default input values. It was determined that default SCS curve numbers tend to overpredict runoff from rainfall events, and a series of simulations using a series of curve numbers may be required to reflect the changes in vegetation and soils over time. The SCS curve numbers (See Section 5) are a method developed by the Soil Conservation Service (SCS) in 1957 that are based on a dimensionless hydrographs (Bedient and Huber, 1988).

Zeiss and Major (1992-93) tested compacted municipal waste in cylindrical cells and determined vertical moisture flow through compacted municipal solid waste layers is more complex than the one-dimensional, uniform Darcian drainage flow as used in Version 1. Channeling and flow along wetting curves produce irregular and more rapid breakthrough times and leakage rates. Tests showed downward flow occurring in narrow flow channels that should be addressed in landfill models.

McEnroe (McEnroe and Schroeder, 1988; McEnroe, 1989a; McEnroe, 1989b; McEnroe, 1993) has performed many studies on the saturated depth over landfill liners. Saturated depth over a liner is dependent on the liner slope, drainage length or drain spacing, and difference between the impingement rate and the liner's hydraulic conductivity. Leakage rate is sensitive to the hydraulic conductivity of the liner under normal conditions (McEnroe and Schroeder, 1988). The EPA technical guidance documents have shown their methods overestimate the maximum saturated depth over a landfill cover and bottom liners (McEnroe, 1993). Models assume that the steady-state relationship also holds from unsteady flow (McEnroe, 1989a). McEnroe (1989a) proposed an algebraic model to estimate the unsteady case of drainage of landfill cover and bottom liners. In arid areas, where leakage is the major concern, procedures based on steady inflow yield unrealistic estimates of leakage.

Gilbert (1993) evaluated the performance reliability of existing liner systems. He determined the major limitation is the inability of the Version 1 to simulate lateral flow and to solve for multi-dimensions. Also, Woyshner and Yanful (1995) modeled waste percolation through experimental soil cover over mine tailings and concluded when covers freeze in winter Version 1 does not adapt to frozen soil.

Warner et al., (1989) evaluated Version 1 extensively in the study "Design, Construction, Instrumentation, Monitoring, and HELP Evaluation of Multi-Layered Soil Cover." He recommended the replacement of several default hydraulic conductivity values, revision of the evapotranspiration algorithm, revision of the snowmelt algorithm to account for surface temperature fluctuations, use more appropriate algorithms for calculating of infiltration, development of an algorithm that predicts the soil parameters of porosity, field capacity, wilting points, and hydraulic conductivity based on soil texture and compaction effort. Also, he stipulated that the lateral flow in the vegetative layer cannot be modeled by the quasi-two-dimensional format of the Version 1 model.

Khanbilvardi et al., (1991) evaluated a mathematical model to predict runoff-evapotranspiration processes using a modified Penman method. He surmised that Version 1 does not consider sideslopes, a factor affecting surface runoff. Barnes and Rogers (1988) evaluated the predictive ability of Version 1 in landfill covers at Los Alamos. The project centered on the ability of the model to predict soil moisture storage, which it was found to underpredict, while overpredicting evapotranspiration.

Version 1 algorithms have been the most studied of the versions of the model. These early versions of the model appear to overpredict the evapotranspiration and runoff, and underpredict drainage and hydraulic conductivity. They are limited in the prediction of lateral flow, insufficient in cold climates, and do not take into account sideslopes of the landfill for runoff calculations.

4.2 HELP MODEL, VERSION 2

Due to subsequent studies, Version 2 made several changes to the original model, including the addition of a synthetic weather generator developed by the USDA Agriculture Research Service. Twenty years of climate input can be simulated. The five-year (1974-1978) climatology database and manual input options were maintained. The program calculates daily values of maximum temperature, minimum temperature, and solar radiation values, for any climate input method chosen. For the synthetic rainfall option the model uses a first-order Markov chain to generate the occurrence of wet or dry days. The model has the statistical parameters needed to generate rainfall for 139 cities synthetically. The snowmelt routine was modified for the differences between the daily maximum and average temperature.

Also, a vegetative growth model from the Simulator for Water Resource in Rural Basins (SWRRB) is used to calculate leaf area indices. The model considers a temperature, water stress, growing season, and maximum leaf area index (LAI). The LAI is specified by selecting the vegetation conditions. Soil default characteristics were revised and allow the option to enter initial moisture contents of individual layers. A soil moisture content initialization routine also was added and the default runoff curve number approach was updated. Version 2 incorporated the Brooks-Corey equation to model unsaturated hydraulic conductivity replacing the linear function. Soil moisture content is predicted using a storage routine procedure, but the free-drainage restriction for vertical peculation layers is no longer applicable. The method of calculating lateral drainage was revised. Drainage is calculated using an approximate solution of the steady state form of the Boussinesq equation, with a non-linear solution.

4.2.1 Version 2 Studies

Dozier (1992) did perhaps the most extensive evaluation of Version 2 for three surface-hydrology processes and suggested several modifications. The projected annual evapotranspiration decreased with the use of the Penman equation, a physical-based formula from Richie adapted for situations of limited soil water content, incorporating wind and humidity effects and long wave radiation losses; the Penman equation is recommended to calculate evapotranspiration. Modeling of snow evaporation and melt produced a superior algorithm compared with the original model where the potential is applied directly to the snowpack. Also, recommended was a modification to include SNOW-17 accumulation and melt equations without the addition of ground melt.

Khganbilvardi et al., (1995) did a comparison study of Version 2 to leachate production from a section of the Fresh Kills Landfill in Stanton Island. It was determined that Version 2 underestimated the surface runoff and does not take into consideration the vertical and lateral components of flow in each layer of the landfill profile. Al-Jobeh (1994) did a study comparing Version 2 to several other models. It was concluded that the model does not use the unsaturated hydraulic conductivity, does not consider gas-phase flow and pressure, flow domain deformation, and any physical characteristic changes of landfill aging. Also, the many simplifications associated with Version 2 are restrictive and do not allow for accurate simulations of the infiltration process through loaded hydraulic barriers.

4.3 HELP MODEL, VERSION 3

Version 3, published in 1994, improves many transport algorithms and makes the program more user friendly (Schroeder et al., 1994). The number of barrier layers that may be modeled has been increased. The default material list has been expanded to contain additional waste materials, geomembranes, geosynthetic drainage nets, and compacted soils. Snow melt calculations are performed with an energy based model. Calculations of evapotranspiration are made with a Penman model. Percolation is calculated with Darcy's law using a modification of the hydraulic conductivity to compensate for unsaturated conditions (Fleener and King, 1995a, 1995b). Leachate recirculation and groundwater drainage has been included. Equations developed by Giroud and Bonaparte (Giroud and Bonaparte, 1989a; Giroud and Bonaparte, 1989b; Giroud et al., 1992) have been added to account for leakage through geomembranes. A frozen soil model has been added to improve infiltration predictions. The unsaturated vertical drainage model has also been improved to aid in storage computations.

4.3.1 Version 3 Studies

Version 3 is a new release with few published evaluations, but the modifications are based on studies of the previous versions. Fleenor and King (1995a, 1995b) compared Version 3 in three test climate conditions in Cincinnati, Ohio (humid), Brownsville, Texas (semi-arid), and Phoenix, Arizona (arid). Simulations were based on a two-year period using climatology data in the default files of Version 3. The model increasingly was limited in its ability to predict reasonable design values of vertical transport in arid regions. Flux through barrier layers was overpredicted by an increasing amount as climate becomes arid. Help overestimates the moisture flux at the bottom of landfills in all cases simulated. Version 3 also failed to show cycles in infiltration. Version 3 requires modification to account for capillary forces or will continue to overpredict downward vertical moisture fluxes. This downward movement of moisture will cause associated errors in the infiltration and runoff values. Errors will be produced in SCS runoff calculations due to the error in the vertical moisture transport.

Benson and Pliska (1996) conducted a four-year study on the hydrologic processes of three field-scale landfill covers. One primary objective was to determine if Version 3 can accurately simulate landfill cover moisture flow. Version 3 underpredicted runoff by approximately 48% and overpredicted percolation by approximately 76% in one cover, which resulted in more soil moisture storage in the simulation than in the field. The model proved accurate in predicting evapotranspiration. They surmised that one reason Version 3 may overpredict percolation is in the model assumption that water in the soil flows vertically downward under a unit hydraulic gradient of one. Examination of field data shows that hydraulic gradient rarely equals one and for most of the year and may be oriented vertically upward. The results of the study have shown that predictions may not be accurate even when most input parameters are known.

Giroud and Bonaparte (Giroud and Bonaparte, 1989a; Giroud and Bonaparte, 1989b; Giroud et al., 1992) work on leakage through geomembrane liners was included in the Version 3. The published equations have become the premier leakage projection model for geomembrane systems. Many factors determine leakage through a geomembrane. Many factors contribute to leakage, including the geometry, configuration, and cross-sections of the landfill. The primary mechanisms of leakage through landfill geomembrane liners are fluid permeation through the undamaged geomembrane cover, and fluid flow through geomembrane defects and holes. Leakage through a geomembrane hole is primarily dependent on three factors: (1) area of hole; (2) hydraulic conductivity of layer above and/or below the geomembrane, and (3) liquid head over the liner. The hydraulic conductivity of the material above and below geomembrane is assumed large. It is assumed no lateral gradient exists which contradicts the landfill's ability to remove leachate. The primary mechanism of leakage through geomembranes is based on expected hole size. The projections provided by Brown et al., (1987) is four holes per acre applied to the entire landfill area. Wallace et al., (1991) disagrees with the Giroud and Bonaparte conclusions for several reasons; the use of the maximum leachate head to determine leakage and extrapolated it through time could exaggerate the expected quantity, standard landfill sideslopes are assumed to model leakage, and the hole size of 1 cm^2 is considered excessive by the authors. Bonaparte and Gross (1990) studied field data for double-liner systems at 30 sites to evaluate the equations. Leakages due to liner failure were considered leaks through the top liner, precipitation in the leakage detection layer during construction, ground-water infiltration, and consolidation of any clay component of the liner. The study concluded the equations presented greatly overpredicted top liner leakage rates at Group I and II surface impoundments. The number and frequency of holes assumed were too high.

A revision of part of the original work was produced by Giroud et al., (1992) which enhanced the original work. Although the leakage rate presented in the work is accepted practice, it was stated that "the method available in this paper allows the calculations of leakage rates for conditions beyond those for which experimental verification exists."

4.3.2 Advantages of HELP

The HELP model has several characteristics that make it a good design tool. It uses published methods to model the effects of the major hydrologic processes of moisture movement through a landfill. The algorithms used are simple enough to be used manually, but are compiled to make large-scale projections possible. HELP makes long-term simulations feasible and potentially meaningful. The predicted value of total runoff may be in error but the surface drainage control devices are designed for peak runoff, limiting the importance of this component.

The ability of HELP to model many different landfill layers is very beneficial. While the features are not tested extensively, they can vary configurations useful for comparisons between alternative designs. Also, the usefulness of the HELP model is enhanced by default data allowed directly from existing files or generated by the model.

4.3.3 Assumptions and Limitations of HELP

The HELP model has been shown to provide reasonable predictions of infiltration of moisture movement through landfills. However, the models theoretical-based algorithms and limited verification studies have several limitations. Schroeder et al., (1994) provides a detailed section of assumptions and limitations in the Version 3 documentation.

Runoff is calculated using the SCSmethod. The SCS curve number approach is an empirically derived runoff model for watersheds. Using the SCS equations with the HELP infiltration approach may carry the method beyond the data on which it was based and produce erroneous results (Barfield et al., 1981). Use of the SCS approach to estimate runoff may limit HELP. The SCS method of estimating runoff does not allow for the impact of varying slopes. The use of SCSto account for different slopes on recompacted soils may also produce false results since development was based on various native soils and considers time distribution of rainfall intensity.

A fundamental limitation is the assumption that the dominant flow mechanism is porous media flow. Water movement other than non-Darcian flow such as cracks, root holes, and animal borrows are not considered (Coats, 1987). Minimizing non-Darcian flow through the upper layer may increase the effectiveness of the cover system. Percolation through the soil liner is assumed Darcian. Leakage occurs only when the soil moisture of the layer above the geomembrane is greater than the field capacity. HELP applies a pressure head over the entire liner system and assumes leakage at the same rate. The leakage of geomembrane liners is based on a function of the hydraulic head. Holes are dispensed uniformly and the average head represents the head over the entire liner system. Also, HELP assumes no aging or breakdown of liner components over time.

Many limitations of HELP are related to its consideration of moisture movement through a landfill. Lateral movement of moisture is only allowed in drainage layers. The Boussinesq equation is used to calculate drainage volume based on the average head above the barrier layer. Water movement through the barrier is also based on the subsequent average head above the barrier and is calculated. Vertical drainage is assumed to be produced by gravity alone.

Another limitation of HELP results from its one-dimensional formulation is its inability to model the effects of alternative slopes. Therefore, many potential changes in geometry cannot be evaluated. Although the drainage algorithm does depend on the slope, clearly using an average head above the barrier layer will model the impact. The model allows only vertical moisture movement in vegetative layers and denies the possibility that lateral movement above a capillary barrier may be much greater in a landfill cover significantly sloped. The HELP model cannot model moisture movement, particularly runoff and drainage, for a landfill with compound slopes on the cover, which are typical of many solid waste landfills.

5. SCS RUNOFF METHOD

Surface runoff is perhaps the largest contributing factor of leachate production in sanitary landfills. It may directly affect moisture content of the landfill system. Runoff begins when the rainfall intensity exceeds the infiltration capacity of the soil matrix (Dass et al., 1977). Factors affecting surface runoff surface topography, cover material, vegetation, permeability, moisture condition, and precipitation. The Soil Conservation Service (SCS) Curve Number method is a widely accepted, computationally efficient method to estimate runoff, water recharge, stream flow, infiltration, soil moisture content, and landfill leachate production (SCS, 1985). SCS can be summarized as a relationship of soil depth and runoff depth. Many factors influence infiltration including rainfall patterns, initial soil moisture, tillage practice, physical soil properties, and influences of vegetation roots and stems. Factors that influence overland flow attenuation include surface roughness, storage, slope, size of watershed, and rate of precipitation. The SCS procedure was developed from rainfall-runoff data for large storms on small watersheds. Runoff was plotted as a function of rainfall on arithmetic graph paper having equal scales, yielding a curve that becomes asymptotic to a straight line with a 1:1 slope at high rainfall.

The SCS method depends on knowledge of the hydrologic classification of soils and vegetative cover. Through experimentation with more than three thousand soil types and cover crops, an empirical relationship was derived relating maximum watershed storage to a curve number that reflects soil type and vegetative cover (Gelhar, 1986; Wanielista and Yousef, 1993). Using the SCS procedure, rainfall excess calculations depend on rainfall volume and curve number. If storage anytime is proportional to maximum storage then rainfall excess is proportional to precipitation volume. The SCS method uses seasons of the year, 5-day antecedent precipitation, the hydrologic soil-cover matrix, and land use that introduces watershed influences on infiltration and overland flow to modify the storage parameter.

The principal application of the SCS method is estimating runoff in flood hydrographs. Rainfall data used in the development generally is from ungauged watersheds. The relationship excludes time as a variable. Runoff amounts for specific time increments of a storm may be estimated. The method was intended as a design procedure for SCS personnel in evaluating watershed response for SCS projects, and it has since been adopted for use by various government agencies including the Environmental Protection Agency. The Soil Conservation Service has defined the following types of runoff (SCS, 1985):

- Channel Runoff - occurs when rain falls on a flowing stream or on the impervious surfaces of a stream flow-measurement instillation;
- Surface Runoff - occurs only when the rainfall is greater than the infiltration rate;
- Subsurface Runoff - occurs when the rainfall meets an underground zone of lower transmission;
- Base Flow - occurs when there is steady flow from the natural storage.

The SCS method is applicable to three different hydrologic problems on small watersheds (SCS, 1985):

- Predicting storm runoff depth from storm rainfall depth;
- Predicting the incremental generation of runoff within a particular storm, using incremental rainfall information;
- Predicting the frequency distribution of annual maximum runoff from the frequency distribution of rainfall depth.

5.1 SCS THEORY

The relationships used to develop the SCS method of runoff-prediction are described below. The method is applicable with the assumption that the following relationships describe the water balance in a storm event. For the simple storm relation between rainfall, runoff, and retention at any point on the mass curve,

$$\frac{F}{S} = \frac{Q}{P} \qquad (5.1)$$

where:

F = actual retention after runoff begins
S = potential maximum retention after runoff begins
Q = actual runoff
P = rainfall

The retention, S, is a constant for a particular storm because it is the maximum that can occur under the existing conditions. The retention, F, varies because it is the difference between P and Q at any point on the mass curve, or:

$$\frac{P - Q}{S} = \frac{Q}{P} \qquad (5.2)$$

Solving for Q:

$$Q = \frac{P^2}{P + S} \qquad (5.3)$$

which is a the rainfall-runoff relation in which the initial abstraction is zero. If the initial abstraction (I_a) greater than zero then the amount rainfall available is P - I_a. Substituting P - I_a for P in equation 5.3 becomes:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (5.4)$$

which is the rainfall-runoff relation with the initial abstract. To remove the necessity for estimating variables in equation 5.4, an empirical relation was developed from experimental watershed runoff data. The empirical relationship is:

$$I_a = 0.2S \qquad (5.5)$$

Substituting 5.5 in 5.4 gives:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (5.6)$$

which is the rainfall relationship used in the SCS method of estimating runoff from storm rainfall. The retention parameter, S, is transformed into a runoff curve number to make interpolating, averaging and weighting operations nearly linear. The relationship between CN and S is:

$$CN = \frac{1000}{S + 10} \qquad (5.7)$$

$$S = \frac{1000}{CN} - 10 \qquad (5.8)$$

The change in S is based on an antecedent moisture condition (AMC) determined by the total rainfall in a 5-day period preceding a storm event. Three levels of AMC are used: AMC-I is the lower limit, AMC-II is the average for which the CN tables apply, and AMC-III is the upper limit of moisture. Relation of I_a and S is based on results from individual storms. The data was derived from watersheds of less then 10 acres in size. Errors in I_a are due to difficulty in determining time of storm event, determining when runoff began, and determining intercepting runoff.

5.2 SCS STUDIES

The SCS method uses only the season of year, precipitation, hydrologic soil cover design, and land use to modify the moisture storage parameter. Researchers have used many factors including rainfall patterns, initial moisture storage, tillage practices, physical soil properties, influences of vegetation, surface storage, slopes, size of watersheds, rate of precipitation and others to improve the SCS method (Mack, 1995). Williams and LaSeur (1976) developed a soil moisture index depletion parameter that required agreement between measured and predicted average annual runoff. The model gave better runoff estimates, but the accuracy and reliability of estimates for ungauged watersheds remain suspect. They surmised that the curve number varies continuously with soil moisture over time.

Hawkins (1973, 1979) modified the SCS method by attempting to predict soil moisture changes by evaluating the influences of rainfall depth. The method used estimates of site evapotranspiration and rainfall to estimate the maximum retention. The method was not equivalent to the original SCS method, but produced a more gradual change in the estimating of the storage parameter.

Martin (1979) considered the effects of rainfall on the runoff predictions and examined the assumption that the initial abstraction does not contribute to the rainfall event and that storm intensity distributions may be neglected. He concluded better estimations of the predicted runoff occurred for large values of moisture conditions and the best predictions were recorded when the watershed had received a total of about two inches of precipitation in the previous five days. The assumption that runoff from events with less than 0.2S will be zero was not correct because runoff from small rainfalls has been observed, recorded, and suggests another weakness be the omission of time as an explicit variable because time distribution of rainfall intensity within the storm may influence the quantity of runoff.

Montgomery (1980) performed a data base analysis of the SCS method. He investigated the predictive accuracy and attempted to modify the method by applying a relationship to measure of rainfall intensity and rainfall patterns. The study attempts to affect the storage parameter with a statistical interpretation that the SCS method is effectively a one-parameter, non-linear regression relation between storm rainfall depth and total runoff depth. He concluded in a study of several watersheds that the rainfall-runoff relationship for most of the watersheds was not well defined by the SCS method.

Clopper (1980) studied the SCS 5-day moisture index and proposed an index that is a direct indicator of soil moisture based on antecedent precipitation and the time of the year. He derived a relationship to predict continuous variations in the storage parameter for given values of the antecedent moisture index through a power function. He showed that the moisture condition of the upper soil zone exerted the greatest influence on water intake rates at the beginning of a storm his conclusion was that no strong relationship exists between the SCS 5-day index and the actual soil moisture and viewed the initial abstraction as consistent of interception, infiltration, and depression storage occurring before runoff begins. A soil moisture index based on antecedent precipitation and season may be effectively used to provide an improved estimate of the storage parameter.

Aron (1992) adapted the SCS infiltration method to a set of complex storms. The SCS method was initially developed to predict runoff and later converted to predict infiltration. He deemed the SCS equations deficient due to the lack of a time relationship in their development. He used a linear filter with two of the Horton parameters to delay the SCS infiltration increments.

In a written discussion paper Ostroff (1996) made observations about the SCS method, illustrating for the curve number response CN = 74, a value taken from a landfill configuration, that there will be no runoff response at all for precipitation values equals to 0.70 inches in an hour. In fact, the data also reveals that the curve response actually rises again to the left of the critical-event volume for which there is no runoff. This is not apparent from the Technical Release 55 (TR-55) documents that explain this method. The rise in the curve does not reflect any actual physical response, and is edited out of the curve number graphs presented in the National Technical Information Service (NITS) documents. This possibly will produce illegitimate runoff values from small storms.

Several conclusions may be derived from the results of previous research. The modifications of the antecedent moisture conditions have the greatest potential for achieving improvement in the SCS method, the storage parameters strongly influenced by soil moisture in the upper soil zone, and direct runoff consists of both overland runoff and subsurface runoff flow of unknown proportions, and the method may be deficient due to lack of a time relationship.

6. GEOMEMBRANE LINER LEAKAGE

Generally, the best approach to impede leachate generation is utilization of an impermeable, geosynthetic final surface cover system. The purpose of the final cover system is to reduce the infiltration of water from precipitation, limit landfill gasses, control vectors, prevent fires, support surface revegetation, and provide support for reclamation (Tchobanoglous et al., 1993). Reduction of infiltration in a landfill is achieved through surface drainage and runoff with minimal erosion, transpiration, and percolation. Traditionally, landfill barriers used within final covers are low-hydraulic-conductivity compacted soil, geomembranes, and geosynthetic clay liners (Daniel, 1995).

Currently, geomembranes are a widely used material in final surface cover design. Geomembranes are engineered polymeric material that are produced to be virtually impermeable. Studies have shown that high-density polyethylene (HDPE) is the material of choice for a mixed range of wastes typically encountered in landfills (LaGrega et al., 1994). Regulations require that post-closure maintenance be conducted for 30 years or for a period approved by the state if the owner can demonstrate the reduced period is sufficient (EPA, 1992). Leachate treatment and disposal are an intricate part of post-closure maintenance.

Many factors contribute to leakage, including the geometry, configuration, and cross-sections of the landfill. Leakage through a geomembrane hole is dependent on the hydraulic conductivity of the surrounding material. The primary mechanisms of leakage through landfill geomembrane liners are fluid permeation through the undamaged geomembrane cover, and fluid flow through geomembrane holes. Another cause of leakage may be material defects that lead to permeation (Giroud and Bonaparte, 1989). Even with the best installation of geomembrane liners, one can expect 1 to 2 defects per acre (3 to 5 geomembrane defects per hectare) (Giroud and Bonaparte, 1989a).

Leakage occurs when liquid infiltrates the vegetative and protective soil layer, migrates through holes in the liner, travels laterally and downward through the low permeable soil, finally penetrating the soil of the landfill cells. Laboratory results suggest some lateral flow usually occurs between the geomembrane and the underlying soil (Bonaparte et al., 1989). Leakage through a liner in contact with fluid is governed by the hydraulic head difference to which the liner is subjected. If the fluid on top of the liner is not flowing, the hydraulic head acting on the liner is related to the depth of the fluid on top of the liner. If the fluid on top of the liner is flowing laterally, the fluid head will be in a dynamic state. Peyton and Schroeder (1990) evaluated landfill designs and concluded that synthetic liner leakage depends on hole size, depth of leachate ponding, and the saturated hydraulic conductivity of the underlying soil.

The premier study on leakage mechanisms of geomembrane liners was completed by Giroud and Bonaparte (1989a, 1989b) and partly revised in 1992 (Giroud et al., 1992). Although the leakage rates presented are reasonable in practice, the studies stated that "the method available in this paper allows the calculations of leakage rates for conditions beyond those for which experimental verification exists" (Giroud et al., 1992), thereby illustrating the non-conclusive nature of the equations.

Test results on liners show that all geomembranes are permeable (Giroud, 1984). A study evaluated data from 27 lined waste impoundments constructed between 1971 and 1983. The facilities selected had a total of 12 failures at 10 sites. The nature of the failures were noted as one to two chemical attacks, five physical tears and/or punctures, one to three problems with field seams or other installation activities, and one large gas bubble under the liner. Bonaparte and Gross (1990) collected field data on liquid flow from leakage detection layers of double-liner systems at 30 landfill surface impoundment facilities. They surmised flow is due to top liner leakage, water percolation during construction, water under compression, water expelled from clay consolidation, and ground water that infiltrates the bottom liner.

6.1 GEOMEMBRANE MATERIAL

New regulations have resulted in the increased use of synthetic liners. Geomembrane is a generic term used to replace terms such as synthetic membranes, polymeric membranes, plastic membranes, flexible membrane liners, impermeable membranes, and impervious sheets (Giroud and Frobel, 1983). For a detailed presentation on designing with geosynthetics see Koerner, (1994). Geomembranes are low permeable membranes used for liners and barriers to control fluid migration. Geomembrane permeability is typically 10^{-14} to 10^{-13} m/s with a low hydraulic conductivity (Knisel and Nicks, 1980). Geomembranes may be composed of asphalt and/or polymers. Asphalt is derived from natural deposits of an oil distillate by-product, and polymers are chemical compounds of high molecular weight. The most common types of polymers are (Knisel and Nicks, 1980):

- Thermoplastics - Polyvinyl chloride (PVC), Oil Resistant PVC (PVC-OR), Thermoplastic Nitride-PVC (TN-PVC), Ethylene Interpolymer Alloy (EIA)

- Crystalline Thermoplastics - Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), High Density Polyethylene-Alloy (HDPE-A), Polypropylene, Elasticized Polyolefin

- Thermoplastic Elastomers - Chlorinated Polyethylene (CPE), Chlorinated Polyethylene-Alloy (CPE-A), Chlorosulfonated Polyethylene (CSPE), Thermoplastic Ethylene-Proylene Diene Monomer (T-EPDM)

- Elastomers - Isoprene - Isobutylene Rubber (IIR), Ethylene-Propylene Polychloroprene (CR), Epichlorohydrin Rubber (CO)

Most geomembranes liners are made of polyethylene because of its strength, durability, and resistence to chemical attack (Boggs, 1995). LDPE was the first polyethylene developed. It is produced at a very high pressure and is used where its flexibility and water vapor barrier properties are important. Another polyethylene, HDPE, is processed at a low pressure and temperature. HDPE is more rigid, stronger, tougher, and has a better chemical resistence than LDPE (Boggs, 1995) and thus is more common in landfills today (Wallace and Akgun, 1991). The three main groups of polyethylene are:

- LDPE: Low density polyethylene (density 920-930 kg/m^3);
- LLDPE: Linear low density polyethylene (density 935-945 kg/m^3);
- HDPE: High density polyethylene (density 940-960 kg/m^3).

Geomembranes commonly contain additives to enhance their performance. Typically asphalt additives are fillers, fibers, and elastomers. Fillers are small particles used to reduce the cost of the compound and increase stiffness. Fibers reinforce the material and are typically chopped glass, polyester or nylon fibers. Elastomers are used to improve the compound mechanical behaviors and their resistance to weathering. Polymer additives are fillers, fibers, processing aids, plasticizer, carbon black, stabilizers, antioxidants and fungicides. Plasticisers are used to increase flexibility. Carbon black is added to resist aging due to ultraviolet light and to increase stiffness. Stabilizers and antioxidants reduce aging and provide stability during the manufacturing process. Fungicides prevent fungi and bacteria from attacking the polymer (Boggs, 1995).

6.2 MASS TRANSPORT THROUGH GEOMEMBRANES

A landfill liner system is exposed to physical, mechanical, and chemical stresses. Polyethylene is chemically resistant to organic and inorganic waste, and is resistant to the physical and mechanical stresses of a liner system. Geomembrane liners are expected to prevent leakage by advective flow when installed properly. Advective flow occurs through faulty seams, punctures, tears and pinholes from a hydraulic head gradient across the geomembrane. Mass transport may occur by diffusive mechanisms either in the liquid or solid phase through the geomembrane along with advective flow. Solid phase diffusion is created by voids between the polymer chains due to thermal motion. These geomembrane defects may release a large volume of leachate (Buss et al., 1995).

Many attempts to characterize the flow through the liner system have used the Darcy equation (Jayawickrama et al, 1988; Walton and Sagar, 1990). Applications of these results to field testing has been hampered by the lack of performance data of in-situ liners (Buss et al., 1995). Investigations demonstrate that when water can flow through a geomembrane, it is non-Darcian. Giroud and Bonaparte (1989) measured the hydraulic conductivities of various geomembranes and showed under normal conditions valid results were obtained, and under a high hydraulic-gradient the equations were not strictly valid (Buss et al., 1995).

Migration through a membrane is the diffusive transport of dissolved materials through the barrier under the influence of a concentration gradient. Mass transport under the condition of a negligible gradient provided support for second mass-transport mechanisms (Buss et al., 1995). Results suggest mass transport through sealed pouches have no significant hydraulic difference. The diffusion process has been described mathematically by Frick's first and second law. The mass transport is a product of the diffusion coefficient and solubility. The rate of transport is affected by each stage of the process: uptake, transport, and release.

Transport is the diffusion of the material through the voids toward regions of lower solute. Mass transport overall is dependent on dissolved waste and the rate at which it is transported through the liner. The presence of a chemical concentration gradient perpetuates the transport process. Solute migration is a chemical process where each constituent will be transported at a different rate based on its chemical composition. The composition of leachate produced by permeation suggests the chemical species transported through the liner.

The permeability of plastics by organic compounds is documented. Evidence exists in the wastewater industry that shows drinking water has been contaminated by permeation of trace organic compounds through plastic pipes (Holsen et al., 1991). Transport of solvent through geomembrane liners has been accomplished in laboratory studies, suggesting these mechanisms might be a significant source of waste release from landfills (Park and Nibras, 1993).

The difference in concentration across a barrier is between the concentration in the waste and a zero concentration on the downstream side. The permeation on the downstream side will increase to a maximum based on the rate of transport of the waste further downstream. When highly permeable material underlies a barrier, transport processes such as evaporation and dilution are at work to maintain a low, downstream concentration. The waste on the inside of a liner will depend on its solubility and partition coefficient for the particular system. The solubility will determine the maximum amount of contaminants that can dissolve in the liner (Buss et al., 1995).

Environmental factors also affect the transport rate through liners. Temperature, pressure, and elongation due to tensile stress all play a role. As temperature increases, the solubility and diffusion coefficient will increase creating more transient voids into which waste may migrate. Stessel and Goldsmith (1992) showed membranes that are prestressed beyond their elastic limit show a significant increase in a mass transport rate. Liner uptake may produce integrity breakdowns and change the mass-transport rate.

6.3 GEOMEMBRANE LINER LEAKAGE

Geomembranes underlain with low-permeable material are subject to a hydraulic head, introducing large amounts of leakage where holes exist. Permeation and geomembrane defects are the primary mechanisms causing liner leakage. When no holes exist in the liner, permeation breakthroughs could occur within a couple of weeks (Giroud and Bonaparte, 1989a). Leakage due to permeation is usually much smaller than leakage due to flow through geomembrane holes (Bonaparte et al., 1989a). This section will review geomembrane liner leakage due to defects according to work based on Giroud and Bonaparte (1989a, 1989b) derived from many other studies (Faure, 1984; Fukuoka, 1986; Brown et al., 1987; Jawawickrama et al., 1988).

Leakages through some geomembrane defects are dependent on hydraulic conductivities of the overlying and underlying material. Comparisons of leakage rates have shown that sand overlying a hole may reduce the leakage rate by a factor of up to 50 (Bonaparte et al., 1989a). When a geomembrane with a hole is placed on a layer of low-permeable soil, the soil significantly impedes the flow of liquid through the hole. Leakage through a geomembrane liner in contact with a liquid is governed by the hydraulic head difference. The hydraulic head difference across a liner, assuming saturation, is:

$$\Delta h = h_w + H_L \qquad (6.1)$$

where:

Δh = hydraulic head difference
h_w = hydraulic head acting on top of liner
H_L = liner thickness

6.3.1 Leakage Through Liner with Geomembrane

Leakage in geomembranes overlain and underlain by high permeable material may be attributed to pinholes, large holes, and seam defects. If the hole is not a slit, and has a width less than the thickness of the liners leak may be considered a pinhole leak. Pinholes are manufacturer defects and may be considered pipes in Poiseuille's equation:

$$Q = \frac{\pi \rho g h_w d^4}{128 \eta T_g} \qquad (6.2)$$

where:

Q = leakage rate through a pinhole (m^3/s)
h_w = liquid depth on top of the geomembrane (m)
T_g = thickness of geomembrane (m)
d = diameter of pinhole (m)
ρ and η = density and dynamic viscosity of the liquid (kg/m^3)(kg/(m s)
g = acceleration due to gravity (m/s^2)
* for water at 20°C, ρ = 1000 kg/m^3 and η = kg/(m s)

Geomembrane holes are considered large if the openings have a dimension greater or equal to the geomembrane thickness. The leakage rate is significantly affected by material under the geomembrane. Bernoulli's equation for free flow through an orifice can be used to evaluate the leakage through a hole when the geomembrane is between two pervious layers:

$$Q = C_B a \sqrt{2 g h_w} \qquad (6.3)$$

where:

Q = leakage rate through a geomembrane hole (m^3/s)
a = acceleration due to gravity (m^2)
h_w = liquid depth on top of the geomembrane (m/s^2)
C_B = dimensionless coefficient

Equation 6.3 may be used to calculate geomembrane leakage for two typical hole sizes (Giroud and Bonaparte 1989a):

(1) A 0.08 inch (2 mm) diameter hole (assumed a result of defective seaming); and

(2) A 0.445 inch (11.3 mm) diameter hole that may a result of poor design or damage during placement of overlying materials.

Important parameters for the calculation of geomembrane leakage is the size and frequency of holes and seams. Common criteria for liner design is listed below (Giroud and Bonaparte 1989a):

- An average of one defect per 30 feet (10 m) of field seam can be expected without quality assurance by a contracted independent firm;

- An average of one defect per 1000 feet (300 m) of field seam can be expected with good installation and quality control.

- One hole per acre (4000 m^2), diameter of circular hole 0.16 $inch^2$ (1 cm^2) is recommended

- One hole per acre (4000 m^2), diameter of circular hole 0.005 $inch^2$ (3.1 mm^2) is recommended to calculate the performance in the leachate collection layer under typical operation conditions.

- A frequency of 10 holes/acre (4000 m^2) or more is possible when quality assurance is limited to engineering spot checks of the geomembrane installation.

6.3.2 Leakage through Composite Liners with Geomembranes

Composite liners may have manufacturer defects before they arrive at a site. Also, some space between liners due to wrinkles and irregularities in the soil matrix may occur. Laboratory tests suggest that some lateral migration occurs between the geomembrane and underlying soil (Bonaparte et al., 1989b).

Model testing has established methods for evaluating composite geomembrane liner leakage. Giroud and Bonaparte (1989a, 1989b) have made a thorough review of the composite liner factors affecting leakage. They have ranked the upper and lower bounds with experimental and theoretical results and have proposed a method of interpolation. Using the interpolation method, the following empirical equations have been developed (Giroud et al., 1992):

$$Q = 0.21\, a^{0.1}\, h^{0.9}\, k_s^{0.74} \quad \text{for good contact} \quad (6.4)$$

$$Q = 1.15\, a^{0.1}\, h^{0.9}\, k_s^{0.74} \quad \text{for poor contact} \quad (6.5)$$

where:

Q = steady-state rate of leakage through one hole (m^3/s)
a = area of hole in geomembrane (m^2)

h = head of liquid on top of geomembrane (m)
k_s = hydraulic conductivity of the low-permeable soil underlying the geomembrane the equations are not dimensionally homogeneous (m/s)

The use of these equations should be restricted to cases where underlying soil is less than 10^{-6} m/s and to cases where the head of liquid on top of the geomembrane is less than the thickness of the soil layer under the geomembrane. The leakage rate does not significantly depend on the thickness of the soil liner and does not show a dependence on the thickness of the soil layer. The good contact is a geomembrane with few wrinkles installed on top of a compacted soil layer with a smooth surface. Poor contact is a liner with several wrinkles installed on top of poorly compacted soil with a rough surface. These parameters are highly dependent on engineering analysis when modeling.

6.3.3 Geomembrane Leakage with a Drainage Material

Drainage material placed above or below a geomembrane will not significantly affect flow through a hole. If a geomembrane is placed on drainage material with medium-permeability, the flow toward the geomembrane hole is impeded. Approximate leak rates of flow in the zone of greater porosity of the drainage material are found by averaging the logarithms of the leakage rates obtained with the lower bound and upper bound solutions. The empirical equation may be used:

$$Q = 3\, a^{0.75}\, h^{0.75}\, k_d^{0.5} \qquad (6.6)$$

where:

Q = steady-state rate of leakage through geomembrane hole (m^3/s)
a = area of hole (m^2)
h = head of liquid on top of geomembrane (m)
k_d = hydraulic conductivity of material overlying the geomembrane (m/s)

The equation is intended for the case of gradual drainage and should be used when hydraulic conductivity is greater than 10^{-6} m/s, and should be limited to the case of a hydraulic head pressure on the top liner less than the thickness of the drainage layer (Bonaparte et al., 1992).

6.4 GEOMEMBRANE LINER LEAKAGE STUDIES

The leakage calculation developed by Giroud and Bonaparte (1989a, 1989b) provide upper bound flow rates attributed to top liner leakage at surface impoundments. The results represent the worst case scenario and calculate leakage for a full range of parameters. Potential leakage sources include leakage through the top liner percolated during construction, groundwater infiltration, and consolidation of soil components of the top liner (Bonaparte and Gross, 1990). Lateral flow through liners occurs usually because perfect contact between the geomembrane and the underlying soil is not possible. No complete analytical solution is available to describe this complex mechanism.

Brown et al., (1987) studied leak rates through flaws in geomembrane components of composite geomembrane soil liners. Evidence was presented indicating that erosion of the subbase can occur just below a flaw, particularly when the liquid head is large. Jackawichrama et al., (1988) also detailed an experimental study into leak rates of geomembranes. The results revealed lateral spread of liquid exists between liner and soil base. Despite precautions, leaks have been detected in many facilities. Performance of geomembranes deteriorates rapidly with the first few flaws.

Kastman indicated field seaming operations resulted in one flaw per 49.2 feet (15 m) of the seam. Typical hazardous waste landfills have several hundred kilometers of seam length with several hundred flaws expected. In an analysis of a recent constructed hazardous waste site landfill with an area of 376,544 ft^2 (35000 m^2) and approximately 16,404 feet (5000 m) of seams, more than 500 flaws were found, or one seam flaw per 29.5 feet (9 m). These flaws were found and repaired, but the large number of flaws would suggest that a comprehensive quality assurance and quality control program is a must (Giroud and Fluet, Jr., 1986).

Laine (1991) presented data on seams and found his estimates were approximately twice that of Giroud and Bonaparte (1989a, 1989b) (EPA, 1992). Quality assurance may cost approximately 20-40% extra, but may be well worth the investment. The cost of quality assurance for each stage of design and manufacture is about 1-2% of the cost of the quality assurance of installation. A typical installation cost for a lining system is approximately \$20/m^2 of liner area. Laine (1991) evaluated pinhole seam leaks in the laboratory and at two facilities. The laboratory analysis and leak rate test results indicate small leaks can have a significant contribution to overall liner performance. Leak rates of two, 0.04 inch (0.1 cm) diameter leaks were 1.85 gallons per day (7.0 l/d) and 3.5 gallons per day (13.2 l/d) with one foot of water pressure. Therefore, approximately 42 gallons/acre-day (159 l/4000 m^2-day) may leak from a facility and have an average of 12 holes per acre (4000 m^2).

7. EXPERIMENTAL SET-UP

The ability of a final cover system to prevent infiltration into underlying material is largely determined by the effectiveness of the final cover system. The infiltration layer is the upper soil layer that intercepts rainfall and removes a segment as surface runoff. Part of the rainfall infiltrates the upper soil layer then penetrates the drainage layer. A large part of the water that migrates from the upper soil layer is expected to drain by gravity moving along the geomembrane to a drainage collection point. Finally, some amount of the water will flow through the geomembrane liner as leakage, but this will be much less than runoff and infiltration.

Furthermore, assuming a "worst case scenario" in which all precipitation moves through the upper soil layer and the drainage layer, the rate of movement would be controlled by several factors including the initial soil water content and hydraulic conductivity of soil. Whatever the actual flow rate through the upper soil layer is, it will not be instantaneous; therefore, the real impact of many storms on the barrier layer, and resulting depth of water build-up, should be attenuated by the upper soil.

The water balance of the landfill cover may be segregated into six components: precipitation (P), runoff (R), infiltration (I), evapotranspiration (ET), soil moisture storage (□S), and Leakage (L). These parameters must be properly estimated to balance the water in the cover system. The water balance methods (Section 3) are used to perform a mass balance on the experimental system. These parameters are addressed in the experiment as follows: precipitation is known, runoff, infiltration, and leakage will be collected and measured, evapotranspiration is insignificant due to the short duration of the storm event, and soil moisture storage is known by using a soil matrix that is at field capacity at the start of each experimental run.

As was noted from the literature review of landfill surface runoff modeling (Sections 3,4 & 5), predicting short-duration, high-intensity storm events need a more thorough assessment. A 30-minute duration storm event was selected for the storm simulations. The time increment is sufficient to achieve a "steady state" condition that produces adequate runoff, infiltration, and leakage flux. The peak flows for the simulations were constrained by the rainfall-simulating misters flow rates. The soil moisture content chosen approximates field capacity of the soil at the start of each simulation. Field capacity was achieved by saturating the soil and allowing excess liquid to gravity drain from the system before initiating a run. The field capacity was experimentally determined to occur at approximately four hours after a saturating storm event. The primary parameters chosen for evaluation were landfill slope, storm intensity, and hydraulic conductivity of the soil matrix. An experimental statistical factorial design was developed to evaluate these parameters and potential interactions.

This section discusses the design and construction of the experimental final cover landfill cell. The cell was designed to simulate a landfill cover for a short-term high-intensity storm event. The cell consisted of a base structure built of pressure-treated wood, a geomembrane liner system, a simulated rainfall system, soil cover material, and recording devices.

7.1 CELL STRUCTURE

A bench scale model of a geomembrane-lined final cover system was constructed to test runoff, infiltration, and leakage components. The initial desired cell configuration was 18 inches (45.7 cm) of underlying soil, a geomembrane liner system, 18 inches (45.7 cm) of cover soil as the overlying material, and a reasonable length for runoff. However, constraints in availability of material to makeup the cover soil lead to configuring the final cover system to approximately 12 and 10 inches (30.5 and 25.4 cm). The cell was built approximately eight feet (2.44 m) in length, two feet (0.61 m) in width, and three feet (0.92 m) in height. Figure 2 shows an isometric view of the experimental cells base structure. The cell structure consists of a base frame, adjustable framed floor, and water system support frame.

Pressure treated 3.5 inch by 3.5 inch (8.9 cm x 8.9 cm) wood beams were used as the main structural frame for the cell as shown on the exploded view of the cell in Figure 3. The base floor of the cell was constructed of 0.5 inch (1.27 cm) plywood fastened to a frame constructed of 1.5 inch by 3.5 inch (3.8 cm x 8.9 cm) wood studs. The base floor of the cell had a level surface hinged at the outlet end to allow manual adjustment of the slope (level to 10% slope) as shown in Figure 4. The sidewalls of the cell structure were 0.5 inch (1.27 cm) plywood fastened to the frame as shown in Figure 3.

Several other wood structures were constructed for data collection. Four framed pilings, approximately three feet (0.91 m) in height, were placed on the four corners of the cell to support the rainfall simulation system and wind protection cover in Figure 2. Also, two bench areas were constructed to support the data collection system and runoff from the cell (not shown in drawings).

7.2 LINER GEOMEMBRANE SYSTEM

The liner system was designed to simulate a final cover system constructed with a high density polyethylene geomembrane that complies with the State of Florida landfill design standards. The geomembrane was seamed to form a rectangular cell resembling a box with no lid. A plan view and a cross section view of the geomembrane liner system are shown in Figures 5 and 6. The liner boxes were designed to be slipped in and out of the structure when the discharge end is left open. The drainage collection liner was placed in the cell directly onto the plywood floor and is three-sided, allowing for discharge at the open end. A strip of geonet was cut and placed to fit in the floor of the drainage collection cell to provide for flow of liquid leaking through the primary liner. The bottom liner extends past the cell structure by several inches for collection of liquid. The primary liner, placed in the drainage collection liner, has a drainage slot at the discharge end allowing infiltration to escape. The drainage liner also extended several inches farther from the cell drainage collection layer, providing a second collection point as shown in Figure 7. A hole with an area of 0.393 inch^2 (1 cm^2) and a diameter of 0.444 inches (1.13 cm) was placed at the centerline of the cell geomembrane liner and approximately 30 inches (76.2 cm) upgradient from the discharge end in the primary liner. A strip of geonet was placed on the cell floor with a geotextile material overlying the primary geonet and up the sidewalls of the primary liner as shown in Figure 6. This served to prevent the soil of the base layer from fouling the hole in the geomembrane and to prevent soil from slipping down along the wall and reaching the geonet.

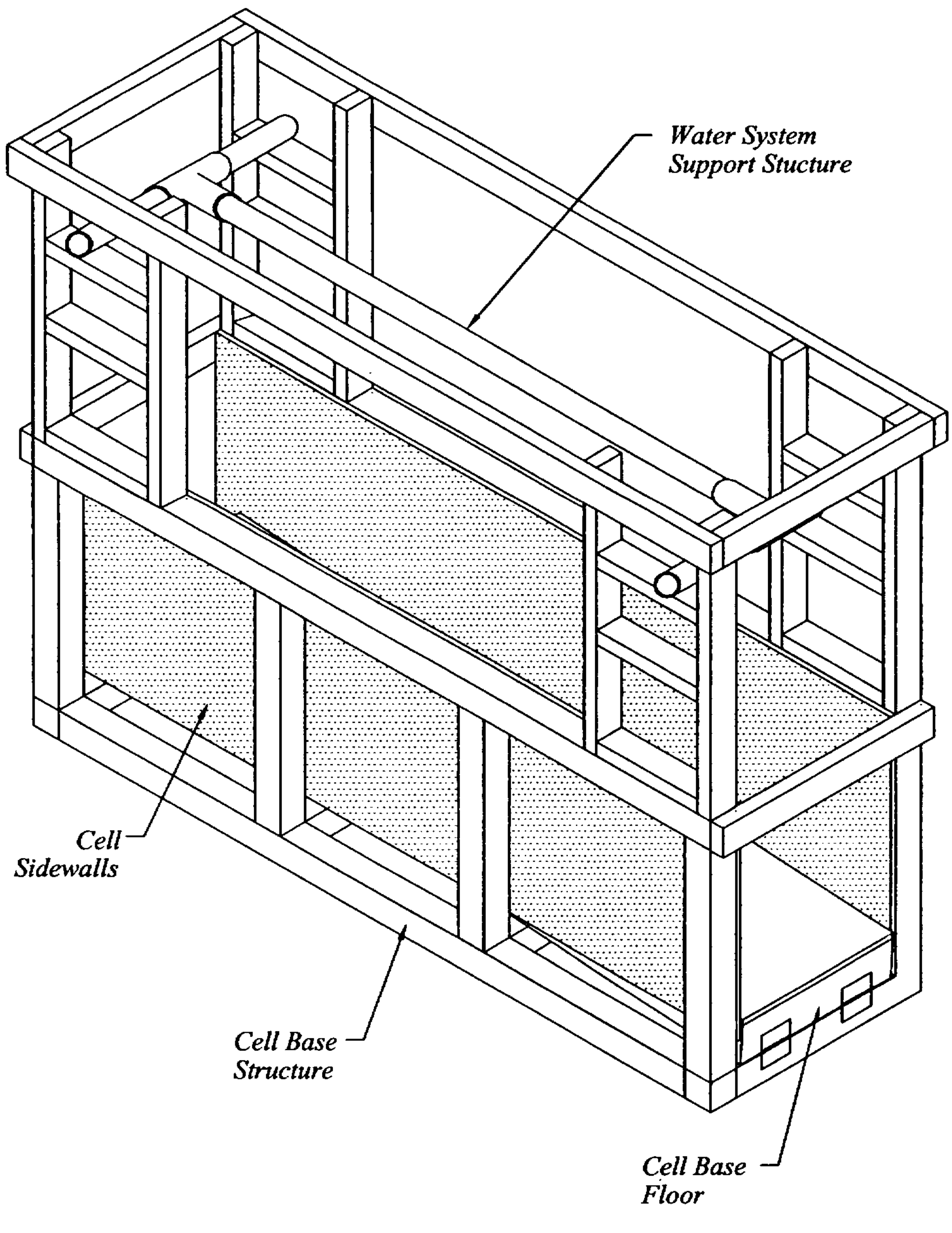


Figure 2 Isometric View of the Experimental Cell Base Structure.

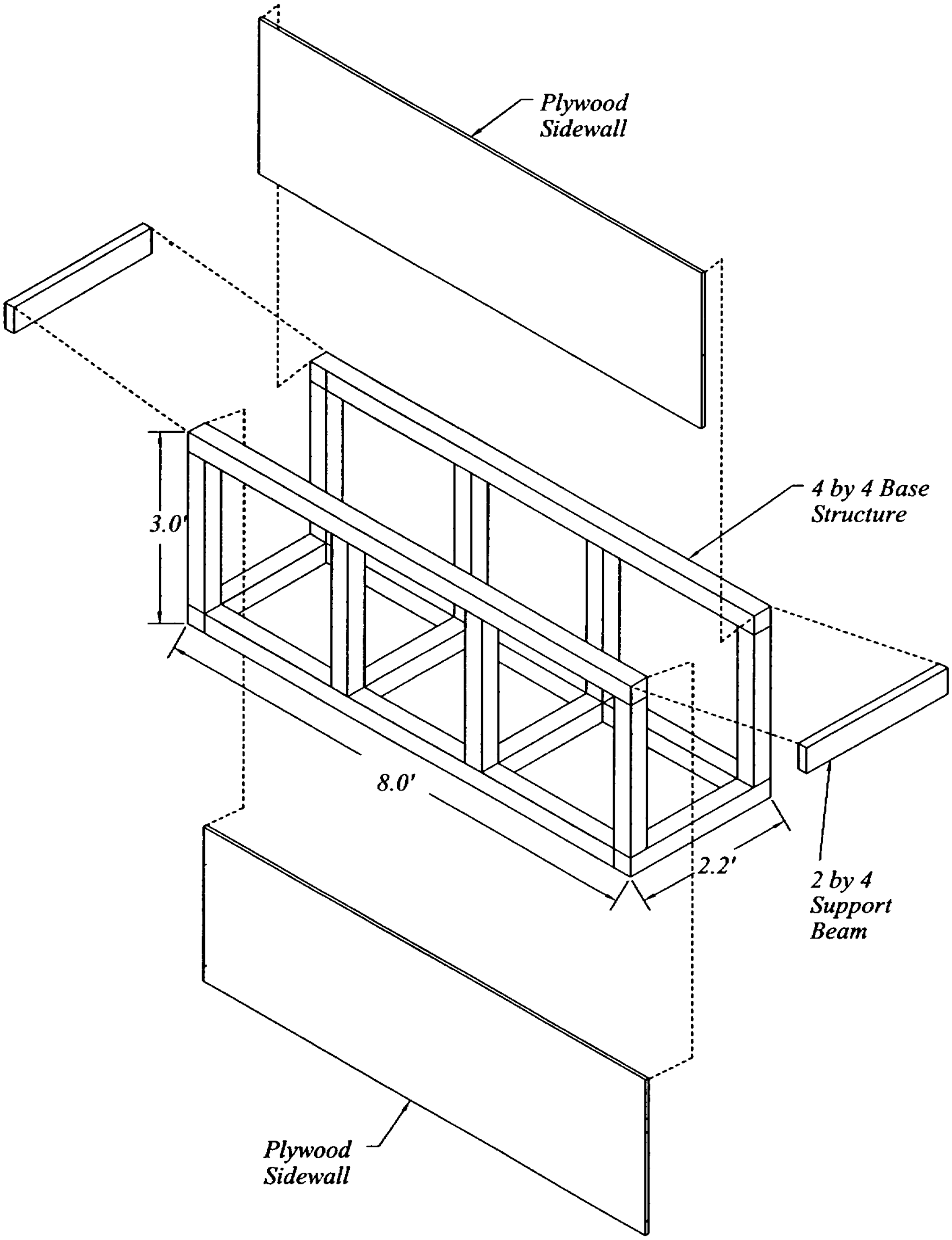


Figure 3 Exploded View of the Experimental Cell Base Structure.

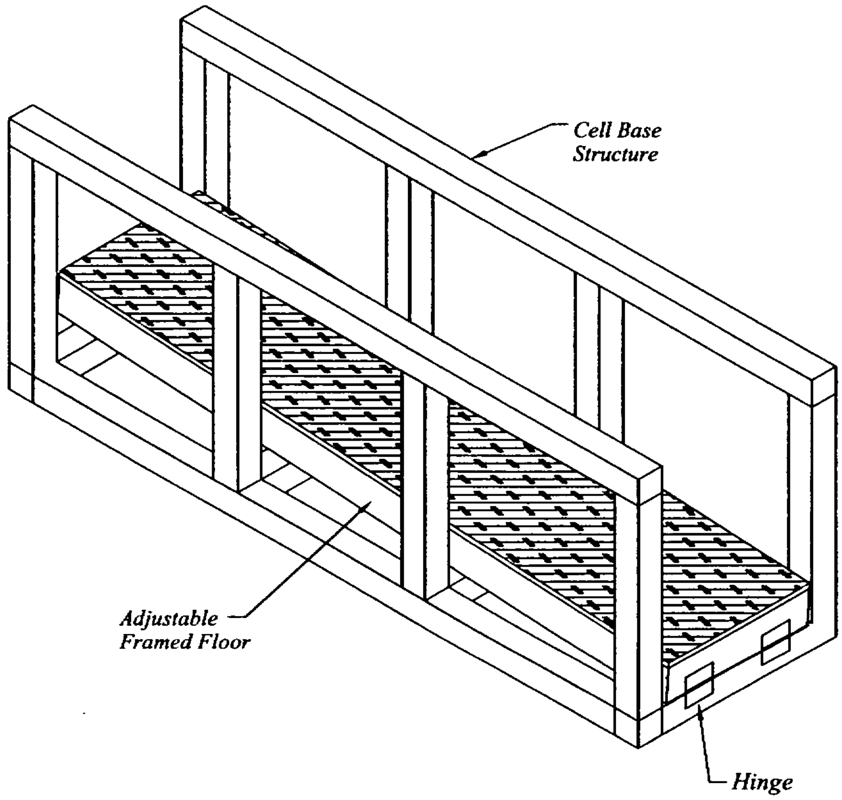


Figure 4 Adjustable Experimental Framed Floor.

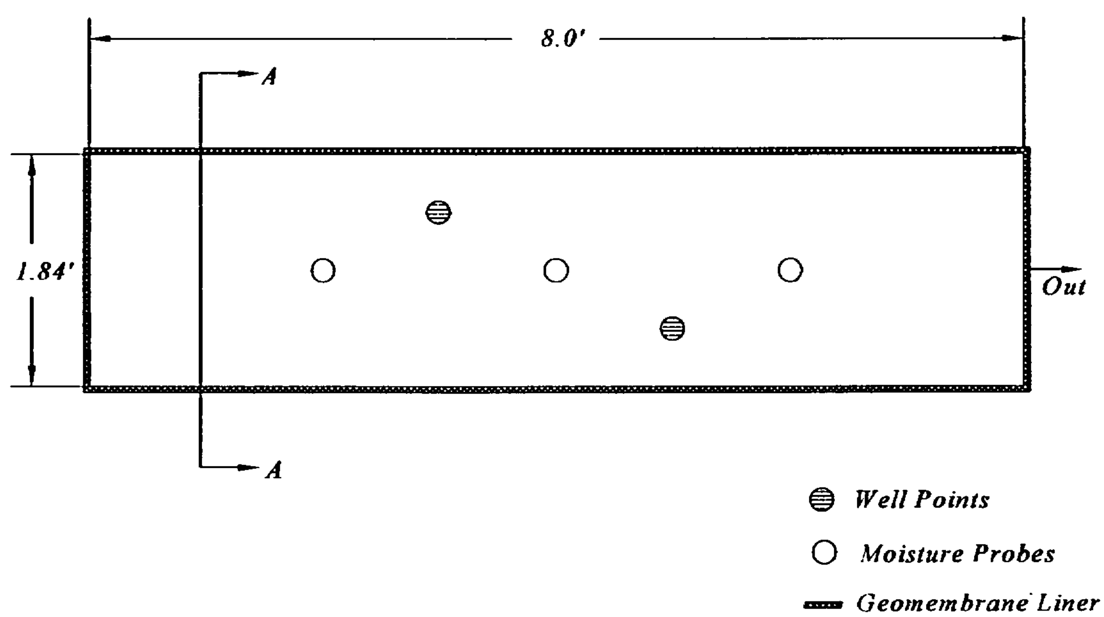


Figure 5 Experimental Liner System Plan View.

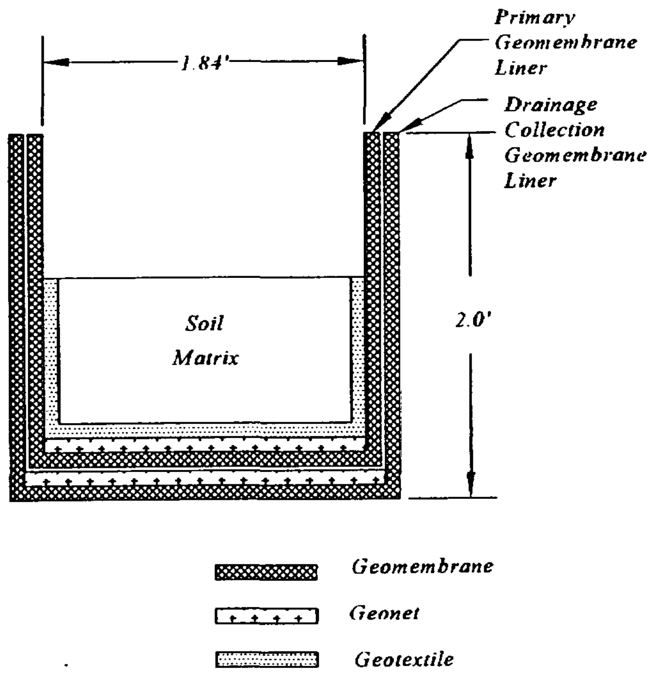


Figure 6 Experimental Liner System Section A-A.

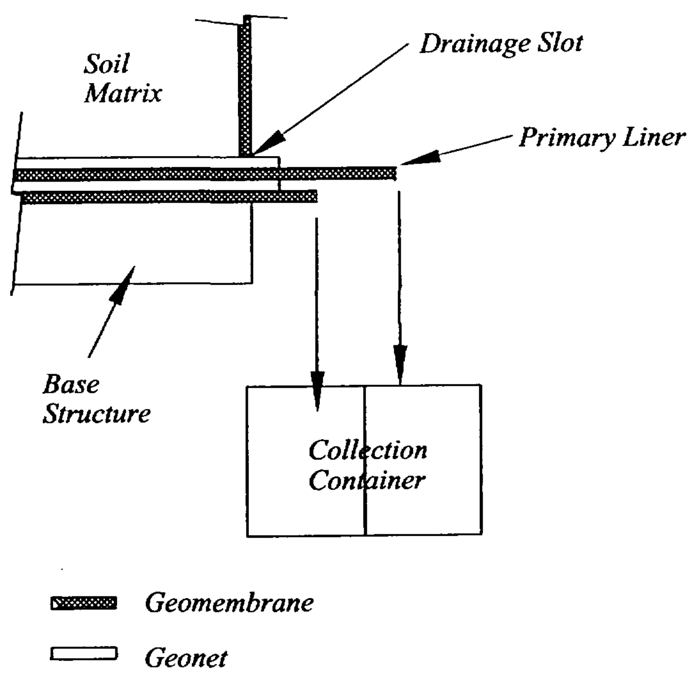


Figure 7 Experimental Collection Points.

7.3 WATER SYSTEM

The water system was suspended from vertical supports that are extended from the four corners of the base structure, approximately three feet (0.914 m) in height above the soil cover as shown in Figure 2. The supports had slots to adjust the slope on the rain simulation system. A three inch (7.6 cm) PVC pipe system was used as a base to support the outlets as shown in Figure 8. A 0.5 inch (1.27 cm) diameter polyethylene tube was duct taped to the PVC pipe. From this tube seven Raindrip Inc., R166C Adjustable Misters with four inch extensions' 4-7 GPH @ 25 psi rain simulating values were attached at 12-inch intervals along the length of the cell as shown in Figures 9 and 10. The storm event system consisted of a influent water flowmeter and rainfall simulating adjustable misters. The water was supplied from a municipal water supply from an outside tap. A PVC system of valves controlled the quantity of flow utilizing a flowmeter connected between the valves and outlets. A Shields Flowmeter with a range of 0.0243 gpm to 1.273 gpm (0.0918 l/min to 4.82 l/min) was used to gauge the influent water supply. The water flowed from a 0.5 inch (1.27 cm) PVC pipe into the 0.5 inch (1.27 cm) polyethylene hose, positioned along the centerline of the cell approximately 35 inches (88.9 cm) over the soil. The misters were equally placed at 12-inch (30.48 cm) intervals as shown. The mister system can supply 28 gph to 49 gph (106 l/hr to 186 l/hr) and have a water distribution that fits the closed cell system. The mister system was raised or lowered to provide a two foot (0.61 m) diameter wetting area on the landfill cell surface. The circular wetting areas provided the best water coverage on the cell surface of the rainfall systems examined for this study. The cell was sectioned into 18 grid as shown in Figure 11. The average percent distribution in each grid was calculated by a mass balance of influent water compared to the collected effluent in each grid section as shown in equation 7.1. Distribution varied, with 12 of the 18 sections falling into the range of 3% to 7% of the total rainfall.

$$D = \frac{\sum Q_{col}}{\sum Q_{tot}} x100 \qquad (7.1)$$

where:

D = Percent Water Distribution (%)

$\sum Q_{col}$ = Total Water Collected in Grid (kg)

$\sum Q_{tot}$ = Total Water into System (kg)

7.4 SOIL BASE MATERIAL

The soil matrix material (two experimental configurations) was placed in approximately four-inch (10.2 cm) compacted lifts for a total depth of 12 inches (30.5 cm) for soil #1 and 10 inches (25.4 cm) for soil #2 as shown in Figure 12. The difference in depths was due to a shortage of material for cell #2, but does not effect the experimental results. The soil materials were tested to assess the soil classification, effective saturated hydraulic conductivity, initial moisture content, specific gravity, and porosity. Table 2 provides a summary of the physical properties of the base material. Figure 6 shows the cross section of the cell and where the base material is placed in the cell. The soil surface of the cell allows runoff to travel onto a geomembrane shelf and into collection containers as shown in Figure 12.

The containers collecting the runoff from the soil surface, the underlying geomembrane, and that leaked through the holes in the geomembrane were weighed after each timed run to determine the mass rate of effluent. The total mass of effluent water was then compared to the influent water mass rate to assess the balance or closure of the water applied to that collected.

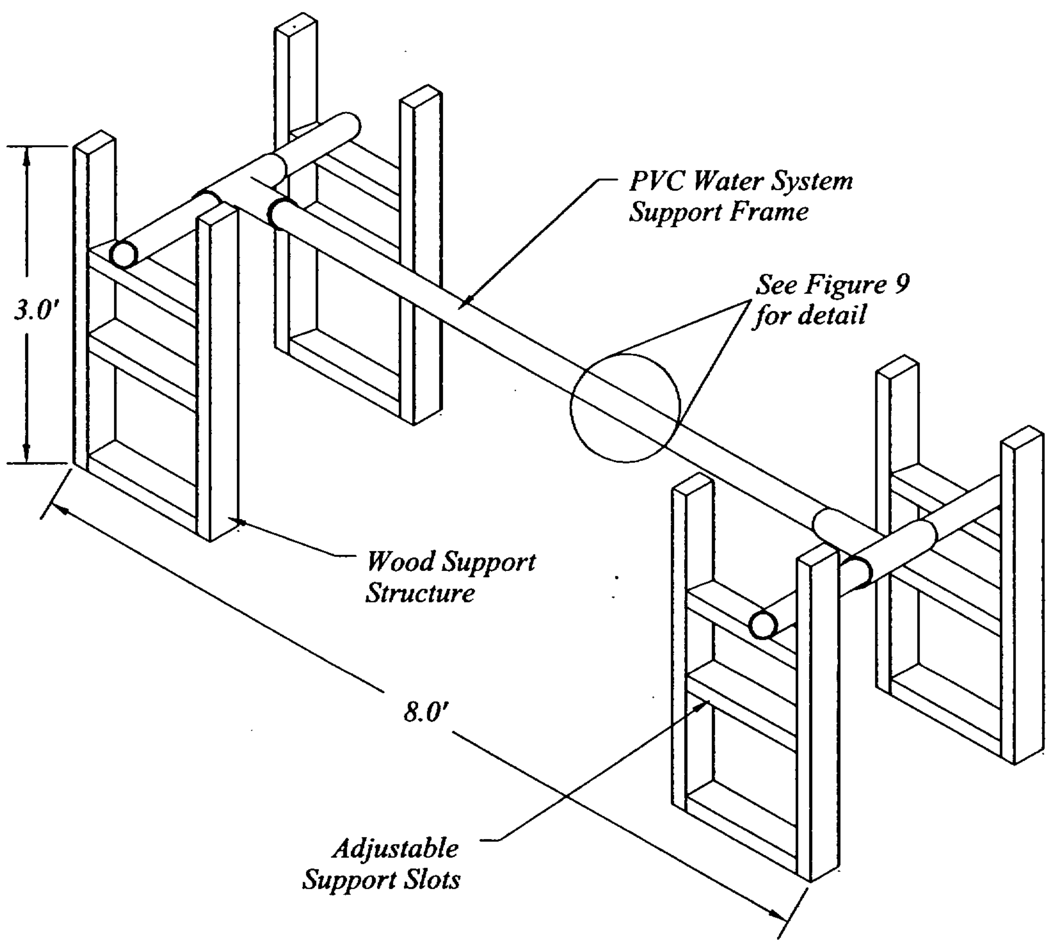


Figure 8 Water System Support Frame.

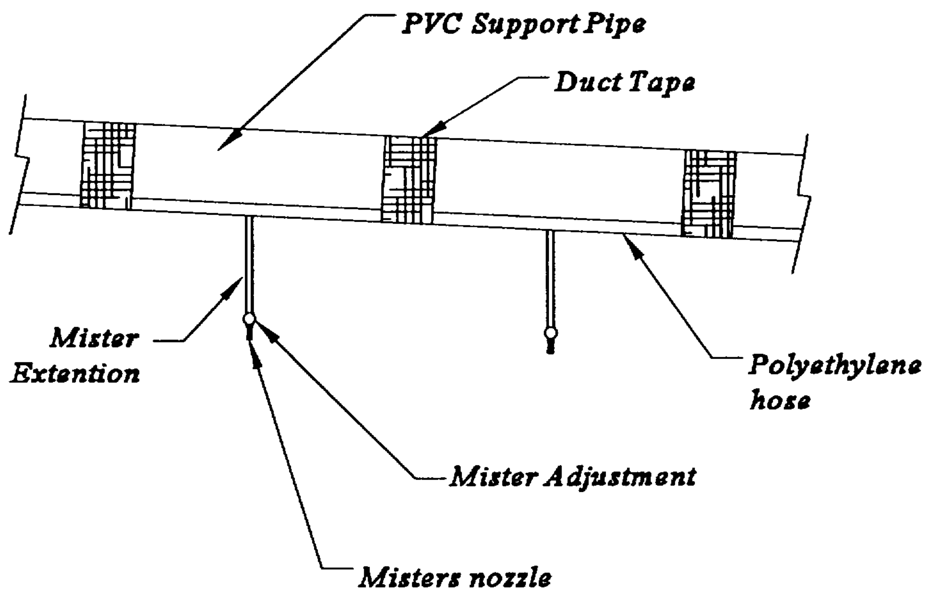


Figure 9 Mister Support System.

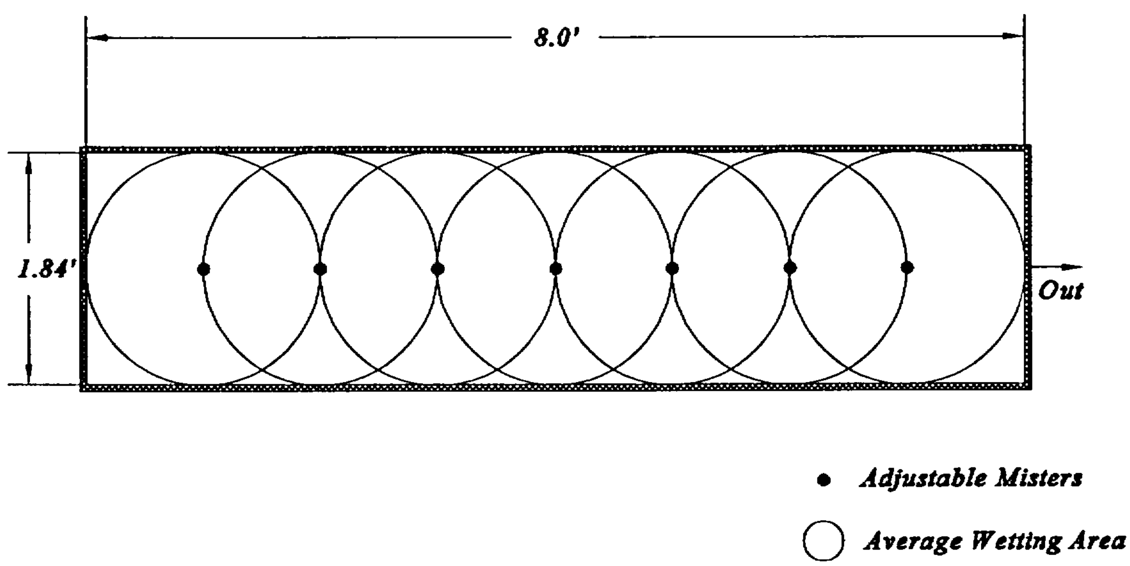


Figure 10 Water System Plan View in the Experimental Cell.

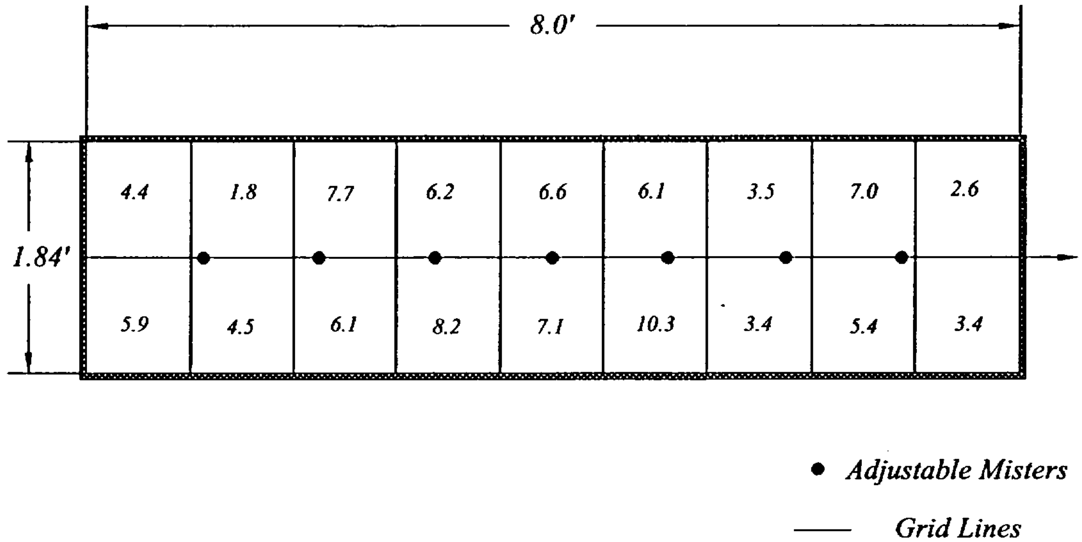


Figure 11 Water System Percent Distribution in the Experimental Cell.

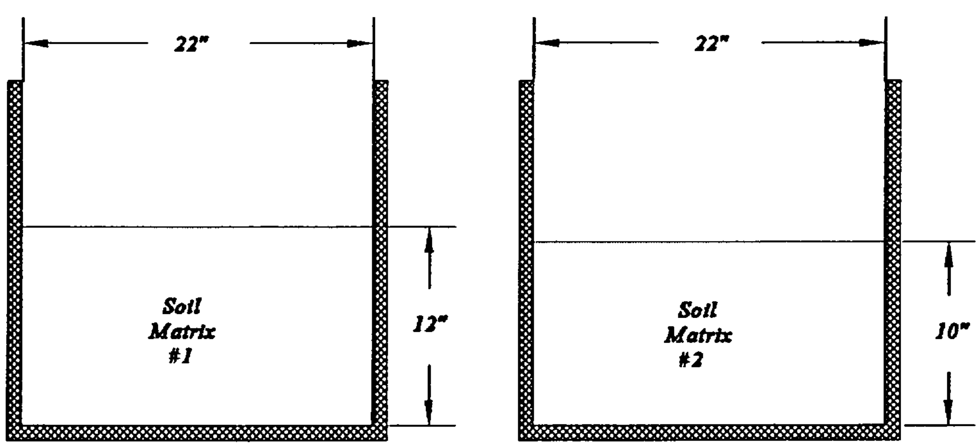


Figure 12 Experimental Soil Matrix.

Table 2 Physical Properties of Base Materials.

Properties	Soil #1	Soil #2
Soil Classification (USC)	SP	SP
Porosity (vol/vol)	0.372	0.371
Initial Soil Moisture Content (%)	17.1	13.9
Effective Saturated Hydraulic Conductivity (cm/sec)	1.6×10^{-4}	1.9×10^{-5}
Layer Thickness (inch)	12	10
Cover slope (%)	2,5,10	2,5,10
Specific Gravity	2.70	2.70
Coefficient of Uniformity (Cu)	2.0	1.75
Coefficient of Curvature (Cc)	0.98	0.89

7.5 RECORDING DEVICES

The cell was initially constructed with two well points and three moisture probes. Their locations are shown in Figure 5. The one inch (2.54 cm) diameter slot well-points were capped at the bottom and measure the pressure head on the geomembrane liner system. A floating bobber was used with a graduating scale to display effective head from the well point. After initial runs of the system the well point were removed due to insufficient buildup of pressure head on the liner. Three Unidata Moisture Probes were placed at six inch (15.2 cm) depths and evenly spaced along the centerline of the system. The moisture data was collected by a Starlogger Model 6004B 128K - Unidata, Australia, and downloaded onto a IBM PC-compatible Laptop. The collection containers were placed at the discharge ends of the liner to collect runoff, infiltration, and leakage, as shown in Figures 7 and 13. The liquid mass collected after each run was measured with a AND FW-150K electronic scale.

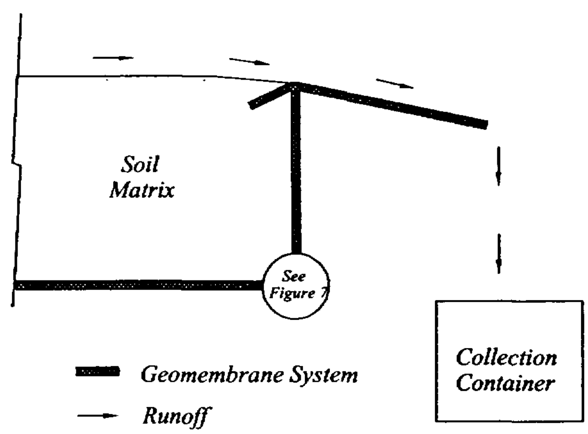


Figure 13 Runoff Collection off of the Experimental Cell.

8. EXPERIMENTAL RESULTS

As was noted from the literature review of landfill surface runoff modeling (Sections 3, 4, & 5), predicting short-duration, high-intensity storm events needed a more thorough assessment. A scenario was developed to assess runoff in such circumstances. A 30-minute duration storm event was selected for the storm simulations, long enough to achieve a steady-state condition. Further, the peak flows were constrained by the rainfall-simulating mister flow rates. The soil moisture content chosen approximates field capacity of the soil at the start of each simulation. Field capacity was achieved by saturating the soil and allowing excess liquid to gravity drain from the system before initiating a run. The field capacity was experimentally determined and occurs at approximately four hours after a saturating storm event. The primary parameters chosen for evaluation were landfill slope, storm intensity, and hydraulic conductivity of the soil matrix. An experimental statistical factorial design was developed to evaluate these parameter interactions.

Factorial designs facilitate the evaluation of the interactions of variables and thus assist the process of model building. These experimental designs provide estimates of the "effects" of the variables interactions, while assuring that such interactions are not experimental errors (Box et al., 1978). In statistical factorial designs, high and low values (within the boundary of reason) for the parameters are used to set up a matrix. The storm events for this project were a 2-year frequency event (0.619 gal/min or 2.3 l/min) and a 10-year event (0.77 gal/min or 2.90 l/min) acquired from rainfall intensity curves for the Tampa area from Volume 2 - Procedures Florida Department of Transportation Drainage Manual. The final cover of landfill crowns typically slope at 2% to 5%. In this experiment, slopes were evaluated at 2%, 5%, and 10%. Typical values for the hydraulic conductivity in actual constructed landfills is on the order of 3.9×10^{-4} in/s (1×10^{-3} cm/s). The hydraulic conductivity of the soil layers used in the experiment were 6.5×10^{-5} inch/sec (1.6×10^{-4} cm/s) and 7.5×10^{-6} inch/sec (1.9×10^{-5} cm/s). The experimental hydraulic conductivity values (higher order of magnitude) are not expected to adversely affect the results. Simulations were performed on all combinations of the primary variables. (Note: This study does not evaluate runoff or infiltration from the sideslopes of geomembrane liner landfill surfaces. The steep sideslopes (20 to 33%) are expected to provide minimal opportunity for infiltration)

At the start of the experimental program, the reliability of the system and data recording process was established in a set of validation simulations. For these simulations, the slope and the hydraulic conductivity were held constant (i.e., 5% and 6.5×10^{-5} inch/s) while the values for storm intensity were varied at 0.526, 0.608, 0.697, and 0.766 gal/min (1.99, 2.30, 2.64, and 2.90 l/min). Figure 14 shows a plot of storm intensity vs. runoff flux data. The data has good replication and suggests a linear relationship clearly exist between the variables. At the upper range of storm intensity (i.e., 2.9 l/min) the incident runoff began to exceed the capacity of the experimental apparatus. Consequently, the variance between replication at this intensity level is greater than for other storm intensities.

Tests were performed to determine the hydraulic characteristics of the cover soils before running simulations. The two soil types used in the experiment were classified as SP or poorly graded sand using the Unified Soil Classification System (USC) and their hydraulic conductivities were 6.5×10^{-5} inch/sec (1.6×10^{-4} cm/s) and 7.5×10^{-6} inch/sec (1.9×10^{-5} cm/s) using the constant head testing method (ASTM D2434). Appendix I and II presents the computations of soil grain size distribution used for categorizing soils the constant head testing method. The initial moisture content for the two soil profiles was calculated using water content determination method (ASTM 2216). Three samples of each soil profile were extracted at two-foot increments along the centerline of the cell. The samples were taken approximately four hours after the soil had been saturated which represents field capacity. The time increment allowed the liquid in excess of field capacity to pass through the cell. As placed at field capacity, soil moisture content reported by mass is approximately 17% and 14% for the experimental soil covers. Testing results may be found in Appendix III.

A total of 61 experimental runs were made from February 27, 1997 to June 25, 1997. The infiltration and leakage parameters were monitored although the primary interest was to evaluate the runoff. Total experimental data from the runs are presented in Appendix IV. The experimental results will be presented as follows: water mass balance across the experimental apparatus; factorial analysis of the main effects and interactions of the principal variables; statistical modeling of the system using regression analysis; and comparison of data to the HELP model.

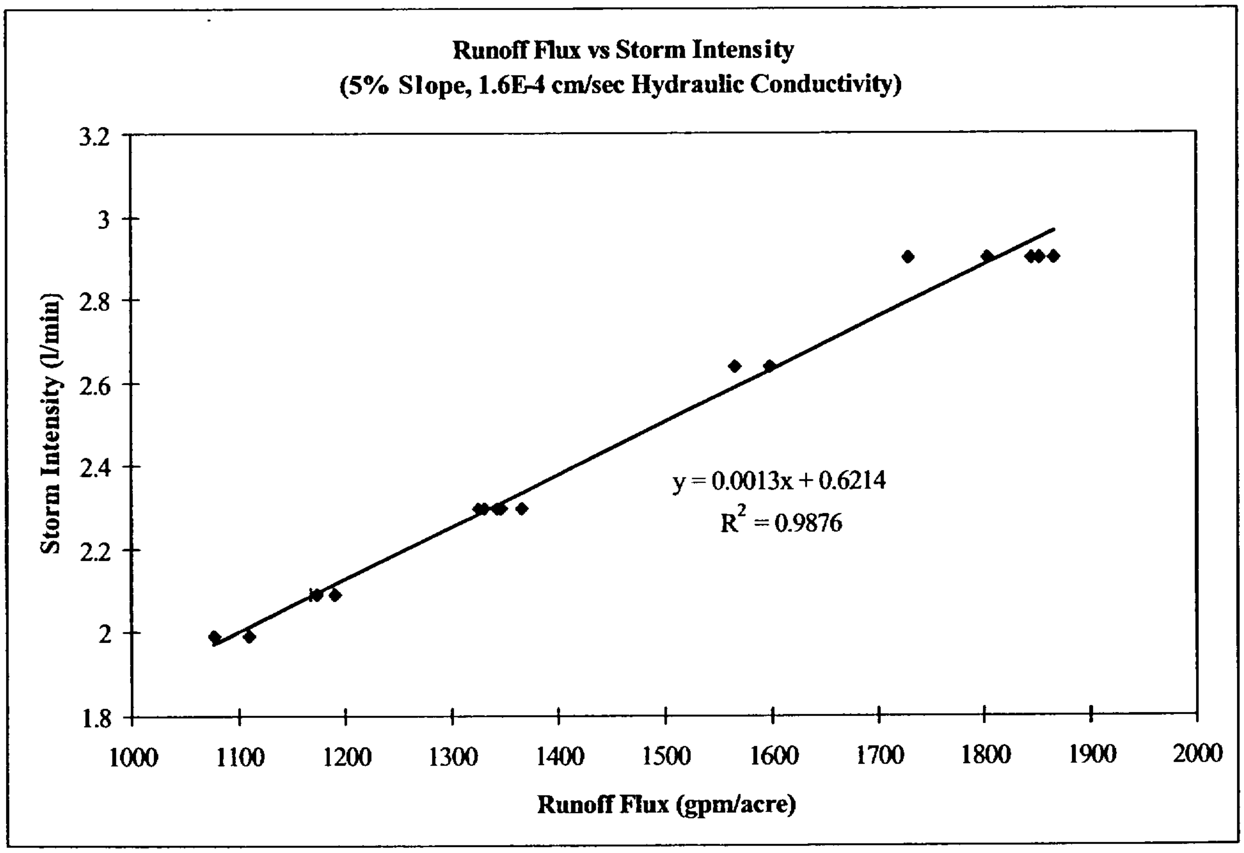


Figure 14 Runoff Flux vs. Storm Intensity.

8.1 WATER MASS BALANCE

The objective of this experiment was to measure the water movement through the final cover system. The liquid is collected from three locations in the experimental cell: (1) Runoff is collected off the top of the soil liner; (2) Infiltration is collected off the top of the primary geomembrane; and (3) Leakage is collected from the secondary geomembrane. Table 3 shows summarized results of the average runoff, infiltration, and geomembrane leakage flux and their standard deviations. A minimum of three replicate runs were used to compute the average values for each data point. Flux values may be plotted against storm intensity to produce relationships similar to that of Figure 14. Column 10 (Average Closure %) presents a mass balance of the system based on the influent through the rainfall simulation system compared with the effluent collected out from the runoff, infiltration, and leakage (calculated using equation 8.1). The average mass balance for the experimental simulations ranged from 93.3% to 96.7%. The low standard deviations for average runoff flux and the high closure rate indicate good reliability of the data.

$$AverageClosure = \frac{\overline{R} + \overline{I} + \overline{L}}{TotalFlux} \times 100 \qquad (8.1)$$

where:

Average Closure = mass balance of liquid applied and collected (%)
$\overline{R}$ = average runoff flux (gpm/acre)
$\overline{I}$ = average infiltration flux (gpm/acre)
$\overline{L}$ = average leakage flux (gpm/acre)
$TotalFlux$ = amount of influent flux (gpm/acre)

Table 3 Experimental Test Results.

Storm Intensity (gal/min)	Hydraulic Conductivity (inch/sec)	Slope (%)	Average Runoff Flux (gpm/acre)	Standard Deviation	Average Infiltration Flux (gpm/acre)	Standard Deviation	Average Leakage Flux (gpm/acre)	Standard Deviation	Average Closure (%)
0.61	6.5×10^{-5}	2	**1360**	**18.5**	151	11.9	208	5.6	**95.7**
		5	**1341**	**15.6**	161	14.6	177	17.9	**93.3**
		10	**1390**	**46.5**	347	8.3	1	1.6	**96.7**
	7.5×10^{-6}	2	**1693**	**25.5**	41	2.6	0	0	**96.5**
		5	**1696**	**10.0**	35	2.9	0	0	**96.3**
		10	**1695**	**32.8**	42	3.1	0	0	**96.6**
0.77	6.5×10^{-5}	2	**1724**	**5.3**	174	51.1	240	15.5	**94.3**
		5	**1804**	**66.2**	193	50.1	206	31.5	**94.8**
		10	**1731**	**25.2**	387	23.3	9	10.1	**94.0**
	7.5×10^{-6}	2	**2086**	**20.4**	49	3.1	0	0.7	**94.2**
		5	**2105**	**17.4**	46	1.6	1	1.2	**94.9**
		10	**2112**	**29.1**	61	2.6	0	0	**95.8**

8.2 FACTORIAL ANALYSIS

The purpose of the factorial design matrix was to statistically test as many parameters as possible simultaneously. A matrix was used to analyze the runoff data using Yates algorithm calculations (Box et al., 1978) and is presented in Table 4. There are two slope values (S), two hydraulic conductivity values (HC), and two storm-water intensity values (ID) designated as either high (+) or low values (-). Columns two, three, and four (ID, S, HC) show the variables tested in each of the eight scenarios or permutations. Column 10 (estimate) shows the actual effects and interactions of the variables listed in column 11 (identity). The high estimates of the effects storm intensity (ID) and hydraulic conductivity (HC) indicate they are the major factors affecting the system and, since the interaction between the two is low (ID-HC = 1.0), were acting independently of each other. The slope parameter appears to have minimal effect on the runoff, as shown by its low effect value (0.6). Consequently, it is concluded that the main independent variables that affect runoff are storm intensity and soil hydraulic conductivity, whereas the slope of the soil surface is not a significant factor within the range of 2% to 10%.

Table 4 Experimental Yates Algorithm.

Variables	-	+
Intensity/Duration (ID)	0.61 gal/min (2.3 l/min)	0.77 gal/min (2.9 l/min)
Slope (S)	2%	10%
Hydraulic Conductivity (HC)	6.5×10^{-5} inch/sec (1.6×10^{-4} cm/sec)	7.5×10^{-6} inch/sec (1.9×10^{-5} cm/sec)

Run	ID	S	HC	Y	1	2	3	divisor	estimate	identity
1	-	-	-	52.23	118.39	238.17	529.3	8	66.2	Avg
2	+	-	-	66.16	119.78	291.13	58.04	4	14.5	ID
3	-	+	-	53.35	145.02	26.97	2.48	4	0.6	S
4	+	+	-	66.43	146.11	31.07	0.1	4	0	ID-S
5	-	-	+	64.97	13.89	1.39	52.96	4	13.2	HC
6	+	-	+	80.05	13.08	1.09	4.1	4	1	ID-HC
7	-	+	+	65.06	15.08	-0.81	-0.3	4	-0.1	S-HC
8	+	+	+	81.05	15.99	0.91	1.71	4	0.4	ID-S-HC

8.3 REGRESSION MODELING

Regression analysis serves as a basis for drawing inferences about relationships among parameters in a system. Statistical models are built using procedures and conclusions drawn in a regression analysis depending on the assumption of a regression model. A model is perceived as the mechanism that generates the data on which the regression analysis is conducted and is usually in algebraic form. For example, if one assumes that the relationship is well represented by a linear structure, a suitable model may be given by:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + \ldots\ldots. B_nX_n + \varepsilon$$

where:

$B_0, B_1, \ldots.. =$ Regression Coefficients
ε = Model Error

Procedures in regression analysis involve drawing conclusions about regression coefficients. The □ term is included to account for any model error and essentially describes the random disturbances. The above model is classified as linear and regression procedures involve fitting the model to a set of data. The term, fitting, involves estimating the regression coefficients and corresponding formulations of the fitted regression model, an empirical device that is the basis of any statistical inference. Measure of the quality of fit is an important statistic that form the foundation of analyzing any regression model.

The experimental program tested a simulated landfill cover cell for moisture movement. Specifically, surface runoff from storm events. Slope, hydraulic conductivity, and storm intensity were chosen for the statistical evaluation based on water balance methods. The Yates algorithm (Table 4) analysis established storm intensity and hydraulic conductivity the main factors affecting predictive modeling of the system. Multiple linear regression techniques were used in the model building process. The statistical analysis used 51 simulations, with the other 10 deemed as outliers. These 10 were considered outliers because they did not achieve a mass balance of at least 90% or appeared to have some experimental error. Errors associated with the simulations were as follows: runs 15,16,17 had a faulty collection container; run 58 had atmospheric rainfall enter into the closed system; and runs 6,7,11,26,27,48 were low due to a loss of soil saturation (18, 30, and 9 days) between runs. Several other runs (8,9,10,12,13,14) were deemed insufficient for the leakage and infiltration parameters because of intermingling of liquid in the collection containers. The system appeared to require several runs after a prolonged drying period to achieve equilibrium in the soil matrix. The experimental data was converted from a mass parameter to flux values, gallons per minute-acre, for a more descriptive output. Regression summary outputs of the data are presented in Appendix VII.

8.3.1 Runoff

Modeling the runoff is the principal concern and uses storm intensity, slope, and hydraulic conductivity to predict runoff flux values. A linear structure is clearly seen from the experimental data. Table 5 shows the runoff regression models proposed. The correlation coefficients for the two runoff models are .983 and .984, respectively, indicating an excellent data fit. The slope parameter in the range tested, 2% to 10%, had little effect and may be deleted from the regression equation for simplification. Residual plots of the three primary variables are presented in Figure 15. As parameter values increase the residuals become increasingly spread indicating a funnel affect where, as the parameters are increased the system becomes more unstable. If the variance were greater, the data may require transformation, but it appears insignificant over the range of variables tested in this study. The residual plots have a normal error response for the runoff model. Storm intensity (b) and hydraulic conductivity (a) clearly have a good linear fit as shown on Figure 16, but the slope (c) parameter has no statistical significant impact. The hydraulic conductivity evaluation may be limited due to the 6.5 x 10^{-5} inch/sec (1.6 x 10^{-4} cm/s) - 7.5 x 10^{-5} inch/sec (1.9 x 10^{-5} cm/s) range of the variable (2 levels) in the study. Although additional ranges of soil hydraulic conductivity were explored in the study, the soil matrix was too impermeable to provide reliable data. The runoff model presented is an excellent estimator of runoff flux when the soil matrix is approximately at field capacity.

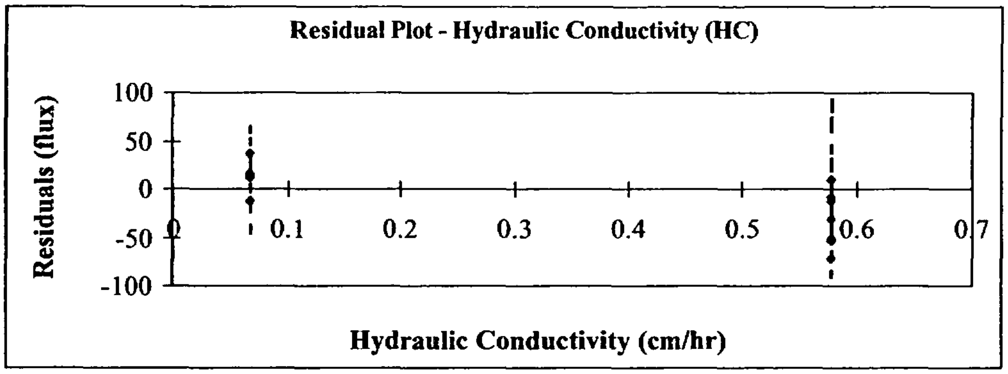
8.3.2 Other Parameters

Infiltration flux, leakage flux, and runoff + infiltration flux parameters were also analyzed for possible predictive characteristics. Table 5 presents these models and their correlation coefficients. The infiltration flux was examined using the same parameters as the runoff model and has a correlation coefficient of 0.73, suggesting a less pronounced linear fit. The infiltration analysis consisted of 45 experimental runs with six observations omitted due to insufficient infiltration observations. Two leakage models are presented: a 3-variable model using 45 observed events and a second model using 27 observed events. The second model uses only data from the first soil matrix where leakage was reported. Data trends for the leakage models were difficult to predict due to the second soil profile producing minimal leakage, which effectively gave only two parameters to evaluate. Residual plots of the 3-variable model are presented in Figure 17. Figure 18 conclusively shows a trend in the data that indicates as the slope is increased the leakage flux decreased. The line fit plots for the slope clearly indicate a linear fit with a correlation coefficient of 0.99 for the second model. The 3-variable model shows a linear trend but is skewed by the second soil matrix producing minimal leakage as seen on Figure 18b. The leakage models have correlation coefficients of 0.76 (3-variable) and 0.91 (second model). The leakage model may be enhanced by further evaluation of soils with a larger range of hydraulic conductivity then the range used in this study.

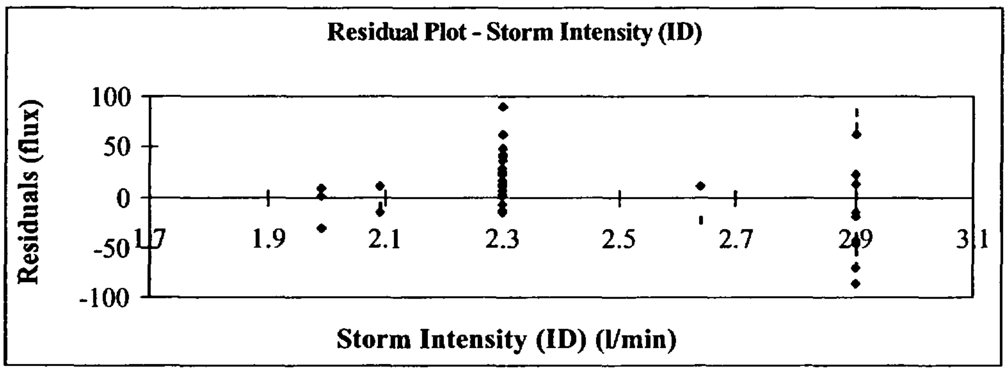
The models presented for the prediction of runoff flux has credibility based on the statistical analysis of the experimental results. The leakage model suggested a strong correlation exists between slope and leakage; further evaluation is warranted. The proposed experimental models may be carefully used within the range of the variables tested.

Table 5 Regression Models.

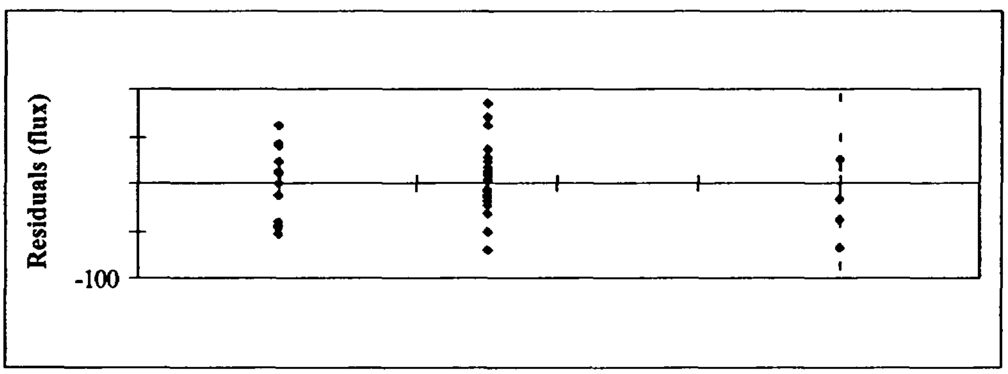
Parameters	R = Runoff Flux (gpm/acre) I = Infiltration Flux (gpm/acre) L = Leakage Flux (gpm/acre) HC = Hydraulic Conductivity (cm/sec) ID = Storm Intensity (l/min) S = Slope (%) R^2 = Correlation Coefficient N = observations
Runoff Model (3-variables)	**R = -654.19(HC) + 738.94(ID) + 2.88(S)** R^2 = 0.984 N = 51 95 % Confidence Interval = -697.99 < HC < -610.39 = 727.59 < ID < 750.29 = -1.02 < S < 6.78
Runoff Model (2-variables)	**R = -653.41(HC) + 744.93(ID)** R^2 = 0.983 N = 51 95 % Confidence Interval = -697.71 < HC < -609.10 = 736.89 < ID < 752.97
Infiltration Model (3-variables)	**I = 318.33(HC) - 17.19(ID) - 13.29(S)** R^2 = 0.73 N = 45 95 % Confidence Interval = 251.06 < HC < 385.60 = -33.95 < ID < -0.29 = 7.53 < S < 19.05
Leakage Model (3-variables)	**L = 308.48(HC) + 21.97(ID) - 14.14(S)** R^2 = 0.76 N = 45 95 % Confidence Interval = 249.31 < HC < 367.68 = 7.16 < ID < 36.78 = -19.21 < S < -9.08
Leakage Model (second model) (one soil matrix)	**L = 393.24(HC) + 21.97(ID) - 14.14(S)** R^2 = 0.91 N = 27 95 % Confidence Interval = 175.09 < HC < 611.39 = -17.78 < ID < 77.72 = -33.05 < S < -23.96
Runoff + Infiltration Model (3-variables)	**R = -346.64(HC) + 719.86(ID) + 16.85(S)** R^2 = 0.96 N = 45 95 % Confidence Interval = -413.94 < HC < -279.34 = 703.02 < ID < 736.70 = 11.09 < S < 22.64



(a)

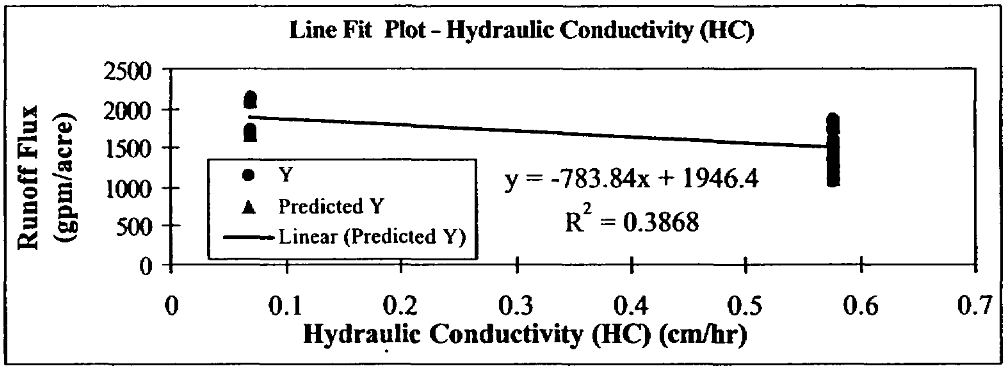


(b)

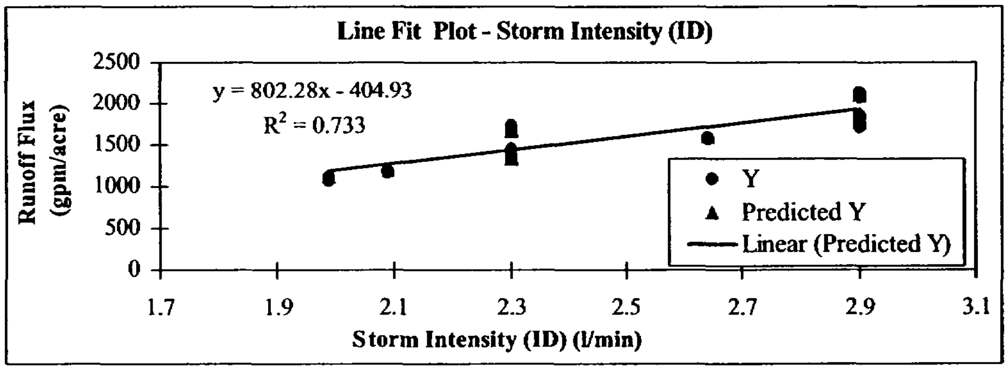


(c)

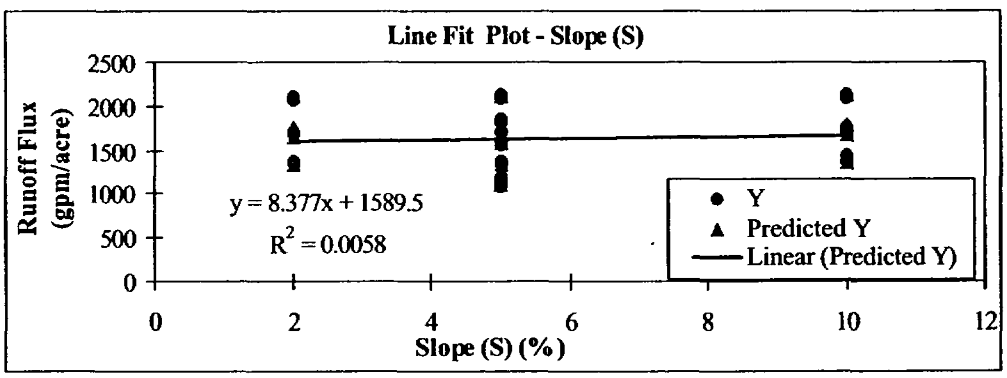
Figure 15 Residual Plots for Runoff Model (3-variables): (a) Hydraulic Conductivity, (b) Storm Intensity, and (c) Slope.



(a)

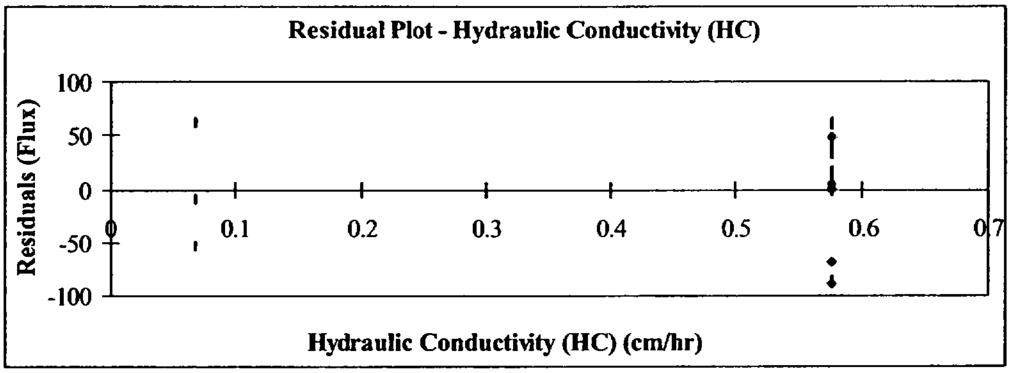


(b)

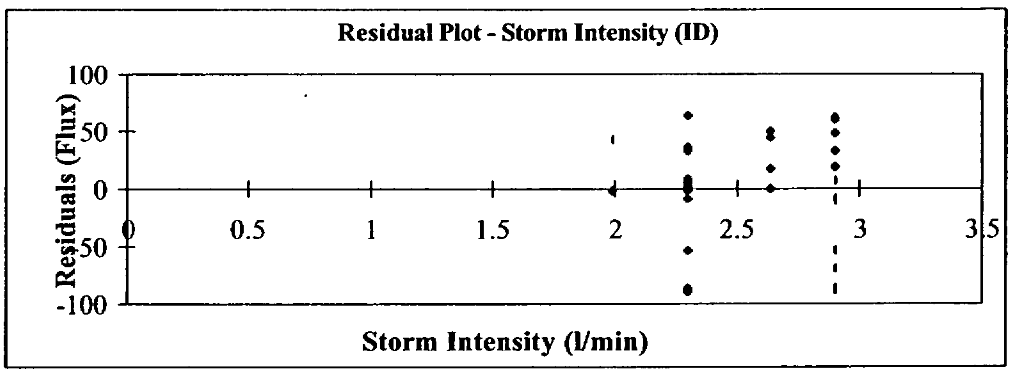


(c)

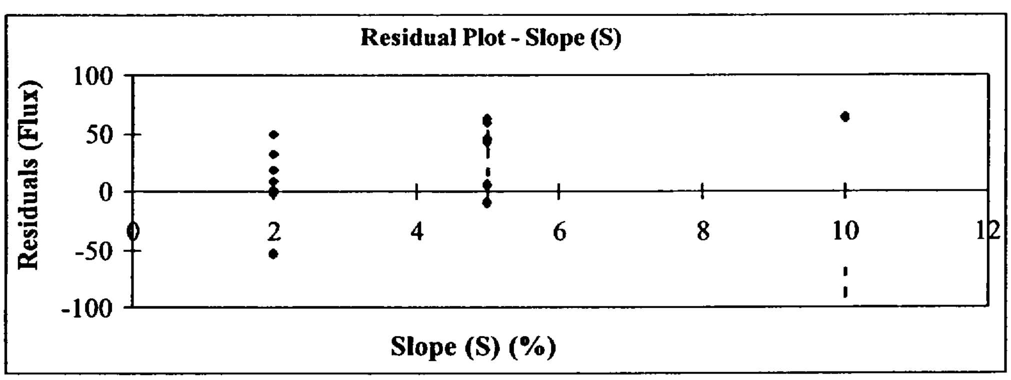
Figure 16 Line Fit Plots for Runoff Model (3-variables): (a) Hydraulic Conductivity, (b) Storm Intensity, and (c) Slope.



(a)

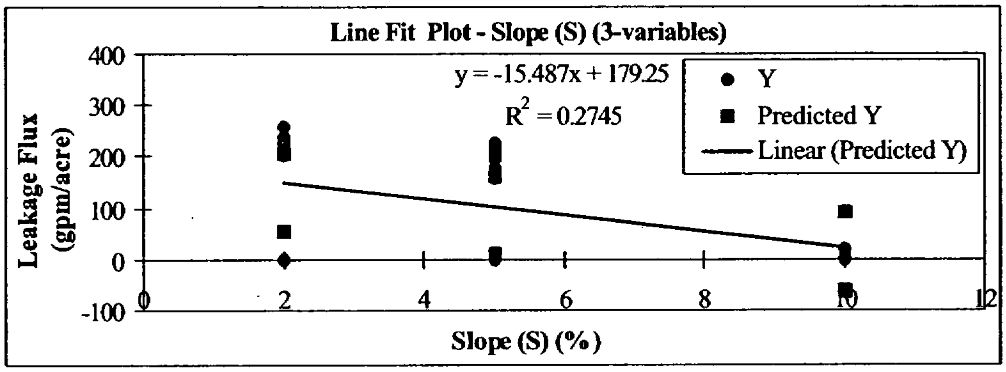


(b)

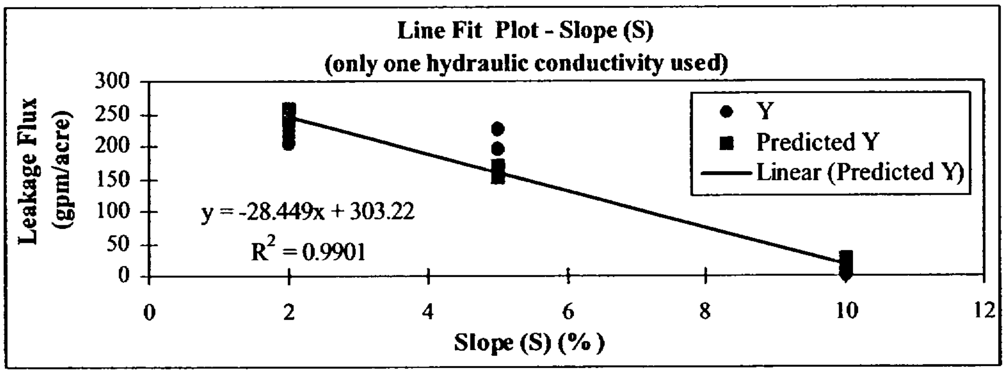


(c)

Figure 17 Residual Plots for Leakage Model (3-variables): (a) Hydraulic Conductivity, (b) Storm Intensity, and (c) Slope.



(a)



(b)

Figure 18 Line Fit Plots for Leakage Models: (a) Slope (3-variable) and (b) Slope (second model).

8.4 COMPARISON WITH HELP MODEL

The water balance methods (Section 3) are the basis for the HELP model analysis of landfill cover systems. Parameters used for the analysis must be properly estimated to balance the moisture in a landfill cover system. For these experimental simulations the evapotranspiration parameter is considered insignificant because of the short duration (30 minute) of the storm-event and the soil moisture content was at approximate field capacity at the initiation of each simulation. Field capacity defined by HELP is the soil moisture storage/content after a prolonged period of gravity drainage from saturation. Input values for the HELP modeling includes soil properties, hydraulic data, vegetative data, meteorologic data, and initial conditions. Table 6 shows parameters for model simulations including the experimental values and the default HELP model values used for the analysis. The HELP model default soils were chosen based on their saturated hydraulic conductivity and porosity values rather than their specific soil classification. Several HELP model output files, consistent with the variables quantified in this study, have been included in Appendix V.

The storm events used in these studies cannot be directly integrated into the HELP model, since the HELP model parameters are based on 24 hour storm events. Consequently, the parameters from this study were manipulated in a manner to provide a format to integrate into the HELP model. For example, a simulated 30 minute-2.3 lpm storm event was converted to english units (inches) over the cell area and then inserted in the HELP model as a 1 day storm event for comparison.

In order to model liner layers with the HELP model, one must classify the layer as a vertical percolation, lateral drainage, barrier soil liner, or geomembrane liner. These classifications result in the model using different parameters for the evaluation. Three liner scenarios were tested using the model defaults to detect the maximum runoff scenario and apply it to the comparison with the experimental cell results. First, a simple 3-layer cover system with the soil layer divided into two parts (6" top soil layer and a 6" second soil layer for soil #1) and a bottom geomembrane liner was analyzed using three different HELP model layer classifications. These HELP model classifications for the three scenarios were (1) soil layers considered both vertical percolation layers, (2) soil layers considered both lateral drainage layers, and (3) with a vertical percolation top layer with the second layer a lateral drainage layer. The results indicate little difference in the simple 3-layer cover and how the soil layers are classified for the simulations. Second, a more complex five layer cover liner system including geotextile and geonet was simulated and achieved no substantial difference than the previous scenarios. Subsequently, the experimental results were compared with the simple 3-layer system with a vertical percolation layer, lateral drainage layer, and geomembrane liner layer as shown in Table 6. Results of all different layer combinations are presented in Appendix VI. The run numbers shown in Table 7 are associated with the Yates algorithm designations (see Table 4) for the experimental simulations. The HELP model estimates runoff lower than field results with the difference ranging from 8% to 24% for the eight simulated scenarios as shown in row 11 (F-D Error) on Table 7. The model underpredicted runoff for all the short-duration storm events simulated. These deductions are consistent with the HELP model documentation that states the model is to be used for long term analysis and may be deficient for short-term events (Schroeder et al., 1994).

Table 6 Parameters for Model Simulation.

Parameter	Parameter Matrix	Experimental Values	Default HELP Values
Soil Classification (USC)	Liner I Soil Liner II Soil	SP SP	# 10 - ML # 15 - CH
Porosity (vol/vol)	Liner I Soil Liner II Soil	0.372 0.371	0.398 0.475
Field Capacity (vol/vol)	Liner I Soil Liner II Soil	- -	0.244 0.265
Wilting Point (vol/vol)	Liner I Soil Liner II Soil	- -	0.136 0.265
Initial Soil Water Content (vol/vol)	Liner I Soil Liner II Soil	0.290 0.236	0.290 0.265
Effective Saturated Hydraulic Conductivity (cm/s)	Liner I Soil Liner II Soil Geomembrane	1.6×10^{-4} 1.9×10^{-5} -	1.2×10^{-4} 1.7×10^{-5} 2.0×10^{-13}
Geomembrane Defects (per acre)	Installation Defects Pinhole Density	1 0	1 0
Evaporative Zone Depth (inch)	Liner I Soil Liner II Soil	- -	8 6
Leaf Area Index	Liner I Soil Liner II Soil	0 0	0 0
Growing Season (Julian day)	Liner I Soil Liner II Soil	- -	0-370 0-370
SCS Surface Runoff Curve Number (CN)	Liner I Liner II	- -	95-97 95-97
Layer Thickness (inch) (mils)	Liner I Soil Liner II Soil Geomembrane	12 10 60	12 10 60
Cover Slope (%)	Liner I Liner II	2, 5, 10 2, 5, 10	2, 10 2, 10
Precipitation (inch)	Liner I Liner II	1.99 2.51	1.99 2.51
Temperature	Runs	-	Tampa, Fl
Solar Radiation	Runs	-	Tampa, Fl
Evaporation	Runs	-	Tampa, Fl

Table 7 HELP Model Comparison with Experimental Results.

		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Total Storm (in)		1.99	2.51	1.99	2.51	1.99	2.51	1.99	2.51
Experimental Field Results (F)	Runoff (in)	**1.51**	**1.91**	**1.54**	**1.94**	**1.88**	**2.31**	**1.88**	**2.34**
	Runoff (%)	75.7	76.1	77.3	76.4	94.2	92.0	94.3	93.2
Default HELP Results (D)	Runoff (in)	**1.34**	**1.39**	**1.35**	**1.42**	**1.39**	**1.91**	**1.40**	**1.95**
	Runoff (%)	67.3	55.4	67.8	56.6	69.9	76.1	70.4	77.7
F-D Error (%)		8.4	20.7	9.5	19.8	24.3	15.9	23.9	15.5

Run 1 - ID=0.61 gpm, S=2%, HC=6.5 x 10^{-5} in/s
Run 2 - ID=0.77 gpm, S=2%, HC=6.5 x 10^{-5} in/s
Run 3 - ID=0.61 gpm, S=10%, HC=6.5 x 10^{-5} in/s
Run 4 - ID=0.77 gpm, S=10%, HC=6.5 x 10^{-5} in/s
Run 5 - ID=0.61 gpm, S=2%, HC=7.5 x 10^{-6} in/s
Run 6 - ID=0.77 gpm, S=2%, HC=7.5 x 10^{-6} in/s
Run 7 - ID=0.61 gpm, S=10%, HC=7.5 x 10^{-6} in/s
Run 8 - ID=0.77 gpm, S=10%, HC=7.5 x 10^{-6} in/s

9. CONCLUSIONS AND RECOMMENDATIONS

A laboratory scale model of a geomembrane liner final cover system was constructed to simulate moisture movement through the system. The experimental program consisted of a mass balance on the test cell for runoff, infiltration, and leakage parameters. Slope, hydraulic conductivity, and storm intensity were chosen for a statistical evaluation based on the water balance methods. Multiple linear regression techniques were used to develop a runoff flux predicative model.

The results of this study serve to identify an approach to predicting surface runoff from saturated landfill liner systems. Consequently, the design of surface runoff collection/storage requirements can be more simply projected within the range of the variables evaluated in this study. Generally, the saturation scenario for such predictions is encompassed in the experiments and resultant regression models are presented herein. Further, the experimental results confirm previous evaluations of the HELP models underprediction of surface runoff from landfills. It is also significant that the experimental results demonstrated that at a slope of 10% the effects of leachate leakage through holes in the underlying surface geomembrane liner are minimized. Obviously, such a slope mitigates the creation of sufficient static head in the soil above the liner to facilitate infiltration through the geomembrane liner. These results may also be translated into the effects of slope on the bottom liner leakage rates in landfills (i.e., a slope of 10% on the bottom liner may inhibit leakage in the bottom liner system).

Limitations of the HELP model may be associated with the SCS curve number methods used. The SCS curve numbers were derived from case studies of ungauged watersheds that may not be applicable to landfill applications and be used beyond their respective scope for application to landfill surfaces. The SCS curve number is a sensitive parameter which must be accurately estimated to obtain good results for model prediction. The experimental regression models indicate a better estimator of runoff during larger storm events. The SCS methods may also suffer from the omission of a time increment. The time increment may have a major impact in the runoff produced. Default curve numbers supplied by the HELP model tend to underpredict runoff.

Follow-up research should be performed using other ranges of the parameters selected for this study. Additional soil matrices with a broader range of hydraulic conductivity may enhance the leakage model. The regression models need to be analyzed to determine whether a single or a series of regression equations should be developed specifically designed for landfill use. Further, based on the literature review, capillary barriers need to be evaluated for the impediment of infiltration. Also, the use of geotextile material to separate soil materials in capillary barriers needs to be investigated to estimate effects this may have on capillary suction. Reduction of leakage with these systems may be possible, but current experimental field data is not sufficient to substantiate this matter.

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APPENDICES

APPENDIX I. COEFFICIENT OF PERMEABILITY

COEFFICIENT OF PERMEABILITY -Constant Head Method (ASTM D2334)

Soil Sample	1
Description of Soil	SP - Poorly Graded Sand
Date of Testing	5/15/97
Sample Diameter	7.62 cm
Sample Area (A)	45.6 cm^2
Sample Height (L)	14.3 cm
Sample Volume	652.1 cm^3
Weight of Sample	1157.2 grams
Constant Head Height (h)	50.2 cm

Test Number	t, seconds	Q, cm^3	Temperature, C
1	1800	54	23
2	1800	53	24
3	1800	49	24
Average	**1800**	**52**	**24**

$$K_T \square QL/Aht = (52)(14.3)/(45.6)(50.2)(1800) = \underline{1.8 \times 10^{-4}\ cm/s}$$
$$\square_T/\square_{20} = \underline{0.91}$$
$$K_{20} \square K_T \square_T/\square_{20} = \underline{1.64 \times 10^{-4}\ cm/s}$$

Soil Sample	2
Description of Soil	SP - Poorly Graded Sand
Date of Testing	6/26/97
Sample Diameter	7.62 cm
Sample Area (A)	45.6 cm^2
Sample Height (L)	14.3 cm
Sample Volume	652.1 cm^3
Weight of Sample	1178.2 grams
Constant Head Height (h)	90.2 cm

Test Number	t, seconds	Q, cm3	Temperature, C
1	1800	10.4	22.5
2	1800	10.4	22.5
3	1800	10.4	22.5
Average	**1800**	**10.4**	**22.5**

$$K_T \square QL/Aht = (10.4)(14.3)/(45.6)(90.2)(1800) = \underline{2.0 \times 10^{-5}\ cm/s}$$
$$\square_T/\square_{20} = \underline{0.953}$$
$$K_{20} \square K_T \square_T/\square_{20} = \underline{1.9 \times 10^{-5}\ cm/s}$$

APPENDIX II. GRAIN SIZE DISTRIBUTION

GRAIN SIZE DISTRIBUTION-MECHANICAL

Sample Preparation - ASTM D421
Soil Sample Size - ASTM D1140-54
Test Soil # 1
Weight of Sample, Ws = 500 g

Sieve Number	Diameter (mm)	5/9/97 Weight Retained (g)	5/13/97 Weight Retained (g)	Average Weight Retained (g)	% Retained	% Passing
4	4.75	2.0	2.1	2.1	0.4	99.6
10	2.00	3.2	4.8	4.0	0.8	98.8
20	0.850	5.9	6.1	6.0	1.2	97.6
40	0.425	10.0	11.2	10.6	2.1	95.5
60	0.250	37.1	57	47.1	9.4	86.1
140	0.106	396.4	379.6	388.0	77.6	8.5
200	0.075	35.7	29.7	32.7	6.5	2.0
		8.4	7.8	8.1	1.6	

Unified Soil Classification System
Soil Classification: SP Poorly Graded Sand

$$Cu = D60/D10 = .20/.10 = 2.0$$
$$Cc = (D30)^2/D10*D60 = (.140)^2/.20*.10 = 0.98$$

Test Soil # 2
Weight of Sample, Ws = 500 g

Sieve Number	Diameter (mm)	6/26/97 Weight Retained (g)	6/26/97 Weight Retained (g)	Average Weight Retained (g)	% Retained	% Passing
4	4.75	0.4	0	0.2	0.04	99.9
10	2.00	3.5	1.5	2.5	0.5	99.5
20	0.850	7.5	4.6	6.1	1.2	98.3
40	0.425	15.9	13.4	14.7	2.9	95.4
60	0.250	54.1	64.5	59.3	11.9	83.5
140	0.106	400.6	384.3	392.5	78.5	5.0
200	0.075	3.3	13.2	8.3	1.7	3.3
		14.1	17.3	15.7	3.1	

Unified Soil Classification System
Soil Classification: SP Poorly Graded Sand

$$Cu = D60/D10 = .20/.10 = 1.75$$
$$Cc = (D30)^2/D10*D60 = (.140)^2/.20*.10 = 0.89$$

APPENDIX III. WATER-CONTENT DETERMINATION

<u>Water-Content Determination</u>
ASTM D2216

Soil # 1 Dish	Dish (grams)	Wet Dish + Sample (grams)	Sample Wet (grams)	Dry Dish + Sample (grams)	Sample Dry (grams)	Water Content (%)
1	90.895	304.0	213.1	265.5	174.6	18.1
2	89.089	265.7	175.9	234.7	144.9	17.6
3	92.912	249.9	156.9	225.1	132.2	15.7
						Avg 17.1

Soil # 2 Dish	Dish (grams)	Wet Dish + Sample (grams)	Sample Wet (grams)	Dry Dish + Sample (grams)	Sample Dry (grams)	Water Content (%)
1	90.895	272.2	181.3	247.2	156.3	13.8
2	89.809	270.2	180.4	245.2	155.4	13.9
3	92.912	267.8	174.9	243.1	150.2	14.1
						Avg 13.9

Moisture content samples taken 4 hours after cell at saturation

Samples taken 2', 4', and 6' from the outlet on center at a 6" depth

$$MOISTURE CONTENT(\%) = \frac{W_w}{W_s} \times 100$$

APPENDIX IV. EXPERIMENTAL RUNS

Date	Run #	Soil Classification (USC)	Hydraulic Conductivity (cm/sec)	Storm Intensity (kg)	Storm Year	Total Rainfall (kg)	Slope (%)	Runoff (kg)	Infiltration (kg)	Leakage (kg)
2/27/97	1	SP	1.6×10^{-4}	2.30	2	69.00	5	50.84	5.88	6.42
2/27/97	2	SP	1.6×10^{-4}	2.30	2	69.00	5	51.46	6.30	7.60
2/27/97	3	SP	1.6×10^{-4}	2.30	2	69.00	5	52.36	6.46	7.44
3/5/97	4	SP	1.6×10^{-4}	2.64	5	79.20	5	60.04	6.98	6.86
3/6/97	5	SP	1.6×10^{-4}	2.64	5	79.20	5	61.36	5.38	6.20
3/24/97	6	SP	1.6×10^{-4}	2.64	5	79.20	5	56.88	2.62	0
3/25/97	7	SP	1.6×10^{-4}	2.64	5	79.20	5	64.99	7.40	1.70
3/26/97	8	SP	1.6×10^{-4}	2.90	10	87.00	5	71.02	8.74	1.58
3/26/97	9	SP	1.6×10^{-4}	2.90	10	87.00	5	70.72	9.76	2.28
3/27/97	10	SP	1.6×10^{-4}	2.90	10	87.00	5	71.56	9.30	1.70
5/1/97	11	SP	1.6×10^{-4}	2.09	-	62.70	5	43.66	10.06	0.84
5/1/97	12	SP	1.6×10^{-4}	2.09	-	62.70	5	44.82	10.56	3.36
5/2/97	13	SP	1.6×10^{-4}	2.09	-	62.70	5	45.74	9.42	3.48
5/2/97	14	SP	1.6×10^{-4}	2.09	-	62.70	5	45.00	9.06	[illegible]
5/5/97	15	SP	1.6×10^{-4}	3.10	-	93.00	5	67.82	6.08	0.64
5/5/97	16	SP	$1.6 \times 10^{-4\,4}$	3.10	-	93.00	5	72.10	10.58	0.80
5/6/97	17	SP	1.6×10^{-4}	2.30	2	69.00	5	52.14	0.62	6.12
5/6/97	18	SP	1.6×10^{-4}	2.30	2	69.00	5	51.04	6.82	6.16
5/7/97	19	SP	1.6×10^{-4}	2.30	2	69.00	5	51.60	5.36	6.26
5/7/97	20	SP	1.6×10^{-4}	2.64	5	79.20	5	61.34	6.04	8.12

X - Data not used

APPENDIX IV. CONTINUED

Date	Run #	Soil Classification (USC)	Hydraulic Conductivity (cm/sec)	Storm Intensity (l/min)	Storm Year	Total Rainfall (kg)	Slope (%)	Runoff (kg)	Infiltration (kg)	Leakage (kg)
5/7/97	21	SP	1.6 x 10^{-4}	2.64	5	79.20	5	61.34	6.50	8.00
5/7/97	22	SP	1.6 x 10^{-4}	2.90	10	87.00	5	66.34	6.76	8.54
5/8/97	23	SP	1.6 x 10^{-4}	2.90	10	87.00	5	69.20	5.88	8.68
5/8/97	24	SP	1.6 x 10^{-4}	1.99	-	59.70	5	42.58	6.40	7.82
5/8/97	25	SP	1.6 x 10^{-4}	1.99	-	59.70	5	41.34	6.38	7.86
5/17/97	26	SP	1.6 x 10^{-4}	2.30	2	69.00	2	50.12	9.14	2.56
5/17/97	27	SP	1.6 x 10^{-4}	2.30	2	69.00	2	52.58	3.90	9.06
5/17/97	28	SP	1.6 x 10^{-4}	2.30	2	69.00	2	51.40	5.26	8.22
5/17/97	29	SP	1.6 x 10^{-4}	2.30	2	69.00	2	52.56	6.12	7.96
5/18/97	30	SP	1.6 x 10^{-4}	2.30	2	69.00	2	52.66	5.98	7.80
5/18/97	31	SP	1.6 x 10^{-4}	2.90	10	87.00	2	66.24	7.84	9.16
5/19/97	32	SP	1.6 x 10^{-4}	2.90	10	87.00	2	66.30	4.40	9.82
5/19/97	33	SP	1.6 x 10^{-4}	2.90	10	87.00	2	65.94	7.80	8.64
5/19/97	34	SP	1.6 x 10^{-4}	2.90	10	87.00	5	65.60	9.56	6.54
5/20/97	35	SP	1.6 x 10^{-4}	1.99	-	59.70	5	42.86	7.20	6.12
5/20/97	36	SP	1.6 x 10^{-4} ^{4}	2.30	2	69.00	10	51.88	13.42	0
5/20/97	37	SP	1.6 x 10^{-4}	2.30	2	69.00	10	52.84	13.58	0.10
5/21/97	38	SP	1.6 x 10^{-4}	2.30	2	69.00	10	55.34	12.98	0.04
5/21/97	39	SP	1.6 x 10^{-4}	2.90	2	69.00	10	65.56	15.84	0.80
5/22/97	40	SP	1.6 x 10^{-4}	2.90	10	87.00	10	67.44	14.18	0.14

X - data not used

Date	Run #	Soil Classification	Hydraulic Conductivity	Storm Intensity	Storm Year	Total Rainfall	Slope (%)	Runoff (kg)	Infiltration (kg)	Leakage (kg)
5/22/97	41	SP	1.6×10^{-4}	2.90	10	87.00	10	66.28	15.62	0.10
6/18/97	42	SP	1.9×10^{-5}	2.30	2	69.00	2	66.08	1.50	0.01
6/18/97	43	SP	1.9×10^{-5}	2.30	2	69.00	2	64.60	1.58	0.01
6/19/97	44	SP	1.9×10^{-5}	2.30	2	69.00	2	64.24	1.70	0.01
6/19/97	45	SP	1.9×10^{-5}	2.90	10	87.00	2	79.20	1.98	0.01
6/19/97	46	SP	1.9×10^{-5}	2.90	10	87.00	2	80.22	1.92	0.04
6/20/97	47	SP	1.9×10^{-5}	2.90	10	87.00	2	80.74	1.75	0.01
6/21/97	48	SP	1.9×10^{-5}	2.30	2	69.00	5	62.76	2.50	0
6/21/97	49	SP	1.9×10^{-5}	2.30	2	69.00	5	65.12	1.44	0.01
6/22/97	50	SP	1.9×10^{-5}	2.30	2	69.00	5	65.46	1.26	0
6/22/97	51	SP	1.9×10^{-5}	2.30	2	69.00	5	64.68	1.26	0
6/22/97	52	SP	1.9×10^{-5}	2.90	10	87.00	5	80.30	1.78	0.01
6/22/97	53	SP	1.9×10^{-5}	2.90	10	87.00	5	80.48	1.84	0.01
6/23/97	54	SP	1.9×10^{-5}	2.90	10	87.00	5	81.54	1.74	0.08
6/23/97	55	SP	1.9×10^{-5}	2.30	2	69.00	10	64.06	1.56	
6/24/97	56	SP	1.9×10^{-5}	2.30	2	69.00	10	66.46	1.50	0.01
6/24/97	57	SP	1.9×10^{-5}	2.30	2	69.00	10	64.66	1.74	0
6/24/97	58	SP	1.9×10^{-5}	2.90	10	87.00	10	82.10	3.46	0
6/24/97	59	SP	1.9×10^{-5}	2.90	10	87.00	10	80.00	2.34	0
6/24/97	60	SP	1.9×10^{-5}	2.90	10	87.00	10	80.94	2.22	0.01
6/25/97	61	SP	1.9×10^{-5}	2.90	10	87.00	10	82.22	2.40	0.01

APPENDIX V. REGRESSION ANALYSIS

FLUX DATA VALUES

Observations	Run #	Runoff Flux (gpm/acre)	Hydraulic Conductivity (cm/hr)	Storm Intensity (l/min)	Slope (%)	Infiltration Flux (gpm/acre)	Leakage Flux (gpm/acre)	Runoff + Infiltration (gpm/acre)
1	1	1325	0.576	2.3	5	153	167	1478
2	2	1341	0.576	2.3	5	164	198	1505
3	3	1365	0.576	2.3	5	168	194	1533
4	18	1330	0.576	2.3	5	178	161	1508
5	19	1345	0.576	2.3	5	140	163	1485
6	22	1729	0.576	2.9	5	176	223	1905
7	23	1803	0.576	2.9	5	153	226	1956
8	28	1339	0.576	2.3	2	137	214	1476
9	29	1370	0.576	2.3	2	159	207	1529
10	30	1372	0.576	2.3	2	156	203	1528
11	31	1726	0.576	2.9	2	204	239	1930
12	32	1728	0.576	2.9	2	115	256	1843
13	33	1718	0.576	2.9	2	203	225	1921
14	34	1710	0.576	2.9	5	249	170	1959
15	36	1352	0.576	2.3	10	350	0	1702
16	37	1377	0.576	2.3	10	354	3	1731
17	38	1442	0.576	2.3	10	338	1	1780
18	39	1708	0.576	2.9	10	413	21	2121
19	40	1757	0.576	2.9	10	370	4	2127
20	41	1727	0.576	2.9	10	407	3	2134
21	42	1722	0.0684	2.3	2	39	0	1761
22	43	1683	0.0684	2.3	2	41	0	1724
23	44	1674	0.0684	2.3	2	44	0	1718
24	45	2064	0.0684	2.9	2	52	0	2116
25	46	2091	0.0684	2.9	2	50	1	2141
26	47	2104	0.0684	2.9	2	46	0	2150
27	49	1697	0.0684	2.3	5	38	0	1735
28	50	1706	0.0684	2.3	5	33	0	1739
29	51	1686	0.0684	2.3	5	33	0	1719
30	52	2093	0.0684	2.9	5	46	0	2139
31	53	2097	0.0684	2.9	5	48	0	2145
32	54	2125	0.0684	2.9	5	45	2	2170
33	55	1669	0.0684	2.3	10	41	0	1710
34	56	1732	0.0684	2.3	10	39	0	1771
35	57	1685	0.0684	2.3	10	45	0	1730
36	59	2085	0.0684	2.9	10	61	0	2146
37	60	2109	0.0684	2.9	10	58	0	2167
38	61	2143	0.0684	2.9	10	63	0	2206
39	4	1565	0.576	2.64	5	182	179	1747
40	5	1599	0.576	2.64	5	140	162	1739
41	20	1599	0.576	2.64	5	157	212	1756
42	21	1599	0.576	2.64	5	169	208	1768
43	24	1110	0.576	1.99	5	167	204	1277
44	25	1077	0.576	1.99	5	166	205	1243
45	35	1117	0.576	1.99	5	188		1305
46	8	1851	0.576	2.9	5	-	-	-
47	9	1843	0.576	2.9	5	-	-	-
48	10	1865	0.576	2.9	5	-	-	-
49	12	1168	0.576	2.09	5	-	-	-
50	13	1192	0.576	2.09	5	-	-	-
51	14	1173	0.576	2.09	5	-	-	-

SUMMARY OUTPUT

Runoff Model
Var 1 - Hydraulic Conductivity
Var 2 - Storm Intensity
Var 3 - Slope

Regression Statistics	
Multiple R	0.991771155
R Square	0.983610025
Adjusted R Square	0.962093776
Standard Error	39.50088847
Observations	51

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	4494688.631	1498229.544	960.2064714	3.73817E-42
Residual	48	74895.36911	1560.32019		
Total	51	4569584			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	-654.1891624	21.78487005	-30.0295187	9.0528E-33	-697.9905536	-610.3877711	-697.9905536	-610.3877711
X Variable 2	738.9402603	5.643131627	130.945069	5.75458E-63	727.5939903	750.2865302	727.5939903	750.2865302
X Variable 3	2.880608113	1.938106202	1.486300446	0.143738975	-1.016213298	6.777429525	-1.016213298	6.777429525

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	1337.152682	-12.15268166	-0.31712445
2	1337.152682	3.847318335	0.100395842
3	1337.152682	27.84731834	0.726676281
4	1337.152682	-7.152681665	-0.186649359
5	1337.152682	7.847318335	0.204775915
6	1780.516838	-51.51683783	-1.344332825
7	1780.516838	22.48316217	0.586698528
8	1328.510857	10.48914268	0.27371437
9	1328.510857	41.48914268	1.082659936
10	1328.510857	43.48914268	1.134849973
11	1771.875013	-45.87501349	-1.197109315
12	1771.875013	-43.87501349	-1.144919279
13	1771.875013	-53.87501349	-1.405869462
14	1780.516838	-70.51683783	-1.840138172
15	1351.555722	0.444277769	0.011593436
16	1351.555722	25.44427777	0.663968893
17	1351.555722	90.44427777	2.360145081
18	1794.919878	-86.9198784	-2.268175815
19	1794.919878	-37.9198784	-0.98951992
20	1794.919878	-67.9198784	-1.772370468
21	1660.577276	61.42272385	1.602827101
22	1660.577276	22.42272385	0.585121389
23	1660.577276	13.42272385	0.350266224
24	2103.941432	-39.94143232	-1.042272406
25	2103.941432	-12.94143232	-0.337706913

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
26	2103.941432	0.05856768	0.001528325
27	1669.2191	27.78089951	0.72494308
28	1669.2191	36.78089951	0.959798245
29	1669.2191	16.78089951	0.437897879
30	2112.583257	-19.58325666	-0.51102544
31	2112.583257	-15.58325666	-0.406645367
32	2112.583257	12.41674334	0.324015144
33	1683.622141	-14.62214106	-0.381565038
34	1683.622141	48.37785894	1.262421113
35	1683.622141	1.377858939	0.035955254
36	2126.986297	-41.98629723	-1.095633193
37	2126.986297	-17.98629723	-0.469352755
38	2126.986297	16.01370277	0.417877867
39	1588.39237	-23.39237016	-0.610424327
40	1588.39237	10.60762984	0.276806295
41	1588.39237	10.60762984	0.276806295
42	1588.39237	10.60762984	0.276806295
43	1108.081201	1.918799021	0.050071096
44	1108.081201	-31.08120098	-0.811064508
45	1108.081201	8.918799021	0.232736223
46	1780.516838	70.48316217	1.839259405
47	1780.516838	62.48316217	1.630499259
48	1780.516838	84.48316217	2.204589661
49	1181.975227	-13.97522701	-0.364683804
50	1181.975227	10.02477299	0.261596634
51	1181.975227	-8.975227007	-0.234208713

SUMMARY OUTPUT

Runoff Model (2-variables)
Var 1 - Hydraulic Conductivity
Var 2 - Storm Intensity
Var 3 - Slope

Regression Statistics	
Multiple R	0.991390798
R Square	0.982855714
Adjusted R Square	0.962097667
Standard Error	39.9852665
Observations	51

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4491241.745	2245620.872	1404.54755	2.55621E-43
Residual	49	78342.2553	1598.821537		
Total	51	4569584			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	-653.4070797	22.04557238	-29.6389256	5.98333E-33	-697.7092892	-609.1048702	-697.7092892	-609.1048702
X Variable 2	744.9293379	3.999128841	186.2729028	1.6307E-71	736.8927924	752.9658833	736.8927924	752.9658833

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	1336.974999	-11.97499915	-0.30553611
2	1336.974999	4.025000848	0.102695882
3	1336.974999	28.02500085	0.71504387
4	1336.974999	-6.974999152	-0.177963612
5	1336.974999	8.025000848	0.20475388
6	1783.932602	-54.93260186	-1.401577842
7	1783.932602	19.06739814	0.48649512
8	1336.974999	2.025000848	0.051666883
9	1336.974999	33.02500085	0.842616367
10	1336.974999	35.02500085	0.893645366
11	1783.932602	-57.93260186	-1.47812134
12	1783.932602	-55.93260186	-1.427092341
13	1783.932602	-65.93260186	-1.682237336
14	1783.932602	-73.93260186	-1.886353332
15	1336.974999	15.02500085	0.383355376
16	1336.974999	40.02500085	1.021217863
17	1336.974999	105.0250008	2.67966033
18	1783.932602	-75.93260186	-1.937382331
19	1783.932602	-26.93260186	-0.687171856
20	1783.932602	-56.93260186	-1.452606841
21	1668.644433	53.35556719	1.361340591
22	1668.644433	14.35556719	0.366275112
23	1668.644433	5.355567195	0.136644616
24	2115.602036	-51.60203552	-1.316600108
25	2115.602036	-24.60203552	-0.627708622

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
26	2115.602036	-11.60203552	-0.296020129
27	1668.644433	28.35556719	0.723478104
28	1668.644433	37.35556719	0.9531086
29	1668.644433	17.35556719	0.44281861
30	2115.602036	-22.60203552	-0.576679623
31	2115.602036	-18.60203552	-0.474621626
32	2115.602036	9.397964484	0.23978436
33	1668.644433	0.355567195	0.009072119
34	1668.644433	63.35556719	1.616485586
35	1668.644433	16.35556719	0.417304111
36	2115.602036	-30.60203552	-0.780795619
37	2115.602036	-6.602035516	-0.168447632
38	2115.602036	27.39796448	0.699045351
39	1590.250974	-25.25097402	-0.644265964
40	1590.250974	8.749025978	0.223227019
41	1590.250974	8.749025978	0.223227019
42	1590.250974	8.749025978	0.223227019
43	1106.046904	3.953095581	0.100861255
44	1106.046904	-29.04690442	-0.741117228
45	1106.046904	10.95309558	0.279462752
46	1783.932602	67.06739814	1.711191095
47	1783.932602	59.06739814	1.507075099
48	1783.932602	81.06739814	2.068394088
49	1180.539838	-12.5398382	-0.319947695
50	1180.539838	11.4601618	0.292400292
51	1180.539838	-7.539838204	-0.192375198

APPENDIX V. CONTINUED

SUMMARY OUTPUT

Infiltration Model (3-variables)
Var 1 - Hydraulic Conductivity
Var 2 - Storm Intensity
Var 3 - Slope

Regression Statistics	
Multiple R	0.854467992
R Square	0.730115549
Adjusted R Square	0.693454385
Standard Error	57.79309881
Observations	45

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	379502.8024	126500.9341	37.87405186	6.83667E-12
Residual	42	140281.7753	3340.04227		
Total	45	519784.5778			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	318.3324974	33.33447514	9.549647806	4.36E-12	251.0607817	385.604213	251.0607817	385.604213
X Variable 2	-17.11848864	8.340568301	-2.052436719	0.046393082	-33.95044224	-0.286535032	-33.95044224	-0.286535032
X Variable 3	13.28845083	2.853340669	4.657155372	3.21424E-05	7.530174408	19.04672724	7.530174408	19.04672724

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	210.4292487	-57.42924874	-1.028581634
2	210.4292487	-46.42924874	-0.831567077
3	210.4292487	-42.42924874	-0.75992542
4	210.4292487	-32.42924874	-0.580821278
5	210.4292487	-70.42924874	-1.261417019
6	200.1581556	-24.15815556	-0.432682573
7	200.1581556	-47.15815556	-0.8446221
8	170.5638963	-33.56389627	-0.601143285
9	170.5638963	-11.56389627	-0.207114172
10	170.5638963	-14.56389627	-0.260845415
11	160.2928031	43.70719691	0.782814001
12	160.2928031	-45.29280309	-0.811212865
13	160.2928031	42.70719691	0.764903587
14	200.1581556	48.84184444	0.874777665
15	276.8715029	73.12849713	1.309761675
16	276.8715029	77.12849713	1.381403332
17	276.8715029	61.12849713	1.094836705
18	266.6004097	146.3995903	2.622077305
19	266.6004097	103.3995903	1.851929493
20	266.6004097	140.3995903	2.51461482
21	8.978320606	30.02167939	0.537700714
22	8.978320606	32.02167939	0.573521542
23	8.978320606	35.02167939	0.627252785
24	-1.292772576	53.29277258	0.954495632
25	-1.292772576	51.29277258	0.918674804

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
26	-1.292772576	47.29277258	0.847033147
27	48.84367308	-10.84367308	-0.194214677
28	48.84367308	-15.84367308	-0.283766748
29	48.84367308	-15.84367308	-0.283766748
30	38.5725799	7.427420101	0.133028171
31	38.5725799	9.427420101	0.168848999
32	38.5725799	6.427420101	0.115117756
33	115.2859272	-74.28592721	-1.330491727
34	115.2859272	-76.28592721	-1.366312556
35	115.2859272	-70.28592721	-1.25885007
36	105.014834	-44.01483403	-0.788323909
37	105.014834	-47.01483403	-0.842055152
38	105.014834	-42.01483403	-0.752503081
39	204.6089626	-22.60896261	-0.404935885
40	204.6089626	-64.60896261	-1.157173283
41	204.6089626	-47.60896261	-0.852696241
42	204.6089626	-35.60896261	-0.63777127
43	215.7359802	-48.73598022	-0.872881593
44	215.7359802	-49.73598022	-0.890792008
45	215.7359802	-27.73598022	-0.496762895

SUMMARY OUTPUT

Infiltration Model (3-variables)

Var 1 - Hydraulic Conductivity

Var 2 - Storm Intensity

Var 3 - Slope

Regression Statistics	
Multiple R	0.87166837
R Square	0.75980574
Adjusted R Square	0.7245584
Standard Error	50.8472803
Observations	45

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	343498.383	114499.461	44.286156	6.2934E-13
Residual	42	108588.728	2585.44591		
Total	45	452087.111			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	308.497034	29.3281972	10.5187861	2.4257E-13	249.310317	367.683751	249.310317	367.683751
X Variable 2	21.9719938	7.3381636	2.99420876	0.00459743	7.16297538	36.7810121	7.16297538	36.7810121
X Variable 3	-14.141946	2.51041414	-5.6333118	1.3358E-06	-19.208168	-9.0757232	-19.208168	-9.0757232

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	157.520149	9.47985088	0.19298137
2	157.520149	40.4798509	0.82404853
3	157.520149	36.4798509	0.74262051
4	157.520149	3.47985088	0.07083934
5	157.520149	5.47985088	0.11155335
6	170.703345	52.2966546	1.06460326
7	170.703345	55.2966546	1.12567427
8	199.945986	14.054014	0.28609763
9	199.945986	7.05401397	0.1435986
10	199.945986	3.05401397	0.06217058
11	213.129182	25.8708177	0.52665237
12	213.129182	42.8708177	0.87272145
13	213.129182	11.8708177	0.2416543
14	170.703345	-0.7033454	-0.014318
15	86.8104209	-86.810421	-1.7672002
16	86.8104209	-83.810421	-1.7061292
17	86.8104209	-85.810421	-1.7468432
18	99.9936172	-78.993617	-1.6080735
19	99.9936172	-95.993617	-1.9541425
20	99.9936172	-96.993617	-1.9744996
21	43.3528915	-43.352892	-0.882535
22	43.3528915	-43.352892	-0.882535
23	43.3528915	-43.352892	-0.882535
24	56.5360878	-56.536088	-1.1509054
25	56.5360878	-55.536088	-1.1305484

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
26	56.5360878	-56.536088	-1.1509054
27	0.92705461	-0.9270546	-0.0188721
28	0.92705461	-0.9270546	-0.0188721
29	0.92705461	-0.9270546	-0.0188721
30	14.1102509	-14.110251	-0.2872424
31	14.1102509	-14.110251	-0.2872424
32	14.1102509	-12.110251	-0.2465284
33	-69.782674	69.7826736	1.42056624
34	-69.782674	69.7826736	1.42056624
35	-69.782674	69.7826736	1.42056624
36	-56.599477	56.5994773	1.15219584
37	-56.599477	56.5994773	1.15219584
38	-56.599477	56.5994773	1.15219584
39	164.990627	14.009373	0.28518888
40	164.990627	-2.990627	-0.0608802
41	164.990627	47.009373	0.95697004
42	164.990627	43.009373	0.87554202
43	150.708831	53.2911689	1.08484859
44	150.708831	54.2911689	1.1052056
45	150.708831	8.29116894	0.16878337

SUMMARY OUTPUT

Leakage Model (3-variables/one soil)

Var 1 - Hydraulic Conductivity
Var 2 - Storm Intensity
Var 3 - Slope

Regression Statistics	
Multiple R	0.955022
R Square	0.912066
Adjusted R Square	0.842898
Standard Error	30.20595
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	160881	53627	58.77578	7.37E-09
Residual	17	15510.79	912.3997		
Total	20	176391.8			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	393.2411	103.3987	3.803154	0.001421	175.0887	611.3936	175.0887	611.3936
X Variable 2	29.96714	22.63179	1.324117	0.202993	-17.78184	77.71612	-17.78184	77.71612
X Variable 3	-28.504	2.153576	-13.23566	2.22E-10	-33.04766	-23.96035	-33.04766	-23.96035

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	152.9113	14.08872	0.505906
2	152.9113	45.08872	1.619071
3	152.9113	41.08872	1.475437
4	152.9113	8.088725	0.290454
5	152.9113	10.08872	0.362272
6	170.8916	52.10844	1.871139
7	170.8916	55.10844	1.978865
8	238.4233	-24.42329	-0.877005
9	238.4233	-31.42329	-1.128365
10	238.4233	-35.42329	-1.271999
11	256.4036	-17.40357	-0.624937
12	256.4036	-0.403574	-0.014492
13	256.4036	-31.40357	-1.127657
14	170.8916	-0.891559	-0.032015
15	10.39125	-10.39125	-0.373135
16	10.39125	-7.391251	-0.265409
17	10.39125	-9.391251	-0.337226
18	28.37153	-7.371534	-0.264701
19	28.37153	-24.37153	-0.875147
20	28.37153	-25.37153	-0.911055

APPENDIX V. CONTINUED

SUMMARY OUTPUT

Runoff+Infiltration Model (3-variables)
Var 1 - Hydraulic Conductivity
Var 2 - Storm Intensity
Var 3 - Slope

Regression Statistics	
Multiple R	0.9773776
R Square	0.95526698
Adjusted R Square	0.92932731
Standard Error	57.8170744
Observations	45

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	2998182.61	999394.203	298.967928	6.914E-28
Residual	42	140398.192	3342.81409		
Total	45	3138580.8			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	-346.63855	33.348304	-10.394488	3.4901E-13	-413.93818	-279.33893	-413.93818	-279.33893
X Variable 2	719.860798	8.3440284	86.2725728	6.5941E-49	703.021861	736.699734	703.021861	736.699734
X Variable 3	16.8531004	2.85452438	5.90399594	5.4587E-07	11.0924351	22.6137656	11.0924351	22.6137656

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	1540.28153	-62.28153	-1.1150254
2	1540.28153	-35.28153	-0.6316448
3	1540.28153	-7.2815304	-0.1303611
4	1540.28153	-32.28153	-0.5779358
5	1540.28153	-55.28153	-0.9897045
6	1972.19801	-67.198009	-1.2030451
7	1972.19801	-16.198009	-0.2899927
8	1489.72223	-13.722229	-0.2456689
9	1489.72223	39.2777706	0.70318942
10	1489.72223	38.2777706	0.68528643
11	1921.63871	8.36129192	0.1496921
12	1921.63871	-78.638708	-1.4078678
13	1921.63871	-0.6387081	-0.0114348
14	1972.19801	-13.198009	-0.2362838
15	1624.54703	77.4529678	1.38663949
16	1624.54703	106.452968	1.90582611
17	1624.54703	155.452968	2.78307248
18	2056.46351	64.5364891	1.15539593
19	2056.46351	70.5364891	1.26281386
20	2056.46351	77.5364891	1.38813477
21	1665.67596	95.3240413	1.70658509
22	1665.67596	58.3240413	1.04417456
23	1665.67596	52.3240413	0.93675664
24	2097.59244	18.4075626	0.32955036
25	2097.59244	43.4075626	0.77712503

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
26	2097.59244	52.4075626	0.93825192
27	1716.23526	18.7647402	0.3359449
28	1716.23526	22.7647402	0.40755685
29	1716.23526	2.76474024	0.04949711
30	2148.15174	-9.1517385	-0.1638435
31	2148.15174	-3.1517385	-0.0564255
32	2148.15174	21.8482615	0.39114915
33	1800.50076	-90.500762	-1.620234
34	1800.50076	-29.500762	-0.5281518
35	1800.50076	-70.500762	-1.2621742
36	2232.41724	-86.41724	-1.5471267
37	2232.41724	-65.41724	-1.171164
38	2232.41724	-26.41724	-0.4729475
39	1785.0342	-38.034202	-0.6809258
40	1785.0342	-46.034202	-0.8241497
41	1785.0342	-29.034202	-0.5197989
42	1785.0342	-17.034202	-0.3049631
43	1317.12468	-40.124683	-0.7183517
44	1317.12468	-74.124683	-1.3270532
45	1317.12468	-12.124683	-0.217068

APPENDIX VI. HELP MODEL RUNS

HELP MODEL RUNS

```
******************************************************************************
**        HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE                     **
**         HELP MODEL VERSION 3.06  (17 AUGUST 1996)                        **
**          DEVELOPED BY ENVIRONMENTAL LABORATORY                           **
**           USAE WATERWAYS EXPERIMENT STATION                              **
**       FOR USEPA RISK REDUCTION ENGINEERING LABORATORY                    **
******************************************************************************

 TITLE: RUNS(3-layer/1.99in Storm/2% Slope/1.6E-4 cm/sec Perm)
******************************************************************************

 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 10
 THICKNESS             =   6.00  INCHES
 POROSITY              =   0.3980 VOL/VOL
 FIELD CAPACITY        =   0.2440 VOL/VOL
 WILTING POINT         =   0.1360 VOL/VOL
 INITIAL SOIL WATER CONTENT =   0.2900 VOL/VOL
 EFFECTIVE SAT. HYD. COND.  = 0.119999997000E-03 CM/SEC

                  LAYER 2
                  -------
         TYPE 2 - LATERAL DRAINAGE LAYER
          MATERIAL TEXTURE NUMBER 10
 THICKNESS             =   6.00  INCHES
 POROSITY              =   0.3980 VOL/VOL
 FIELD CAPACITY        =   0.2440 VOL/VOL
 WILTING POINT         =   0.1360 VOL/VOL
 INITIAL SOIL WATER CONTENT =   0.2900 VOL/VOL
 EFFECTIVE SAT. HYD. COND.  = 0.119999997000E-03 CM/SEC
 SLOPE                 =   2.00  PERCENT
 DRAINAGE LENGTH       =   8.0   FEET

                  LAYER 3
                  -------
         TYPE 4 - FLEXIBLE MEMBRANE LINER
          MATERIAL TEXTURE NUMBER 35
 THICKNESS             =   0.06  INCHES
 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.  = 0.199999996000E-12 CM/SEC
 FML PINHOLE DENSITY      =   0.00  HOLES/ACRE
 FML INSTALLATION DEFECTS =   1.00  HOLES/ACRE
 FML PLACEMENT QUALITY    =  1 - PERFECT

       GENERAL DESIGN AND EVAPORATIVE ZONE DATA
       ----------------------------------------
 NOTE:  SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT
        SOIL DATA BASE USING SOIL TEXTURE #10 WITH BARE
        GROUND CONDITIONS, A SURFACE SLOPE OF  2.% AND
        A SLOPE LENGTH OF   8. FEET.
 SCS RUNOFF CURVE NUMBER          =  94.90
 FRACTION OF AREA ALLOWING RUNOFF =  100.0   PERCENT
 AREA PROJECTED ON HORIZONTAL PLANE =  0.000  ACRES
 EVAPORATIVE ZONE DEPTH           =   6.0   INCHES
 INITIAL WATER IN EVAPORATIVE ZONE =   1.740  INCHES
 UPPER LIMIT OF EVAPORATIVE STORAGE =   2.388  INCHES
 LOWER LIMIT OF EVAPORATIVE STORAGE =   0.816  INCHES
 INITIAL SNOW WATER               =   0.000  INCHES
 INITIAL WATER IN LAYER MATERIALS =   3.480  INCHES
 TOTAL INITIAL WATER              =   3.480  INCHES
 TOTAL SUBSURFACE INFLOW          =   0.00   INCHES/YEAR
```

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
TAMPA FLORIDA
STATION LATITUDE = 27.58 DEGREES
MAXIMUM LEAF AREA INDEX = 0.00
START OF GROWING SEASON (JULIAN DATE) = 0
END OF GROWING SEASON (JULIAN DATE) = 367
EVAPORATIVE ZONE DEPTH = 6.0 INCHES
AVERAGE ANNUAL WIND SPEED = 8.60 MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 74.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 72.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 78.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 76.00 %

NOTE: PRECIPITATION DATA FOR Tampa Florida
WAS ENTERED BY THE USER.
NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR TAMPA FLORIDA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
59.80	60.80	66.20	71.60	77.10	80.90
82.20	82.20	80.90	74.50	66.70	61.30

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR TAMPA FLORIDA
AND STATION LATITUDE = 27.58 DEGREES
HEAD #1: AVERAGE HEAD ON TOP OF LAYER 3
DRAIN #1: LATERAL DRAINAGE FROM LAYER 2 (RECIRCULATION AND COLLECTION)
LEAK #1: PERCOLATION OR LEAKAGE THROUGH LAYER 3
****

DAILY OUTPUT FOR YEAR 1997

DAY	A I R	O I L	RAIN IN.	RUNOFF IN.	ET IN.	E. ZONE WATER IN./IN.	HEAD #1 IN.	DRAIN #1 IN.	LEAK #1 IN.
1			1.99	1.342	0.005	0.2869	3.4110	.1298E-01	.3489E-05
2			0.00	0.000	0.005	0.2803	6.2681	.3431E-01	.6412E-05
3			0.00	0.000	0.005	0.2737	6.2337	.3399E-01	.6377E-05
4			0.00	0.000	0.005	0.2669	6.3762	.3538E-01	.6523E-05
5			0.00	0.000	0.005	0.2602	6.3203	.3482E-01	.6466E-05
6			0.00	0.000	0.005	0.2544	6.1775	.3344E-01	.6320E-05
7			0.00	0.000	0.005	0.2504	5.9461	.3123E-01	.6083E-05
8			0.00	0.000	0.005	0.2468	5.8596	.3043E-01	.5994E-05
9			0.00	0.000	0.005	0.2434	5.7670	.2958E-01	.5900E-05
10			0.00	0.000	0.005	0.2404	5.6696	.2870E-01	.5800E-05

****

AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1997 THROUGH 1997

	INCHES	CU. FEET	PERCENT
PRECIPITATION	1.99 (0.000)	2.9	100.00
RUNOFF	1.342 (0.0000)	1.95	67.457
EVAPOTRANSPIRATION	0.672 (0.0000)	0.98	33.758
LATERAL DRAINAGE COLLECTED FROM LAYER 2	1.16706 (0.00000)	1.695	58.64628
PERCOLATION/LEAKAGE THROUGH LAYER 3	0.00037 (0.00000)	0.001	0.01869
AVERAGE HEAD ON TOP OF LAYER 3	1.002 (0.000)		
CHANGE IN WATER STORAGE	-1.192 (0.0000)	-1.73	-59.880

```
******************************************************************************
**          HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE                   **
**              HELP MODEL VERSION 3.06 (17 AUGUST 1996)                    **
**              DEVELOPED BY ENVIRONMENTAL LABORATORY                       **
**                USAE WATERWAYS EXPERIMENT STATION                         **
**          FOR USEPA RISK REDUCTION ENGINEERING LABORATORY                 **
******************************************************************************
TITLE: RUNS(3-layer/1.99in Storm/2% Slope/1.9E-5cm/sec Perm)
******************************************************************************
```

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 15

```
THICKNESS                 =    6.00  INCHES
POROSITY                  =    0.4750 VOL/VOL
FIELD CAPACITY            =    0.3780 VOL/VOL
WILTING POINT             =    0.2650 VOL/VOL
INITIAL SOIL WATER CONTENT =   0.2650 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.170000003000E-04 CM/SEC
```

LAYER 2

TYPE 2 - LATERAL DRAINAGE LAYER
MATERIAL TEXTURE NUMBER 15

```
THICKNESS                 =    6.00  INCHES
POROSITY                  =    0.4750 VOL/VOL
FIELD CAPACITY            =    0.3780 VOL/VOL
WILTING POINT             =    0.2650 VOL/VOL
INITIAL SOIL WATER CONTENT =   0.2650 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 0.170000003000E-04 CM/SEC
SLOPE                     =    2.00  PERCENT
DRAINAGE LENGTH           =    8.0   FEET
```

LAYER 3

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER

```
THICKNESS                 =    0.06  INCHES
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. = 0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY       =    0.00  HOLES/ACRE
FML INSTALLATION DEFECTS  =    1.00  HOLES/ACRE
FML PLACEMENT QUALITY     =    1 - PERFECT
```

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE #15 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 2.% AND A SLOPE LENGTH OF 8. FEET.

```
SCS RUNOFF CURVE NUMBER              =   97.10
FRACTION OF AREA ALLOWING RUNOFF     =  100.0   PERCENT
AREA PROJECTED ON HORIZONTAL PLANE   =    0.000 ACRES
EVAPORATIVE ZONE DEPTH               =    6.0   INCHES
INITIAL WATER IN EVAPORATIVE ZONE    =    1.590 INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE   =    2.850 INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE   =    1.590 INCHES
INITIAL SNOW WATER                   =    0.000 INCHES
INITIAL WATER IN LAYER MATERIALS     =    3.180 INCHES
TOTAL INITIAL WATER                  =    3.180 INCHES
TOTAL SUBSURFACE INFLOW              =    0.00  INCHES/YEAR
```

EVAPOTRANSPIRATION AND WEATHER DATA

```
NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
    TAMPA          FLORIDA
  STATION LATITUDE                    = 27.58 DEGREES
  MAXIMUM LEAF AREA INDEX              = 0.00
  START OF GROWING SEASON (JULIAN DATE) =    0
  END OF GROWING SEASON (JULIAN DATE)   =  367
  EVAPORATIVE ZONE DEPTH               = 6.0  INCHES
  AVERAGE ANNUAL WIND SPEED            = 8.60 MPH
  AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 74.00 %
  AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 72.00 %
  AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 78.00 %
  AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 76.00 %

NOTE: PRECIPITATION DATA FOR   Tampa        Florida
    WAS ENTERED BY THE USER.
NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
    COEFFICIENTS FOR   TAMPA        FLORIDA

  NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)
JAN/JUL  FEB/AUG  MAR/SEP  APR/OCT  MAY/NOV  JUN/DEC
-------  -------  -------  -------  -------  -------
 59.80    60.80    66.20    71.60    77.10    80.90
 82.20    82.20    80.90    74.50    66.70    61.30

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
    COEFFICIENTS FOR   TAMPA        FLORIDA
    AND STATION LATITUDE = 27.58 DEGREES

HEAD #1: AVERAGE HEAD ON TOP OF LAYER 3
DRAIN #1: LATERAL DRAINAGE FROM LAYER 2 (RECIRCULATION AND COLLECTION)
LEAK #1: PERCOLATION OR LEAKAGE THROUGH LAYER 3
*************************************************************************

        DAILY OUTPUT FOR YEAR 1997
------------------------------------------------

DAY A O RAIN RUNOFF ET  E. ZONE HEAD    DRAIN   LEAK
 I I            WATER  #1     #1     #1
 R L IN.  IN.  IN. IN./IN.  IN.   IN.    IN.
--- - - ---- ----- ----- ------ ------ ------ ------
 1      1.99 1.392 0.005 0.3639  0.0000 .0000E+00 .0000E+00
 2      0.00 0.000 0.004 0.3632  0.0000 .0000E+00 .0000E+00
 3      0.00 0.000 0.005 0.3624  0.0000 .0000E+00 .0000E+00
 4      0.00 0.000 0.005 0.3616  0.0000 .0000E+00 .0000E+00
 5      0.00 0.000 0.005 0.3609  0.0000 .0000E+00 .0000E+00
 6      0.00 0.000 0.005 0.3601  0.0000 .0000E+00 .0000E+00
 7      0.00 0.000 0.005 0.3593  0.0000 .0000E+00 .0000E+00
 8      0.00 0.000 0.005 0.3586  0.0000 .0000E+00 .0000E+00
 9      0.00 0.000 0.005 0.3578  0.0000 .0000E+00 .0000E+00
10      0.00 0.000 0.005 0.3570  0.0000 .0000E+00 .0000E+00
*************************************************************************
  AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1997 THROUGH 1997
------------------------------------------------------------------------
                     INCHES        CU. FEET    PERCENT
                  ----------    --------    -------
PRECIPITATION               1.99  ( 0.000)       2.9   100.00
RUNOFF                     1.392  ( 0.0000)     2.02   69.941
EVAPOTRANSPIRATION         0.566  ( 0.0000)     0.82   28.422
LATERAL DRAINAGE COLLECTED 0.00000 ( 0.00000)    0.000  0.00000
 FROM LAYER 2
PERCOLATION/LEAKAGE THROUGH 0.00000 ( 0.00000)   0.000  0.00000
LAYER 3
 AVERAGE HEAD ON TOP        0.000 (  0.000)
 OF LAYER 3
CHANGE IN WATER STORAGE    0.033  ( 0.0000)     0.05    1.637
```

```
******************************************************************************
******************************************************************************
**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**             HELP MODEL VERSION 3.06  (17 AUGUST 1996)                    **
**             DEVELOPED BY ENVIRONMENTAL LABORATORY                        **
**              USAE WATERWAYS EXPERIMENT STATION                           **
**         FOR USEPA RISK REDUCTION ENGINEERING LABORATORY                  **
**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************

TITLE: RUNS(1.99 in Storm/2% Slope/ 1.6E-5 cm/sec Perm)

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

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 10
THICKNESS              =    6.00 INCHES
POROSITY               =    0.3980 VOL/VOL
FIELD CAPACITY         =    0.2440 VOL/VOL
WILTING POINT          =    0.1360 VOL/VOL
INITIAL SOIL WATER CONTENT =    0.2900 VOL/VOL
EFFECTIVE SAT. HYD. COND.  = 0.119999997000E-03 CM/SEC

                    LAYER 2
                    --------

          TYPE 2 - LATERAL DRAINAGE LAYER
           MATERIAL TEXTURE NUMBER 10
THICKNESS              =    6.00 INCHES
POROSITY               =    0.3980 VOL/VOL
FIELD CAPACITY         =    0.2440 VOL/VOL
WILTING POINT          =    0.1360 VOL/VOL
INITIAL SOIL WATER CONTENT =    0.2900 VOL/VOL
EFFECTIVE SAT. HYD. COND.  = 0.119999997000E-03 CM/SEC

                    LAYER 3
                    --------

          TYPE 2 - LATERAL DRAINAGE LAYER
           MATERIAL TEXTURE NUMBER 0
THICKNESS              =    0.10 INCHES
POROSITY               =    0.3500 VOL/VOL
FIELD CAPACITY         =    0.0100 VOL/VOL
WILTING POINT          =    0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT =    0.0050 VOL/VOL
EFFECTIVE SAT. HYD. COND.  = 0.400000019000E-02 CM/SEC

                    LAYER 4
                    --------

          TYPE 2 - LATERAL DRAINAGE LAYER
           MATERIAL TEXTURE NUMBER 34
THICKNESS              =    0.12 INCHES
```

POROSITY = 0.8500 VOL/VOL
FIELD CAPACITY = 0.0100 VOL/VOL
WILTING POINT = 0.0050 VOL/VOL
INITIAL SOIL WATER CONTENT = 0.0050 VOL/VOL
EFFECTIVE SAT. HYD. COND. = 33.0000000000 CM/SEC
SLOPE = 2.00 PERCENT
DRAINAGE LENGTH = 8.0 FEET

LAYER 5

TYPE 4 - FLEXIBLE MEMBRANE LINER
MATERIAL TEXTURE NUMBER 35
THICKNESS = 0.06 INCHES
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. = 0.199999996000E-12 CM/SEC
FML PINHOLE DENSITY = 0.00 HOLES/ACRE
FML INSTALLATION DEFECTS = 1.00 HOLES/ACRE
FML PLACEMENT QUALITY = 1 - PERFECT

GENERAL DESIGN AND EVAPORATIVE ZONE DATA

NOTE: SCS RUNOFF CURVE NUMBER WAS COMPUTED FROM DEFAULT SOIL DATA BASE USING SOIL TEXTURE #10 WITH BARE GROUND CONDITIONS, A SURFACE SLOPE OF 2.% AND A SLOPE LENGTH OF 8. FEET.

SCS RUNOFF CURVE NUMBER = 94.90
FRACTION OF AREA ALLOWING RUNOFF = 100.0 PERCENT
AREA PROJECTED ON HORIZONTAL PLANE = 0.000 ACRES
EVAPORATIVE ZONE DEPTH = 6.0 INCHES
INITIAL WATER IN EVAPORATIVE ZONE = 1.740 INCHES
UPPER LIMIT OF EVAPORATIVE STORAGE = 2.388 INCHES
LOWER LIMIT OF EVAPORATIVE STORAGE = 0.816 INCHES
INITIAL SNOW WATER = 0.000 INCHES

INITIAL WATER IN LAYER MATERIALS = 3.481 INCHES
TOTAL INITIAL WATER = 3.481 INCHES
TOTAL SUBSURFACE INFLOW = 0.00 INCHES/YEAR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM TAMPA FLORIDA

STATION LATITUDE = 27.58 DEGREES
MAXIMUM LEAF AREA INDEX = 0.00
START OF GROWING SEASON (JULIAN DATE) = 0
END OF GROWING SEASON (JULIAN DATE) = 367
EVAPORATIVE ZONE DEPTH = 6.0 INCHES
AVERAGE ANNUAL WIND SPEED = 8.60 MPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY = 74.00 %
AVERAGE 2ND QUARTER RELATIVE HUMIDITY = 72.00 %
AVERAGE 3RD QUARTER RELATIVE HUMIDITY = 78.00 %
AVERAGE 4TH QUARTER RELATIVE HUMIDITY = 76.00 %

NOTE: PRECIPITATION DATA FOR Tampa Florida WAS ENTERED BY THE USER.

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING

COEFFICIENTS FOR TAMPA FLORIDA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES FAHRENHEIT)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
59.80	60.80	66.20	71.60	77.10	80.90
82.20	82.20	80.90	74.50	66.70	61.30

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR TAMPA FLORIDA
AND STATION LATITUDE = 27.58 DEGREES

HEAD #1: AVERAGE HEAD ON TOP OF LAYER 5
DRAIN #1: LATERAL DRAINAGE FROM LAYER 4 (RECIRCULATION AND COLLECTION)
LEAK #1: PERCOLATION OR LEAKAGE THROUGH LAYER 5

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DAILY OUTPUT FOR YEAR 1997

DAY	S A I R	O I L	RAIN IN.	RUNOFF IN.	ET IN.	E. ZONE WATER IN./IN.	HEAD #1 IN.	DRAIN #1 IN.	LEAK #1 IN.
1			1.99	1.342	0.005	0.3476	0.0001	.1604E-01	.7852E-04
2			0.00	0.000	0.005	0.2913	0.0016	.4073	.5402E-03
3			0.00	0.000	0.005	0.2766	0.0007	.1763	.3631E-03
4			0.00	0.000	0.005	0.2679	0.0004	.1000E+00	.2746E-03
5			0.00	0.000	0.005	0.2619	0.0003	.6912E-01	.2283E-03
6			0.00	0.000	0.005	0.2570	0.0002	.5245E-01	.1991E-03
7			0.00	0.000	0.005	0.2529	0.0002	.4139E-01	.1769E-03
8			0.00	0.000	0.005	0.2490	0.0001	.3379E-01	.1597E-03
9			0.00	0.000	0.005	0.2455	0.0001	.2932E-01	.1487E-03
10			0.00	0.000	0.005	0.2422	0.0001	.2631E-01	.1409E-03

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AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1997 THROUGH 1997

	INCHES		CU. FEET	PERCENT
PRECIPITATION	1.99	(0.000)	2.9	100.00
RUNOFF	1.342	(0.0000)	1.95	67.457
EVAPOTRANSPIRATION	0.674	(0.0000)	0.98	33.881
LATERAL DRAINAGE COLLECTED FROM LAYER 4	1.16552	(0.00000)	1.692	58.56909
PERCOLATION/LEAKAGE THROUGH LAYER 5	0.00442	(0.00000)	0.006	0.22212
AVERAGE HEAD ON TOP OF LAYER 5	0.000	(0.000)		
CHANGE IN WATER STORAGE	-1.197	(0.0000)	-1.74	-60.129

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