

THE FLORIDA STATE UNIVERSITY

COLLEGE OF ENGINEERING

**DESIGN OF COST – EFFECTIVE LYSIMETER FOR FIELD
EVALUATION OF ALTERNATIVE LANDFILL COVER PROJECTS
USING HYDRYS 2D SIMULATION**

By

Xiaoli Liu

A Thesis submitted to the
Department of Civil and Environmental Engineering
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded:
Spring Semester, 2004

The members of the committee approve the thesis of Xiaoli Liu defended on March 3th, 2004.

Tarek Abichou
Professor Directing Thesis

Amy Chan Hilton
Committee Member

Kamal Tawfiq
Committee Member

The Office of Graduate Studies has verified and approved the above named committee members

ACKNOWLEDGEMENT

The author sincerely thanks all the people whose encouragement and support have made this thesis possible. Special thanks are given to Dr. Tarek Abichou, this thesis could not possibly have existed without his instructions. Dr. Abichou helped me with this thesis at every stage: he taught me almost everything I know about solid waste landfill, including liner system, leachate collection system, and cover system. He brought me the idea of alternative evapotranspiration covers (ET) and hydraulic equivalency, he gave me valuable instructions about lysimeter geometry simulations using Hydrus 2D and constructive comments of my work, and he provided a critical review of the manuscript. I am grateful to Dr. Abichou for all his help and encouragement.

I also wish to thank Dr. Amy Chan Hilton who brought me into the world of environmental engineering and taught me the knowledge of groundwater and surface water, environment contamination and remediation. She taught me how to think scientifically and express clearly. Many thanks to Dr. Kamal Tawfiq for the knowledge of geotechnical engineering and for being on my committee. Finally I would like to thank the coworkers in our group who offered me various helps.

TABLE OF CONTENTS

LIST OF FIGURES	vi
LIST OF TABLES	viii
ABSTRACT	ix
1. INTRODUCTION	1
2. BACKGROUND	3
2.1 Conventional Landfill Covers	3
2.2 Introduction to Evapo – Transpiration (ET) Covers	6
2.3 Hydraulic Equivalency	8
2.3.1 Indirect Methods of Field Evaluation of Percolation Rate	9
2.3.1.1 Tread Analysis	10
2.3.1.2 Water Balance Method	10
2.3.1.3 Darcy’s Law Method	13
2.3.1.4 Tracer Method	14
2.3.2 Direct Methods of Field Evaluation of Percolation Rate (Lysimeter)	15
2.3.2.1 Introduction to Lysimeters	15
2.3.2.2 Design of Lysimeters	15
2.3.2.3 Advantages and Concerns of Lysimeter	16
3. MATERIALS AND METHODS	18
3.1 HYDRUS - 2D	18
3.1.1 HYDRUS 2D (version 1.0) Code Description	18
3.1.2 Verification	22
3.1.3 Validation	23

3.1.4 Sensitivity Analysis	24
3.1.5 Application	24
3.2 Simulations	25
3.2.1 Full Scale Landfill Covers	28
3.2.2 Effects of Lysimeter Geometry	30
4. RESULTS AND ANALYSIS	34
4.1 BaseLine Cover Simulations	34
4.2 Simulation With Flat Lysimeters	37
4.2.1 The Effect of Size on the Performance of Flat Lysimeters	37
4.2.2 Effect of Sidewalls on the Performance of Flat Lysimeters	39
4.3 Lysimeters for Sloped Covers	47
4.4 Synthesis	51
5. SUMMARY AND CONCLUSIONS	53
5.1 The Effect of Size on the Performance of Flat Lysimeters	54
5.2 Effect of Sidewalls on the Performance of Flat Lysimeters	54
5.3 Lysimeters in Slope ET Landfill Covers	58
5.4 Conclusions	62
5.5 Recommendations for Future Work	62
REFERENCES	64
BIOGRAPHICAL SKETCH	69

LIST OF FIGURES

Figure 2.1	Prescriptive Cover Profile (After SAIC, 2000)	5
Figure 2.2	Profile of Evapo – Transpiration Cover	7
Figure 2.3	A Plot of Soil Water Content and Total Water Applied in Albany Georgia	11
Figure 3.1	A Cross Section of a Simulation Domain Generated During This Study.....	26
Figure 3.2	Mesh Generated by HYDRUS - 2D	27
Figure 3.3	Sketch of Simulation With Full Scale Cover.....	29
Figure 3.4	Profile of Lysimeter Without Sidewalls.....	31
Figure 3.5	Profile of Lysimeter With Short Sidewalls.....	32
Figure 3.6	Profile of Inclined Lysimeter	33
Figure 4.1	BaseLine Unit Cumulative Flux of Full Scale Covers After Two Years Simulations	38
Figure 4.2	Performance Ratio of Lysimeters Without Sidewall After Two Years Simulations	40
Figure 4.3	Illustration of Lateral Diversion of Lysimeter Without Sidewall.....	41
Figure 4.4	Performance Ratio of Small Lysimeters With Sidewall After Two Years Simulations	43
Figure 4.5	Performance Ratio of Medium Lysimeters With Sidewall After Two Years Simulations	44
Figure 4.6	Performance Ratio of Large Lysimeters With Sidewall After Two Years Simulations	46
Figure 4.7	Performance Ratio of Large Lysimeters With Sidewalls on	

	Slope 1:5 After Two Years Simulations.....	48
Figure 4.8	Performance Ratio of Large Lysimeters With Sidewalls on Slope 1:4 After Two Years Simulations.....	49
Figure 4.9	Performance Ratio of Large Lysimeters With Sidewalls on Slope 1:4 After Two Years Simulations.....	50

LIST OF TABLES

Table 2.1 Prescribed Regulatory Landfill Cover Designs	4
Table 4.1 Simulations of Lysimeters Conducted in This Study	35
Table 4.2 The Hydraulic Properties of Loam, Silt and Clay Loam	36
Table 5.1 Performance Ratio of Small Lysimeters With Sidewalls	55
Table 5.2 Performance Ratio of Medium Lysimeters With Sidewalls	56
Table 5.3 Performance Ratio of Large Lysimeters With Sidewalls	57
Table 5.4 Performance Ratio of Large Lysimeters on Slope 1:5	59
Table 5.5 Performance Ratio of Large Lysimeters on Slope 1:4.....	60
Table 5.6 Performance Ratio of Large Lysimeters on Slope 1:3	61

ABSTRACT

Landfills are the most widely used facilities for solid waste disposal. Landfill covers are used to reduce the quantity of water that infiltrates into solid waste landfills, isolate solid waste from the environment and control gas migration. Resource Conservation and Recovery Act (RCRA) regulations prescribe that the covers employ layers which have low saturated hydraulic conductivity as hydraulic barriers. Those barriers can limit flow into underlying solid wastes, and consequently, reduce the rate of leachate generation and risk of additional groundwater contamination.

Experience has shown that the prescribed clay barrier layers are susceptible to failure caused by desiccation and cracking damage by freeze – thaw actions, and are expensive to build. An effective alternative cover design is Evapor-Transpiration (ET) cover. ET covers possess many advantages over prescribed covers such as working with nature, long life time, easy maintenance and lower cost.

Once the feasibility of an ET cover is verified in a region, an evaluation of hydraulic equivalency is required for alternative cover to be approved by regulatory authorities. The hydraulic equivalency requires that percolation from the base of the alternative cover is less than or equal to percolation rate from the prescriptive cover. Lysimeters was suggested to be used in facilities measuring the percolation rate. There are some concerns about the precision with which percolation rate can be measured with lysimeters.

A series of numerical simulations were performed in this study to investigate the performance of lysimeters of various geometries and develop the optimal lysimeters dimensions for percolation rate measurement. The simulations consist of inputting data for lysimeter geometry, soil hydraulic property, weather condition, boundary condition, vegetation distribution and density. The output cumulative flux data was used to evaluate the performance of lysimeters.

The study shows at the specific weather condition, the lysimeters without sidewalls underestimate percolation rate by at least 25%. Installation of full sidewalls remarkably improved the lysimeter performance. The lysimeter with full scale sidewalls still underestimate

by at least 10%. Lateral diversion and no-flow boundary at the bottom of lysimeter and the drainage layer right above the bottom pan caused the decrement of lysimeter performance. To measure percolation rate accurately, soil - specific and site - specific coefficients have to be determined. The coefficients can to be used to correct lysimeter performance.

CHAPTER ONE

INTRODUCTION

Final covers are constructed for solid and hazardous waste landfills to reduce the amount of water infiltrating into the waste deposit, isolate waste and control gas migration. Resource Conservation and Recovery Act (RCRA) regulations require that final covers be constructed with clayey soils or with geosynthetic clay liners (GCLs), with or without geomembrane. These types of covers are susceptible to failure caused by desiccation and cracking damage, expensive to construct and maintain. Evapo - Transpiration (ET) covers can be an alternative approach to the traditional covers. ET covers exploit the water storage capacity of finer textured soils and the water removal capability of vegetation to reduce infiltration into the underlying waste. ET covers work with nature rather than attempting to control them.

Before the acceptance of ET landfill covers by the regulatory agencies, and the full-scale implementation of ET covers can be conducted, field studies are needed to verify the effectiveness of the designs. RCRA regulations require that percolation from any alternative covers must be equivalent to the prescriptive cover.

Five methods are typically considered to assess the field performance of ET cover test sections: 1) Water balance methods, 2) Trend evaluation, 3) Tracer experiments, 4) Darcy's Law method, 5) Lysimetry . Only lysimetry provides a direct measurement of percolation rate from an alternative cover. However, the following disadvantages of lysimeters are being challenged by the engineering community:

- The artificial no-flow boundary induced by the lysimeter at the base of the profile prevents upward and downward flow of vapor and liquid across the base of the lysimeter.
- Most lysimeters also include a drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers induce a capillary break at the base of the cover profile that might not exist under natural

conditions. As a result, an artificial increase in the storage capacity of the cover profile may be incurred relative to natural conditions, as well as an artificial reduction in percolation rate.

- Lateral diversion can be a significant problem with lysimetry. Lysimeters that are too small collect too little water and underestimate the percolation rate.

This study is a numerical study that investigates the influence of the above three factors on the lysimeter performance, how lysimeter geometry and boundary conditions affect lysimeter performance. Section Two describes five available methods for percolation rate measurement, and review different concerns about lysimeter application. Section Three describes the properties of HYDRUS - 2D, its application and validation, parameters used in this study. Section Four encapsulates the results from simulations using HYDRUS - 2D. A summary of results, along with recommendations based on this study is provided in Section Five. Section 6 includes a list of references used in this study.

CHAPTER TWO BACKGROUND

2.1 Conventional Landfill Covers

Landfills are the most commonly used facilities for disposal of industrial, municipal, and low-level radioactive waste. Once a landfill is closed, final covers are required. Final covers are used to reduce the amount of water infiltrating into the waste deposit. They also act to isolate waste, and control gas migration. The Resource Conservation and Recovery Act (RCRA) Subtitle 'C' and 'D' prescribes the requirements of landfill covers. Under Subtitle D of RCRA, the United States Environmental Protection Agency (USEPA) provides the minimum criteria for covers and liner designs of municipal solid waste landfills. The regulations provide four types of cover designs based on the liner system at the base of the landfills (Table 2.1). Those cover designs are referred to as prescribed covers.

The prescribed covers make use of resistive principles, i.e., layers with low saturated hydraulic conductivity (compacted clay barriers, or geosynthetic clay liners with or without a geomembrane) to minimize the infiltration into the landfill by maximizing runoff and evaporation. The primary components of the prescriptive cover include a layer of vegetative cover underlain by a drainage composite and a 60-mil HDPE geomembrane. Underneath the geomembrane is the low - permeability layer and a foundation layer. The prescriptive final cover overlays an interim native soil typically used to cover the waste on a daily basis (Fig. 2.1). Thickness of each layer varies from one state to another. Native vegetation is applied to the top layer for erosion control. Experience has shown that the prescribed clay barrier layers have several disadvantages, such as susceptible to failure caused by desiccation and cracking (Landreth et al., 1991) damage. These types of cover are also expensive to construct and maintain. In addition, the performance of these covers decreases with time and degradation due to erosion.

Table 2.1 Prescribed Regulatory Landfill Cover Designs (After SAIC, 2000).

Category	Existing Liner	Cover Requirement
A	No Liner	6 in. erosion layer, 18 in. barrier layer with $K_{\text{sat}} < 10^{-5}$ cm/s or Ksat of underlying soils, whichever is smaller
B	Soil Liner with $K_{\text{sat}} < 10^{-6}$ cm/s	6 in. erosion layer, 18 in. barrier layer with $K_{\text{sat}} < 10^{-6}$ cm/s
C	Soil Liner with $K_{\text{sat}} < 10^{-6}$ cm/s	6 in. erosion layer, 18 in. barrier layer with $K_{\text{sat}} < 10^{-7}$ cm/s
D	Composite liner (soil overlain by Geomembrane) having a $K_{\text{sat}} < 10^{-7}$ cm/s	6 in. erosion layer, 18 in. barrier layer with $K_{\text{sat}} < 10^{-5}$ cm/s

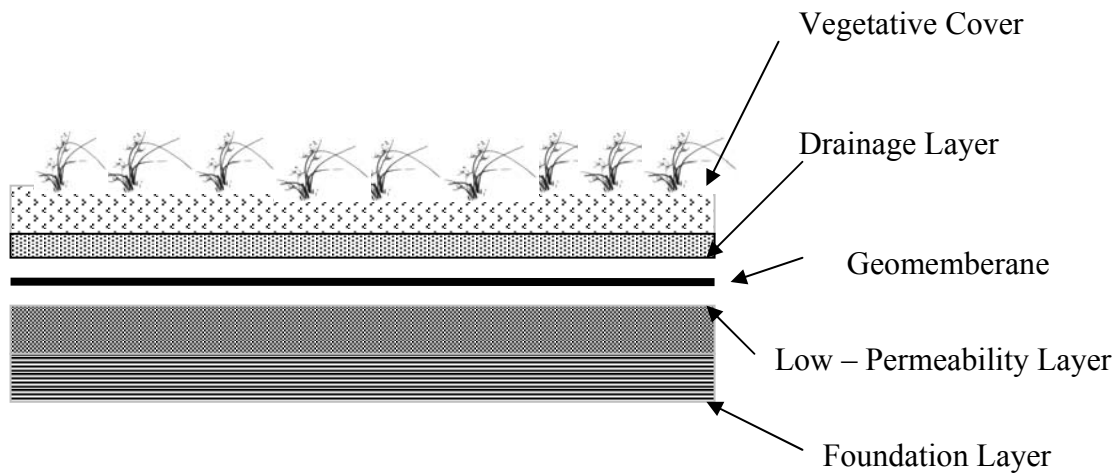


Fig. 2.1 Prescriptive Cover Profile (After SAIC, 2000).

2.2 Introduction to Evapo – Transpiration (ET) Covers

The environment performance limitations and high cost of prescriptive cover designs and the requirements for long - term protection of human health stimulate the interest in alternative cover designs. In 1998, the USEPA initiated the Alternative Cover Assessment Program (ACAP) to promote innovative alternatives to the conventional landfill final cover designs. An effective alternative cover design is the "evapo - transpiration cover" (ET cover) which exploits the water storage capacity of finer - textured soils and the water removal capability of vegetation (Licht, 1993; Wing and Gee, 1994; Benson and Khire, 1995; Stormont and Morris, 1998; Nyhan et. al., 1997; Ward and Gee, 1997; Benson et al., 2001). In ET cover design, the role of vegetation is critical, because root water uptake is the key means in removing water stored in the cover (Benson et. al., 2001). The general profile of ET cover is shown in Fig. 2.2. ET cover consists of a layer of vegetation designed to enhance evapotranspiration during growing season, and a compacted support layer which provides storage during seasons of low evapotranspiration. Underneath the compacted layer is the foundation layer. The ET cover seats on an interim cover layer which is used to cover the waste on the daily basis (SAIC, 2000).

The water balance of ET cover can be represented in Equation (2.1):

$$P_t = P - R - S - T - E - L \quad (2.1)$$

where P_t is percolation, P is precipitation, R is runoff, S is storage of fine – texture soil layer, T is transpiration of vegetation, E is evaporation, and L is lateral drainage (Khire 1997; Langoni, 2002). ET covers make use of the water uptake capabilities of vegetation roots, and the storage capacity of fine – texture soils to reduce the amount of percolation into landfill. By maximizing transpiration of vegetation, evaporation, and storage of soils, ET covers reduce the percolation in the water balance equation.

The performance of ET cover designs are determined by: (1) water retention characteristics of soil, (2) meteorological conditions, and 3) type of vegetation. Sufficient storage capacity is required to retain water that accumulates during winter when evapotranspiration is limited, and the storage capacity is a function of the soil texture and thickness. The soil type and thickness is influenced by the meteorological conditions. Vegetation with sufficient rooting depth, root density is also required.

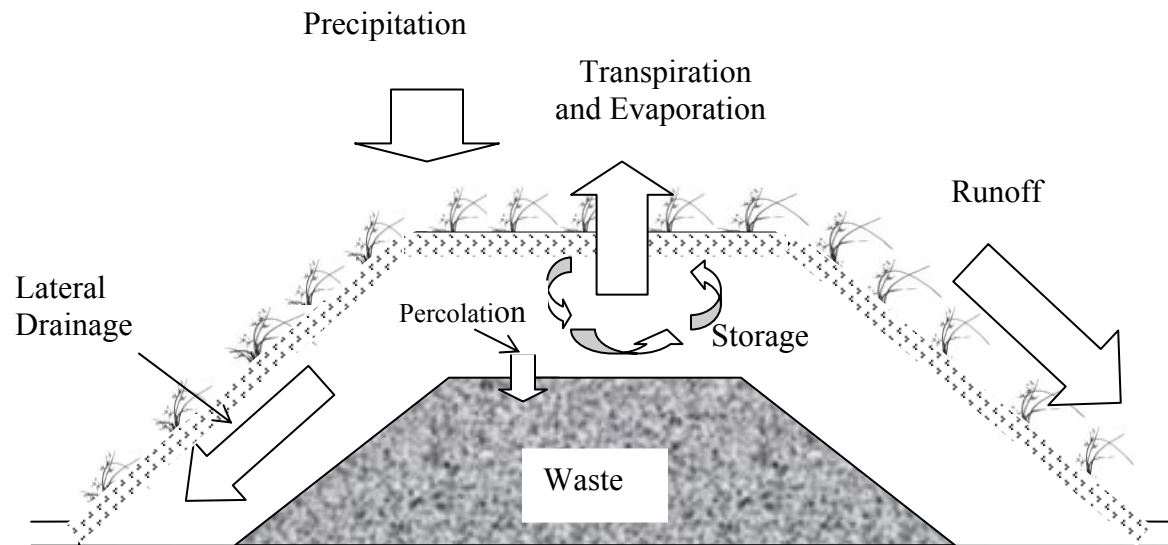


Fig. 2.2 Profile of Evapo - Transpiration Cover.

Two basic designs of alternative covers were developed: monolithic covers and capillary barriers. Monolithic covers are composed of only one thick earthen layer of low hydraulic conductivity and high storage capacity, which increase the storage capacity and evaporation of monolithic cover and limit the percolation through the cover. The thickness of the cover is determined by the precipitation and the storage capacity of the soil. Monolithic covers work well when water is readily stored near the surface. Capillary barriers utilize two layer designs, fine grained layer seating above coarse grained layer. The capillary force generated between fine layer and coarse layer prevents water infiltrating into the coarse layer, which forces water to be stored in finer surface layer and thus contributes to higher evaporation.

The design of ET cover possesses theoretical and technical advantages over that of traditional prescribed cover. ET cover is based on the idea of working with nature to create better landfill covers (Benson et. al., 2000). Water accumulating in the fine – grained soil layer is pumped up by vegetation during plant growing season via evapotranspiration. Vegetation improves slope stability for ET covers and slope failure has been a technical problem for prescriptive covers especially in areas of heavy rainfall (Langoni, 2002). While the performance of prescribed covers decreases with time because of the desiccation and erosion, the performance of ET cover improves with time as the root system of vegetation develops vertically and horizontally. Expected life of evapotranspiration covers is thousands of years because they work with nature, while the life of prescribed covers is often uncertain (Langoni, 2002).

ET covers also have remarkable economic advantage over prescribed covers. Prescriptive covers can be costly, and especially if the required low permeability soil materials are not available locally and have to be transported over long distances to the landfill site. The ET covers are built with soils easily acquired locally and \$50,000 to \$75,000 per acre can be saved when using alternative covers (Benson et. al., 2000).

2.3. Hydraulic Equivalency

The hydraulic performance of ET covers, however, is the most important concern when comparing ET covers and prescriptive covers. Once the feasibility of an alternative earthen final cover is verified in a region, an evaluation of hydraulic equivalency is required for alternative cover to be approved by regulatory authorities. Hydraulic equivalency is generally defined as the situation when the percolation from the bottom of the alternative cover is less than or equal to

percolation from the prescribed cover (Benson et. al., 2001). RCRA USEPA final cover regulations permit alternative covers provided the infiltration layer of the alternative cover achieves an equivalent reduction in infiltration as the infiltration layer of the prescribed cover, e.g. hydraulic equivalency. The demonstration of hydraulic equivalency can be conducted by comparing the percolation rate at the bottom of the ET cover to a predefined equivalency criterion for the prescriptive cover, or by comparing between percolation rates for the ET covers and prescriptive covers under identical climate conditions(e.g., SAIC, 2000; Benson, 2000; Benson et. al., 2001).

The percolation rate of a prescriptive cover is generally site specific, and the regulation in Subtitle C and D of RCRA did not set percolation rate criterion for prescriptive covers. To perform the assessment of alternative covers hydraulic equivalency, ACAP provided some guidance on typical equivalent percolation rate evaluations. Benson et al. (2001) provided a summary of the evaluation of those methods: “In lieu of a site – specific equivalency criterion, an alternative cover is equivalent to a soil cover (e.g., a resistive cover design employing compacted clay) if the percolation rate is less than 10mm/yr in semiarid and drier climates or 30 mm/yr in humid climates. For composite prescriptive covers (i.e., resistive cover designs employing a compacted clay layer overlain by a geomembrane), the percolation rate criterion is 3 mm/yr regardless of climate conditions”. More stringent criteria have been adopted at other sites (Wing and Gee, 1994; Boehm et al., 1998; Chadwick et al., 1999; Benson et al., 2001).

2.3.1 Indirect Methods of Field Evaluation of Percolation Rate

To demonstrate the hydraulic equivalency of an alternative cover to prescriptive covers, field evaluation is necessary. Several methods (trend analysis, tracer methods, water balance method, Darcy’s Law calculation, and lysimetry) have been used to estimate the percolation rate through a soil profile. The following is a brief summary of each method. Trend analysis, water balance method and Darcy’s Law calculations are based on the monitoring of the water content profile with depth.

2.3.1.1 Trend Analysis.

Trend analysis assumes that the absence of a trend or variation in water content at depth means no flow is occurring and percolation is not transmitted at that depth. Darcy's law indicated that the flow of liquid water is caused by a gradient in total hydraulic head (comprised of pressure and gravitational heads) rather than a gradient in water content. In addition, water may also flow in the form of vapor as a result of gradients in vapor pressure and temperature (Scanlon and Milly, 1994). So trend analysis is not based on a sound assumption.

Another obvious flaw of trend analysis is that the percolation rate is calculated from water content and pore water pressure data which are collected by using nests of probes. It is assumed that soils are homogeneous and no cracks or holes made by worms or plant roots developing in the soils. Cracks and holes of worms or plant root, however, are common in landfill covers, especially for those several years old. This phenomenon can be illustrated from the water content data collected from a test section constructed by the ACAP research team in Albany Georgia (Fig. 2.3).

Fig 2.3 is a plot of soil water content and total water applied over the period April, 2000 to October, 2002. During the first eight months, the response to the amount of total applied was similar in shallow and deep soil. After January, 2001, the soil water content at depth 48 inches was more sensitive to total water applied than that in shallow soil. It is suggested that water migrated through cracks or holes and reached deep soil and bypassed shallow soils. In addition, water content is also affected by the position of the water content probes with respect to roots.

2.3.1.2 Water Balance Method

The water balance method can be expressed in equation (2.2):

$$Pr = P - ET - R - \Delta S \quad (2.2)$$

where Pr is percolation rate, P is precipitation, R is runoff, ET is evapotranspiration, and ΔS is the change in soil water storage during a fixed period of time (Benson et al., 2001). The precision of percolation rate measurement depends on the measurement precision with which all the parameters on the right side of the above equation can be measured.

Precision with which precipitation is measured is influenced by such factors as the method used to make the measurements, the form of precipitation (solid, liquid or gas), the

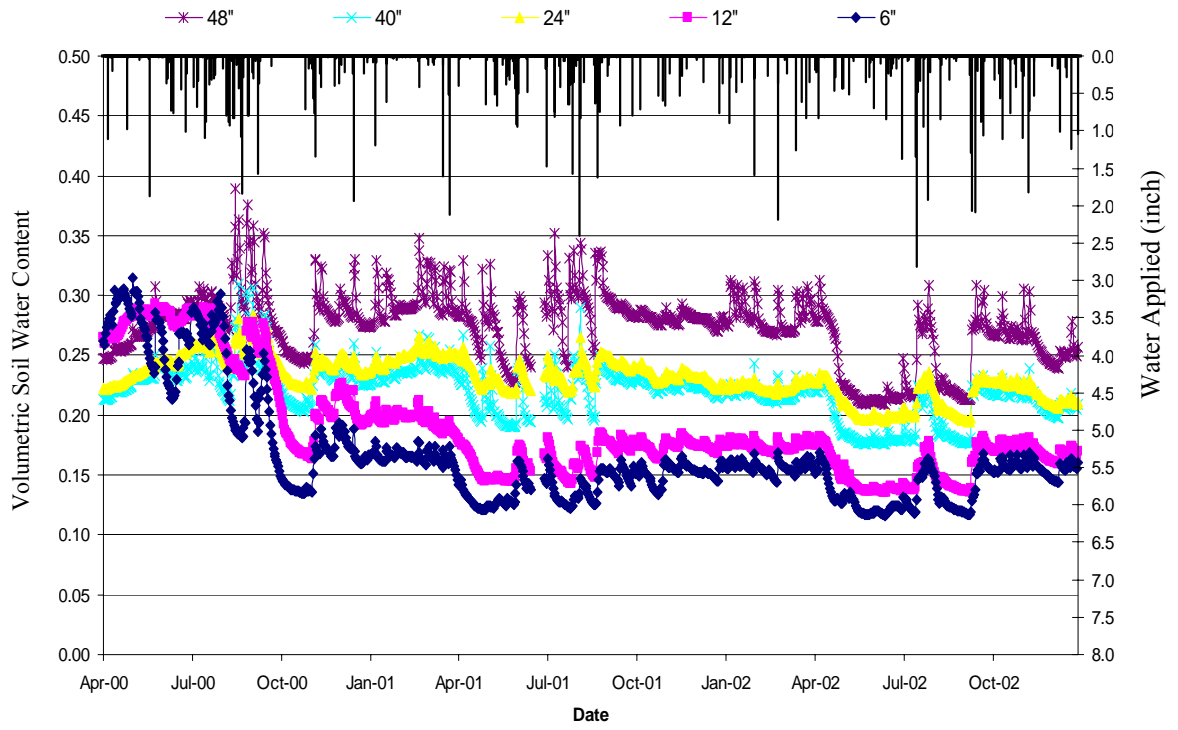


Fig. 2.3 A Plot of Soil Water Content and Total Water Applied in Albany Georgia.

amount of spatial variability existing in the precipitation, and the location of measurements (Smith, 1992; Benson, et. al., 2001). Radiation and high wind velocity are two of the main sources of measurement error. Inadequate wind shielding of rain gauges can also bias the precipitation measurement by 50% or more (Larson and Peck, 1974; Benson, et. al., 2001). With appropriate shielding, up to 30% error still might exist at high wind velocity ($> 8\text{m/s}$). Even under ideal conditions, precipitation measurements have a precision less than 10% (Gee and Hillel, 1988; Benson et. al., 2001).

Measurement of evapotranspiration consists of measuring potential evapotranspiration and actual evapotranspiration. Potential Evapotranspiration (PET) is the amount of water that evaporates from land, water, and plant surfaces if soil water were in unlimited supply. Actual Evapotranspiration (AET) is the amount of water that is actually removed from a surface due to the processes of evaporation and transpiration. It is influenced by climate conditions, water availability, soil characteristics and vegetation conditions. In some portion of the year, AET is less than PET at most sites due to the existence of water stress caused by vegetation root water uptake. PET can be estimated with reasonable accuracy, and AET can be calculated from PET and the ratio of available soil moisture to available water capacity. Errors up to 20% of the estimated AET are common (Gee and Hillel, 1988; Benson, et. al., 2001).

Surface runoff from AEFCs can be measured with a precision of 2 to 3% of precipitation if the catchment being monitored is well defined and the outflow monitoring points are limited (Winter, 1981). Delineation of the catchment area and direct run off for measurement is critical for reasonable definition of the catchment. And it's required that drainage from the catchment not be impeded by the measurement system. If impediments exist, infiltration into the cover will be unrealistically large and runoff will be underestimated.

The best water content measurement devices (those employing nuclear or dielectric techniques) can provide water contents within $\pm 2\%$ (Topp et al, 1980; Gee and Ward, 1999; Benson et al, 2001). Similarly, the cracks in soil might be a source of error of the measurement. Calibration bias also result in errors in water content on the order of 5% (Benson and Bosscher, 1999; Benson et al., 2001), especially for fine – textured soils often used for earthen covers. Thus, for a 1m thick cover, measured soil water storage can be determined with a precision of 20 mm at best (Benson, et. al., 2001).

The precision with which percolation rate is measured is determined by the measurement precisions of the variables described previously. The reported precision of percolation rate measuring with this method is 100 mm/year in humid area (Abichou, 2003).

2.3.1.3 Darcy's Law Method

If the unsaturated hydraulic properties of the cover soils are known (soil water characteristic curve [SWCC] and hydraulic conductivity), the percolation rate can be calculated with Darcy's law method, which can be expressed as:

$$Pr = K_{\Psi}i \quad (2.3)$$

where Pr is percolation rate, K_{Ψ} is the hydraulic conductivity at suction Ψ and i is the hydraulic gradient (Allison et. al., 1983; Stephens and Knowlton, 1986; Boehm et. al., 1998; Benson et. al., 2001). The value of suctions Ψ can be determined from SWCC provided the corresponding water content data have already been measured in the cover soils. The hydraulic gradient can be calculated from suctions (Ψ) and the elevations at which the water contents are measured. The hydraulic conductivity is estimated from the average suction at the depths where the gradient is calculated and the unsaturated hydraulic conductivity curve.

The water content measurement, as in trend analysis and water balance method, is the most significant potential source of error because of preferential flow through such macroscopic features as cracks, holes made by animals or plant roots or lateral flow due to fine variations in textures or anisotropy in hydraulic properties (McCord and Stephens, 1987; Benson et. al., 2001). In most cases, the probes used to measure water content yield data characteristic of conditions within the soil matrix and not along cracks, fissures, or macropores which are preferential flow paths.

Hysteresis in the SWCC is another source of error (i. e., the suction corresponding to a given water content depends on whether the soil is wetting, drying, or is in transition between wetting and drying). Most calculations made using the Darcy's law method employ a single SWCC (typically a drying curve) and ignore hysteresis. This error can be avoided by monitoring suctions (using devices such as tensiometers, psychrometers, or heat dissipation units) at the same depths at which the water content probes are placed. However, suctions measured with these devices are also subject to error (Benson et al., 2001).

Errors in estimation of K_{Ψ} also have a significant effect on the precision of percolation rate calculation. K_{Ψ} is estimated from the saturated hydraulic conductivity (K_{sat}) and the shape of the SWCC using equations based on capillary tube models (e.g., the van Genuchten – Mualem model [van Genuchten 1980]). Capillary tube models provide reasonable estimates of unsaturated hydraulic conductivity for coarse – grained soils, but often underestimate the unsaturated hydraulic conductivity of fine – textured soils such as those used for AEFCS (Fredlund et al., 1994; Meerdink et al., 1995; Chiu and Shackelford, 1998; Benson, et al., 2001). Measurements of the unsaturated hydraulic conductivity can be made to reduce this error, but they are tedious, time consuming, and expensive. These measurements can also be subject to errors as large as those present in capillary tube models (Stephens, 1996; Benson and Gribb, 1997; Benson et al., 2001).

If preferential flow is ignored, the precision with which percolation rate can be measured using Darcy’s law method can be estimated. Errors in Ψ due to hysteresis can be as large as an order of magnitude as are errors in K_{Ψ} . Thus, estimates of percolation rate using the “Darcy’s law method” have a precision of one to two orders of magnitude. In addition, spatial variability in the SWCC and K_{Ψ} may increase the precision by an order of magnitude. This relatively poor precision may be acceptable if the calculated percolation rate is very low (e.g., 0.0001 mm/yr), but is unacceptable if the calculated percolation rate is close to the equivalent percolation rate (Benson et al., 2001).

2.3.1.4 Tracer Method

Tracer method is conducted by spiking soils to be tested with a conservative solute which does not exist in pore water with detectable amount (e.g., bromide or deuterium oxide). The assumption behind tracer method is percolation only occur to the depth at which the tracer can be detected. Soil samples are collected from various depths in tested soils for chemical analysis.

The precision of percolation measured with tracer method is influenced by quite a few factors such as the concentration of the solute when it is spiked into the soils, the amount of uptake of the solute by plant roots, the accuracy of chemical analysis, the amount of water flowing through the cover during the monitoring period, the presence of preferential flow paths, and the quality of the mass balance achieved. Given the number of factors that can affect the

precision of testing results, a quantitative assessment of precision is not possible (Benson et al., 2001).

2.3.2 Direct Method of Field Evaluation of Percolation Rate (Lysimeter)

2.3.2.1 Introduction to Lysimeter

Lysimeters are devices used to measure percolation of water infiltrating through soils and to sample soil water for chemical analysis. The main components of lysimetry are the buried containers with open tops which collect and measure soil water. Water infiltrating through soils reaches those buried containers and accumulates, and then is conducted into a measuring facility. There are two types of lysimeters: weighing and volumetric. Volumetric lysimeters are generally employed to monitor the percolation rate of an ET cover. A volumetric lysimeter consists of a pan for collecting water infiltrating through soils monitored, and sidewalls in most cases to prevent water from losing around the bottom pan.

2.3.2.2 Design of Lysimeters

Lysimeter consists mainly of a base pan with or without sidewalls. The pan acts as a collector of percolation. The pans of most lysimeters used to monitor landfill cover sections are rectangular while circle pans are used in some agricultural research. The depth of lysimeter is a critical design parameter and varies with the intended purposes of the tests. Because of the critical role of plants in removing water from landfill cover, the depth, distribution and density of plant roots have to be taken into account in determining depth of a lysimeter under a landfill cover. It was suggested that lysimeter depth should permit the development of normal rooting density and rooting depth and provide similar “available” water profiles to the field profile (Van Bavel, et al.,1961). The areal extent of lysimeters depends on the spatial variability in the properties of cover soils and vegetation. The length and width are usually 5 times larger than depth to ensure that preferential flow processes (e.g., rapid flow in such features as cracks, fissures, root channels, and worm holes) are captured in the test and that the construction process would mimic full – scale conditions (Bews et.al., 1999; Benson et al., 2001).

Some lysimeters have sidewalls along the side of pans while some don't. The sidewalls are used to prevent moisture lateral diversion. The height of sidewalls varies from zero (without sidewalls) to the depth of lysimeter. Flat lysimeters are used on the top of landfill cover while the

inclined lysimeters are usually used on the slopes of landfill covers. The lysimeter construction generally employs linear low – density polyethylene a synthetic geomembrane which is highly puncture resistant and readily welded in the field. A geocomposite drainage layer containing nonwoven geotextiles heatbonded to each side of a geonet is placed directly on the geomembrane to function as a drainage layer and as a cushion during placement of soils (Benson et al., 2001).

2.3.2.3 Advantages and Concerns of Lysimeters

The key advantage of lysimetry over the four methods described in section 2.3.1 is its direct measurement of the percolation rate and higher precision. It was shown that percolation rates can be measured with a precision of 0.5 mm/yr or better using lysimeters (Gee and Hillel, 1988; Benson et al., 1994; Ward and Gee, 1997; Benson et al., 2001). The installation of lysimeters measurement system into soil, however, would introduce disturbance on the soils inside as well as outside lysimeters, which is thought to affect the percolation rate through the soil cover, and consequently affect the precision with which percolation rate is measured with lysimeter. The following concerns have been raised about using lysimeters as percolation measuring facility:

(1) Lateral diversion can be one of the primary sources of error with lysimetry if the areal extent of the lysimeter is insufficient and the lysimeter does not have vertical sidewalls. Lysimeters that are too small and collect too little water underestimate the percolation rate (Benson et al., 2001).

(2) Most lysimeters also include an earthen or geosynthetic drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers induce a capillary break at the base of the cover profile that might not exist under natural conditions (Khire et al. 1997). As a result, an artificial increase in the storage capacity of the cover profile may be incurred relative to natural conditions, as well as a possible reduction in percolation rate (Benson et al., 2001).

(3) The artificial no-flow boundary induced by the lysimeter at the base of the profile. This boundary, which does not exist in the actual field setting, prevents upward and downward flow of vapor and liquid and heat flux across the base of the lysimeter. In effect, the lysimeter acts as a rectifier. All water that migrates downward to the base of the profile is collected and

routed out of the system. Consequently, the collected water can never move upward as a result of natural upward gradients induced by evapotranspiration. And moisture under the lysimeter could not be moved up either. Heat flux, an important parameter in soil moisture migration, is also intercepted by the insertion of the base of lysimeter (Benson et al., 2001). The other problem is disturbance of void space connection between soil under and above the lysimeter base, which might pose some problems on the measurement precision of lysimeter (Gebet and Cuenca, 1991).

(4) For the lysimeters with side walls, the side walls intercept the lateral flow of water and heat flux inside as well as outside lysimeters while bottom restricts vertical water movement, the phenomenon is more obvious on the slope of landfill cover. As a result, vertical flow is increased at the interface between the soil and the lysimeter side walls. The magnitude of this boundary effect is a function of the soil type and texture and the geometry of the side walls (Gebet and Cuenca, 1991). The side walls may also interrupt the development of vegetation roots which uptake water out of soil.

CHAPTER THREE MATERIALS AND METHODS

The objectives of this study were to investigate performance of lysimeters in measuring percolations and to develop optimal lysimetry designs for ET covers. A numerical model, HYDRUS-2D, which can accurately simulate water balance through soils under variably saturated conditions, was used to assess the performance of lysimeters. HYDRUS-2D is one of the models developed for water balance simulation in variably saturated soils, and it can simulate flow in response to meteorological forcing and plant root water uptake. It is fairly well documented, has been widely used and tested, and it is in public domain (Scanlon et al., 2002). The following sections describe the HYDRUS-2D code.

3.1 HYDRUS-2D

3.1.1 HYDRUS-2D (version 1.0) Code Description

HYDRUS-2D was developed by J. Simunek, M. Sejna, and M. Th. Van Genuchten in 1996. It is a computer program used for analysis of water flow and solute transport in variably saturated porous media. Two forms of HYDRUS-2D are available:

Option A includes the HYDRUS-2D executable code and a graphics – based user interface. A mesh generator is available for a relatively simple rectangle domain geometry in this version. Users can either create the input files describing the domain geometry and associated finite element mesh by themselves or use the internal mesh generator to make a simple rectangular structured transport domain.

Option B consists of version A and a CAD program MESHGEN2D for designing a more general domain geometry, and its discretization into an unstructured finite element mesh for a variety of problems involving variably – saturated subsurface flow and transport. Version B is used in this study.

HYDRUS-2D is derived from the variably flow codes SWMS-2D of Simunek et al. (1992) and CHAIN-2D of Simunek and van Gneuchten (1994). A complete HYDRUS-2D package consists of seven main modules: HYDRUS2D, PROJECT MANAGER, MESHGEN2D, H2D_BERC (boundary), H2D_CALC (HYDRUS2), H2D_CLCI (HYDRUS2) and H2D_GRAF (Graphics).

HYDRUS2D is the main program which controls execution of the program and determines which other modules need to be run for a particular simulation. HYDRUS2D contains a project manager and both the pre-processing and post – processing units.

MESHGEN2D is a mesh generator for unstructured finite element grids. This program, based on Delaunay triangulation, is seamlessly integrated in the HYDRUS-2D environment. MESHGEN2D is used to define virtually any two – dimensional geometric transport domain and subsequently to design a finite element discretization for that domain.

BOUNDARY module helps user to specify boundary and initial conditions for both water flow and solute transport, and define the spatial distribution of other parameters characterizing the flow domain (e.g., spatial distribution of soil materials, hydraulic scaling factors, root – water uptake parameters, and possible hydraulic anisotropy) and/or observation nodes. Three types of boundary conditions are possible with Richards' equation – based models: Dirichlet is prescribed head, Cauchy is prescribed flux, and Neumann is a prescribed hydraulic gradient. All the three types can be used in HYDRUS-2D. Nine options are available in HYDRUS-2D to specify boundary condition (BC): no flux, constant pressure, constant flux, variable pressure, variable flux, free drainage, seepage face, and atmospheric. Free drainage BC is a Neumann – type, in which a unit vertical hydraulic gradient is imposed at the boundary. The atmospheric BC is a Cauchy type BC, in which the precipitation, potential evaporation, and potential transpiration rates must be specified. In the landfill cover simulations, free drainage BC is recommended for the bottom BC, seepage face BC is selected when drainage layer is installed above lysimeter bottom pan. Atmospheric boundary condition is for the surface condition, although one may wish to specify the infiltration rate as a constant or variable flux BC when testing landfill cover performance for an individual precipitation event. HYDRUS-2D cannot simulate erosion.

HYDRUS2 (H2D_CALC, H2D_CLCI) implements the primary data analysis and calculations for HYDRUS-2D. The HYDRUS2 program is a finite element model for simulating movement of water, heat, and multiple solutes in variably saturated media. The program

numerically solves the Richards' equation for saturated-unsaturated water flow and the Fickian-based advection-dispersion equations for heat and solute transport. The governing flow equation was modified from Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i} \left[K (K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iz}^A) \right] - S \quad (3.1)$$

where θ is volumetric water content [L^3L^{-3}], h is pressure head [L], x_i are the spatial coordinates [L], t is time [T], K_{ij}^A are components of a dimensionless anisotropy tensor K^A , K is unsaturated hydraulic conductivity function [L/T^{-1}] given by:

$$K(h, x, z) = K_s(x, z) K_r(h, x, z) \quad (3.2)$$

S is the sink term to account for water uptake by plant roots. It is defined as

$$S(h) = a(h)(L_s T_p)/(L_x L_z) \quad (3.3)$$

where, $a(h)$ is the plant water stress function, T_p is the potential transpiration rate, L_s is the width of the surface, L_x is the width of the root zone, and L_z is the depth of the root zone.

A Galerkin type linear finite element method was used to solve the governing equations. An implicit (backwards) finite difference scheme is used to achieve integration in time for both saturated and unsaturated conditions. The resulting equations are solved in an iterative fashion, by linearization and subsequent Gaussian elimination for banded matrices, a conjugate gradient method for symmetric matrices, or the ORTHOMIN method for asymmetric matrices. Additional measures are taken to improve solution efficiency in transient problems, including automatic time step adjustment and checking if the Courant and Peclet numbers do not exceed preset levels. The mass-conservative method proposed by Celia et al. (1990) is used to evaluate the water content term. Upstream weighting is included as an option for solving the transport equation to minimize numerical oscillations.

The ability of HYDRUS-2D to converge to a stable solution depends upon the discretization and temporal iteration schemes. The finite element mesh was recommended by Simunek et al. (1996) to be constructed with close nodal spacing where the hydraulic gradient is expected to be large, such as the soil surface for atmospheric BCs, and near internal source/sinks like tile drains. A closely spaced mesh is particularly needed for coarse-textured soil with high n -values and small α values. This principle is also true for layer interfaces where hydraulic

properties change sharply and further applies to the time iteration criteria for minimum time steps.

The unsaturated soil hydraulic properties are defined by a set of closed-form equations resembling the 1980 van Genuchten equations. To improve the description of hydraulic properties near saturation, certain modifications were made. This improvement included the incorporation of the ability to prescribe an air-entry pressure head, h_a , and a pressure head, h_k , for matching the relative hydraulic conductivity function to a measured value below saturation, K_k , such that:

$$\theta(h) = \theta_r + \frac{\theta_m - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \quad \text{for } h < h_s \quad (3.4)$$

$$\theta(h) = \theta_s \quad \text{for } h \geq h_s \quad (3.5)$$

and

$$K(h) = K_s K_r(h) \quad \text{for } h < h_k \quad (3.6)$$

$$K(h) = K_r + (K_s - K_k) \left[\frac{(h - h_k)}{(h_s - h_k)} \right] \quad \text{for } h_k < h < h_s \quad (3.7)$$

$$K(h) = K_s \quad \text{for } h \geq h_s \quad (3.8)$$

The effect of the prescribed heads, h_k and h_s , allows the use of a field-saturated water content (θ_s in Eq. 19), which is commonly found to be 10-15% lower than the laboratory measured saturated water content (θ_m in Eq. 18). It further provides a means of incorporating the effect of macropore flow on the hydraulic properties by making $K(h)$ a two-region function (Wilson et al., 1992; Mohanty et al., 1997), whereby K_s represents the hydraulic conductivity when all pores are contributing and K_k is the hydraulic conductivity after the macropores empty.

GRAPHICS manages the geographical, hydrogeologic and physical inputs required to run HYDRUS2D and present results of a simulation by means of contour maps, isolines, spectral maps, and velocity vectors, and /or by animation using both contour and spectral maps. Output graphics include 2D contours (isolines or color spectra) in areal or cross-sectional view for heads, water contents, velocities, and concentrations. Areas of interest can be zoomed into, and vertical scale can be enlarged for cross-sectional views. The mesh can be displayed with

boundaries, and numbering of triangles, edges and points. Observation points can be added anywhere in the grid. Viewing of grid and/or spatially distributed results (pressure head, water content, velocity, or concentration) is facilitated using high resolution color or gray scales.

HYDRUS – 2D can handle flow regions delineated by irregular boundaries. The flow region itself may be composed of nonuniform soils with an arbitrary degree of local anisotropy. Flow and transport can occur in the vertical plane, the horizontal plane, or in a three dimensional region exhibiting radial symmetry about the vertical axis.

HYDRUS - 2D also implements a scaling procedure to approximate hydraulic variability in a given soil profile by means of a set of linear scaling transformations which relate the individual soil hydraulic characteristics to those of a reference soil. A small catalog of soil hydraulic properties is included in the program. While the soil property catalog was derived from Carsel and Parrish (1988), it should be used with care, as some of the key parameters do not appear to be realistic.

3.1.2 Verification

Verification of the HYDRUS-2D code was accomplished by the developers by comparing simulations with both the UNSAT2 (Neuman, 1973) and SWATRE (Belmans et al., 1983) codes. The transport portion of HYDRUS-2D was verified by comparison with an analytical solution for a two-dimensional steady-state groundwater flow problem (Simunek et al., 1996). The comparison with UNSAT2 was made for a one-dimensional infiltration experiment modeled by UNSAT2 (Davis and Neuman, 1983). A homogenous soil column at an initial pressure head of -150 cm was subjected to ponded infiltration at the surface (a constant head BC). The open bottom boundary was modeled as a seepage face BC, and the column sides as no flux BC. Good agreement between UNSAT2 and HYDRUS-2D was observed to demonstrate verification. A more rigorous verification test was made by comparing HYDRUS-2D to SWATRE (Feddes et al., 1978) results for a one-dimensional field profile. The soil profile consisted of two layers with a 30-cm thick root zone. Actual precipitation and potential transpiration rates were used for the atmospheric BC at the surface. The bottom BC was a deep drainage BC with the groundwater level set to 55 cm below the surface and the initial condition was taken to be in equilibrium with the groundwater level. Pressure heads, transpiration rates,

and bottom discharge rates showed excellent agreement with SWATRE results to show verification. Gribb and Sewell (1998) further verified the parent code (SWMS_2D) by making comparisons to a general purpose partial differential equation solver, PDE2D. They found that water volumes in the flow domain were consistent for the four scenarios tested.

3.1.3 Validation

Pohll et al. (1996) coupled SWMS_2D with an overland flow model to simulate recharge below nuclear subsidence craters. They calibrated the overland flow model by adjusting the catchment area to match field measurements of runoff into the crater and calibrated the crater topography to match the measured pond depths in the crater. Since only the boundary condition on the subsurface flow model was calibrated, comparisons of the simulated to measured moisture profiles serve as a validation test for HYDRUS-2D. They found that the simulated water contents were slightly lower (4%) than measured values and with considerably less variability. They considered the model to be in good agreement with measurements given the apparent vertical heterogeneity of the single vertical profile within a three-dimensional flow field and the approach of simulating the profile as homogenous.

Although water balance models are not able to fully investigate the hydrology of capillary barriers, a Richards' equation-based model can be utilized. Kampf et al. (1998) used HYDRUS-2D to simulate the capillary barrier system of an engineered landfill cover. They investigated the process known as capillary diversion, or the breakthrough point of a capillary barrier where the downward vertical flow through the capillary layer equals the infiltration rate, q , from the top of the cover. The field measurements of two landfill facilities in Germany were used to compare the simulation results of the HYDRUS-2D model. The HYDRUS-2D model was calibrated using a number of flumes prior to the larger, field-scale experiment. The authors determined that the HYDRUS-2D model could effectively model capillary barriers with fair precision, as long as the model hydraulic parameters are calibrated to the specific site. The authors stress that soil properties taken from cores alone may not be sufficient to accurately characterize the performance of a capillary barrier at a site.

3.1.4 Sensitivity Analysis

Nofziger et al. (1994) performed sensitivity analyses on four widely used vadose zone transport models (RITZ, VIP, CMLS, and HYDRUS) to compare their behavior. HYDRUS is a predecessor of HYDRUS-2D and should behave similarly, since they are both founded upon the SWMS code. Nofziger et al. (1994) stated that of these four models, the HYDRUS model is most suited for detailed use by research scientists. The sensitivity analysis found that the HYDRUS model was particularly sensitive with respect to the amount of pollutant leached, to the partition coefficient, saturated water content, and the van Genuchten n parameters. For travel time, the model was especially sensitive to the van Genuchten n parameters, saturated water content, partition coefficient, root water uptake potential, and bulk density. For the pulse width, the model was sensitive to the van Genuchten n coefficient, bulk density, saturated water content, and dispersivity. All three of these processes were insensitive to the residual water content and diffusion coefficient. Sensitivity of the flow predictions was not addressed.

3.1.5 Application

HYDRUS-2D and its parent code, SWMS_2D, have been used for a wide range of applications and conditions. Several studies have used HYDRUS-2D to estimate soil hydraulic parameters from multi-step extraction technique (Inoue et al., 1998), transient flow (Simunek et al., 1998), cone penetrometer data (Kodesova et al., 1998), and disc infiltrometer data (Simunek et al., 1998). Mohanty et al. (1998) used HYDRUS-2D to simulate preferential flow and transport of nitrate to tile drains. Davis et al. (1997) coupled SWMS_2D with MODFLOW and MT3D for risk-based remediation modeling of contaminated sites.

HYDRUS-2D has been used for risk analysis (Abbaspour et al., 1997) of landfill covers and performance evaluation of landfill covers (Wilson et al., 1998). Abbaspour et al. (1997) included parameter uncertainty in the risk assessment of a landfill in Switzerland using SWMS_2D to analyze two-dimensional flow and transport. Wilson et al. (1998) used HYDRUS-2D to compare the performance of a monolayer to a subtle-layered ET cover design with regard to the ability of layering to disrupt preferential flowpaths. They ran compaction tests on various particle-size fractions of material from the borrow source for a low-level waste repository at the Nevada test Site. They determined the saturated hydraulic conductivity, and water retention

