WATER BALANCE MEASUREMENTS AND COMPUTER SIMULATIONS OF LANDFILL COVERS

BY

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DISSERTATION

Submitted in Partial Fulfillment of the
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Doctor of Philosophy
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ABSRACT

Six large-scale landfill test covers were constructed and monitored for water balance from May 1997 through June 2002. Two of the covers were used as U.S. EPA standard baseline prototypes for comparison: one that met minimum requirements set forth for municipal landfills (RCRA Subtitle D Cover) and the other meeting minimum requirements set forth for hazardous waste landfills (RCRA Subtitle C Cover). Four alternative covers were then constructed side-by-side with the baseline covers to enable direct comparison under the same ambient conditions. The first alternative cover featured a geosynthetic clay liner (GCL) designed for low saturated hydraulic

conductivity. The remaining three covers were designed specifically for optimal performance in dry environments; specifically, they were designed to take advantage of the storage capacity of the cover and maximize removal of water via evapotranspiration (ET). Two of the dry environment alternative landfill covers featured capillary barriers within their profiles while the last cover consisted of a simple monolithic soil cover, referred to as an ET Cover.

The covers' water balance and vegetation aspects were measured from May 1, 1997 through June 30, 2002. Using flux to compare performance among the six covers, the ET Cover and capillary barriers performed very well, as did the Subtitle C Cover. The Subtitle D Cover was the worst performing cover (i.e. experienced the greatest water flux), while the GCL Cover had a flux less than the Subtitle D Cover but greater than the other covers. Field measurements revealed that all subsurface water flow occurred as unsaturated flow with preferential flow contributing significantly to each cover's total flux.

Two common water balance computer programs (Hydrologic Evaluation of Landfill Performance and UNSAT-H) were evaluated for their applicability as a design tool for landfill covers and for their accurate prediction of a cover's flux. The first evaluation involved using input parameters that simulated a typical design process; the second involved using soil hydraulic properties measured on the covers in their initial or as-built condition along with actual vegetation and weather measurements made on-site; and the final evaluation involved the use of soil hydraulic properties measured on the covers at the end of the monitoring period along with actual vegetation and weather data as input parameters. Neither program predicted flux through these landfill cover profiles with the accuracy desired by regulators and design engineers.

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Chapter 1. Introduction

1.1 Background

The United States is undertaking the monumental task of cleaning up its waste disposal sites. This is costing governments and private concerns trillions of dollars. Perhaps the single largest and most expensive portion of this undertaking is closing landfills across the country. A key element of landfill closure is the design and construction of a final cover intended to isolate the underlying waste material from the surrounding environment.

There are in excess of 250,000 landfills in the United States (Dwyer 2000b). The Department of Energy alone has over 3000 landfills covering thousands of acres (Dwyer 2000b). These landfills can vary considerably in size and cost. An example of a small landfill is the 2.5-acre Mixed Waste Landfill at Sandia National Laboratories in Albuquerque, NM. Large landfills include the 1000-acre Sunrise Mountain Landfill near Las Vegas, Nevada, and the largest of all landfills, the 3000-acre Fresh Kills Landfill on Staten Island, New York.

Prescriptive covers recommended by the U.S. Environmental Protection Agency (EPA) are used throughout the United States with little regard for regional conditions. The compacted soil layer, a principal barrier layer in EPA-recommended designs, is subject to a myriad of problems including desiccation cracking and deterioration due to freeze/thaw cycles. Desiccation, which can occur by several mechanisms, is an important failure mode for compacted soil layers, especially in arid environments (Suter et al. 1993). A study by the California EPA (Mulder and Haven 1995) revealed that compacted clay barrier layers fail regardless of climate or site geology. Geosynthetics (i.e., plastics) are often used in prescriptive cover designs, but introduce planes of weakness, will typically have some construction flaws, increase design and construction complexity, and have a limited database regarding their long-term durability. An EPA design guidance document for final landfill covers states: "In arid regions, a barrier layer composed of clay (natural soil) and a geomembrane is not very effective. Since the soil is compacted 'wet of optimum', the layer will dry and crack" (EPA 1991). Prescriptive covers are not only inherently problematic but are very expensive (Dwyer 1998b) and difficult to construct (Dwyer 2000a).

As pointed out above, there is some observational evidence that the performance of some landfill covers decreases with time. The amount of water that moves through a landfill cover into the underlying waste is generally not monitored or measured, so the contribution of poorly performing covers to eventual environmental problems is not well known. However, it is known that virtually all parts of the nation have experienced water contamination to some degree caused by leachate leaking from landfills (EPA 1988). Inadequate landfill covers are undoubtedly contributing to some of these problems. In addition to problematic covers, many older landfills were crudely installed (e.g., poor siting or no bottom liner) and thus destined for failure, but capping the entire landfill with a properly designed cover can mitigate these problems.

Regulators have the authority to accept alternative landfill covers in lieu of prescriptive covers. These governing authorities need acceptable field data, which demonstrates that an alternative cover will perform as well as a prescriptive cover. Furthermore, regulators must develop confidence that design tools (e.g. computer programs) reliably predict cover performance; typically as indicated by the prediction of the water balance. Currently, there is little data that provides either field performance comparisons or studies of the accuracy of available design tools.

To address some of the issues regarding alternative cover systems, a research program was conducted to investigate the performance of various cover systems including alternatives that may be well suited for arid and semi-arid climates. This research involved the design, construction and monitoring of six large-scale cover systems at a test facility located at Sandia National Laboratories in Albuquerque, NM. Water balance and vegetation aspects were monitored beginning in 1995 and continued through 2002 for each cover system. Soil hydraulic properties were measured in the laboratory and field. Numerical simulations of the water balance for each cover system were conducted to assess current design approaches and gain insight into the cover performance.

Performance of the covers was based on their ability to minimize the movement of water through each profile. In other words, the cover with the lowest flux was deemed the best performer while the cover that yields the highest flux was the worst performer. The EPA suggests a final landfill cover limit flux to between 0.1 mm to 1.0 mm per year (Dwyer et al, in press, a). In a typical arid climate such as Albuquerque, NM, the cover's flux can be a fraction of 1% of the precipitation, while ET can be close to 100%. Nevertheless, flux is the value used by regulators and consequently design engineers to determine the adequacy of a cover.

1.2 Objectives

The overall objective of the research was to provide data and analyses of the performance of six landfill cover designs to aid designers, owners and regulators in selecting appropriate cover designs. Although the field data were site-specific, the results can be judiciously extrapolated to other locations. Specific objectives of this research were:

- **Obtain and compare water balance field data**. Obtain large-scale water balance field data from six landfill covers subjected to identical field and climatic conditions.

- **Design tool accuracy**. Numerically predict the water balance performance of the landfill test covers with the two most common computer programs (i.e., UNSAT-H and HELP) used for design of landfill cover systems. These simulations utilized input parameters intended to represent a typical design process. Compare the predicted flux rates from forward simulations with the field data to assess the usefulness of the design tools.

- **Simulations using field data.** Refine the input parameters used for the water balance simulations of the landfill covers with data collected during the field test (i.e., actual climate, as-built soil property, and vegetation data). Determine the degree to which these simulations predicted observed behavior.

- **Modeling study using soil hydraulic properties measured in the field**. Measure the final soil conditions (i.e., soil hydraulic properties) of the test covers using a tension infiltrometer seven years after construction was completed. Perform water balance simulations based on these soil data measured at the end of the monitoring period with actual climate and vegetation data. Determine the degree to which these simulations predict the observed data.

1.3 Organization of Dissertation

Chapter 1: This chapter includes an introduction to the subject matter, summarizes the importance of the research to fill current technology voids, and outlines the research objectives.

Chapter 2: Provides a regulatory background including an overview of prior field and simulation studies.

Chapter 3: Contains results of the water balance and vegetation data collected from May 1997 through June 2002. In addition, brief descriptions of each test cover and the instrumentation utilized are included.

Chapter 4: Presented results of forward simulations intended to evaluate design tool accuracy. Descriptions of the UNSAT-H and HELP computer programs are also provided.

Chapter 5: Simulation results that utilized the "best available data" as input parameters are directly compared to field obtained data.

Chapter 6: Results of a modeling study are presented and compared with field water balance data as well as prior simulation results contained in chapter 5. The input parameters used for this study contained soil hydraulic properties collected in the field using a tension infiltrometer.

Chapter 7: This chapter provides a discussion of field and simulation results with conclusions based on analyses of these data. In addition, future research needs in the area of landfill closure design and evaluation are included.

Chapter 2. Background

2.1 Prescriptive designs

Land disposal of waste is governed under the Resource Conservation and Recovery Act (RCRA). The two principal types of landfills are regulated under RCRA Subtitles "C" and "D". A RCRA Subtitle "C" disposal facility contains hazardous solid waste while a RCRA Subtitle "D" disposal facility contains municipal solid waste. The regulations for Subtitle C facilities (40 CFR 264 and 265) state that a design should attempt to minimize percolation of water through the cover into the underlying waste thus minimizing the creation of leachate that can in turn leak from the landfill and potentially harm the surrounding environment. They also state that erosion of the final cover is to be kept to a minimum however, the terms minimize and minimum are not defined quantitatively.

In an attempt to clarify this vagueness, the EPA published a design guidance document (EPA 1991). This design guidance document recommended that landfill closures for RCRA Subtitle "C" and/or Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) facilities incorporate the following layers (Figure 2.1) in a cover profile:

1. <u>Composite Barrier Layer.</u> Consists of a low hydraulic conductivity geomembrane/soil layer. This is the first layer encountered above the

landfill material. It consists of a 60-cm layer of compacted natural or amended soil with a maximum saturated hydraulic conductivity of 1 x 10^{-7} cm/sec in intimate contact with an overlying 0.5-mm (20-mil) thick (minimum) geomembrane liner. The function of this composite barrier layer is to limit downward moisture movement.

2. <u>Drainage Layer.</u> Consists of a minimum 30-cm soil layer having a minimum hydraulic conductivity of 1 x 10^{-2} cm/sec, or a layer of geosynthetic material having equivalent characteristics. This layer exists directly above the composite barrier layer. The drainage layer's purpose is to minimize the time the infiltrated water is in contact with the composite barrier layer and hence lessen the potential for the water to reach the waste.

3. <u>Topsoil Vegetation Layer.</u> A top layer with vegetation (or an armored top surface) and a minimum of 60-cm of soil graded at a slope between 3 and 5 percent. This layer should be capable of sustaining nonwoody plants, have an adequate water-holding capacity, and be sufficiently deep to allow for expected, long-term erosion losses as well as protect the underlying soil barrier layer from damage due to freeze/thaw cycles. This is the uppermost surface layer of the landfill cover.

4. Optional Layers. Optional layers include gas vent and biointrusion layers.

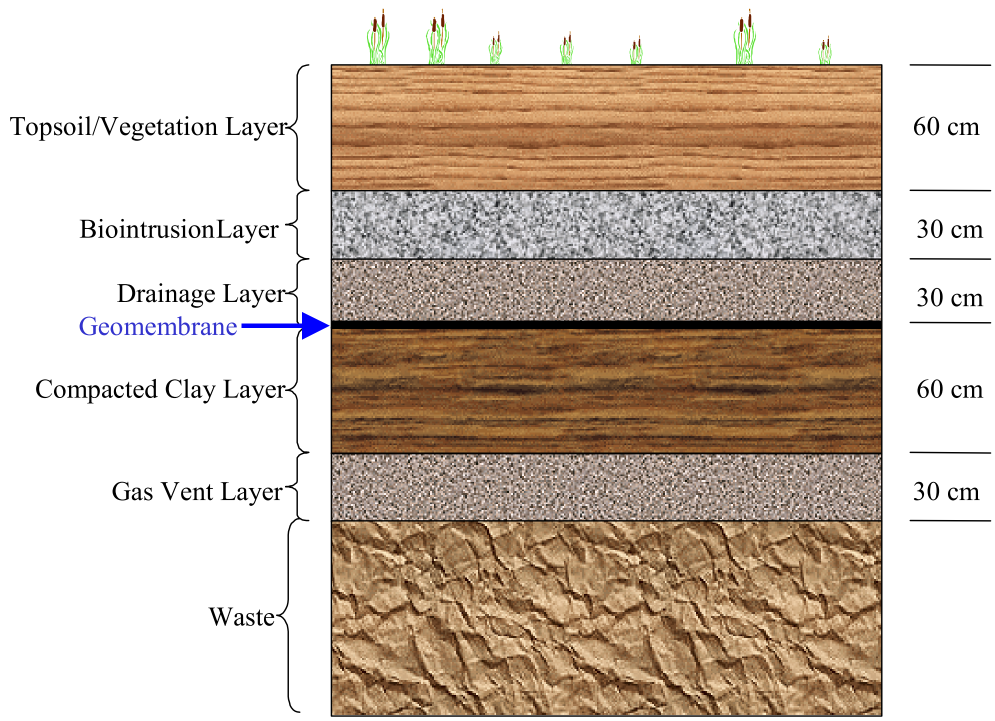


Figure 2.1. RCRA Subtitle 'C' Compacted Clay Cover (EPA 1991)

The regulations for the final cover of a RCRA Subtitle "D" facility are much more specific than those for Subtitle "C" facilities. These regulations are contained in 40CFR258. The owner/operator of the landfill must install a final cover system (Figure 2.2) designed to effectively isolate the waste from the surrounding environment by minimizing the infiltration and erosion. Specifically the cover system must:

1. have a permeability or saturated hydraulic conductivity less than or equal to that of the bottom liner or natural subsoils present, or no greater than 1 x 10^{-5} cm/sec, whichever is less [40CFR258.60(a)(1)];

2. minimize infiltration through the closed Municipal Solid Waste Landfill (MSWL) by the use of an infiltration layer containing a minimum 45 cm of earthen material [40CFR258.60(a)(2); and

3. minimize erosion of the final cover by the use of an erosion layer containing a minimum 15 cm of earthen material that is capable of sustaining native plant growth [40CFR258.60(a)(3)].

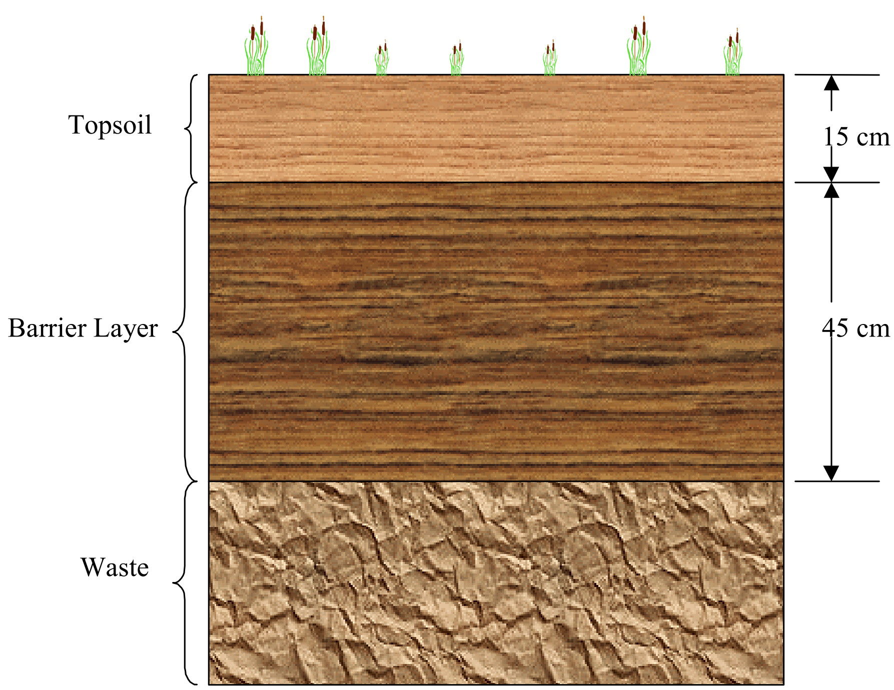


Figure 2.2. RCRA Subtitle 'D' Soil Cover (40CFR258)

2.1.1. Critique of prescriptive designs

Gross et al (2001) states that many problems with landfill closures such as excessive flux or erosion are due to design flaws. Prescriptive designs are predicated on the existence of layers within the cover system that possess a low saturated hydraulic conductivity. These layers are referred to as barrier layers or infiltration layers, and covers that employ these layers have been termed resistive covers (Benson 1997). In reality, saturation seldom if ever occurs, especially in dry climates. That is, water movement within a cover system occurs almost exclusively under unsaturated conditions.

The fact that landfill covers and barrier layers in particular are almost always unsaturated has important consequences. First, compacted soil layers can desiccate, or dry to the extent that they crack which creates irrevocable changes in hydraulic properties. This seemingly obvious possibility was overlooked for many years until problems began to arise in installed barrier layers (Suter et al., 1993, Mulder and Haven, 1995). Water movement under unsaturated conditions is different compared to saturated flow in that it is driven by matric potential gradients as well as gravity. Thus, water can be drawn upward and/or laterally as well as move downward.

A further problem with prescriptive designs and unsaturated conditions is that the design tool used to evaluate cover designs (the HELP computer program described in subsequent section) assumes barrier soil layers are saturated, and does not include matric potential gradients in cover soils. Thus, especially in a dry climate, predictions of cover performance using the standard design tool do not include the physics and operative processes that are known to exist in the field.

Compacted soil layers are typically installed in a wet condition (wet of the optimum moisture content) in order to achieve a low saturated hydraulic conductivity (EPA 1991). This renders the cover more susceptible to desiccation damage. In addition, the wet condition may encourage plant roots to invade the barrier layer. For example, at the uranium mill tailings facility in Shiprock, NM, summer cypress and salt cedar invaded the cover and were determined to have rooted into the 2-m thick compacted soil layer because of its available moisture (Caldwell and Reith, 1993). Compacted soil layers are also vulnerable to burrowing animals (Pratt 2000, Bowerman and Redente 1998, Johnson and Blom 1997, Hakonson 1986) and freeze-thaw action (Benson and Othman 1993). Such macropores increase the saturated hydraulic conductivity of the layer, and will compromise its integrity as a barrier.

Barrier soil layers are generally difficult to construct (Dwyer, 2000a). Issues include control of water content and density, uniformity of compaction, bonding between layers, and achieving the target saturated hydraulic conductivity. It is generally accepted that a comprehensive field and laboratory-testing program is required in order to ensure that the compacted soil layer is emplaced as specified (Qian, Koerner and Gray, 2002).

To address some of the limitations of compacted soil barriers and to introduce an element of redundancy into the design, geomembranes are often used in conjunction with compacted soil layers. Geomembranes are thin (typically 0.5 to 2.0 mm thick) polymeric sheets usually fabricated from polyethylene or polyvinyl chloride, and when placed in contact with underlying compacted soil layers form a “composite barrier” (EPA 1991). The performance of geomembranes is usually assumed to be a function of the installation quality; when installed perfectly, geomembranes have extraordinary low hydraulic conductivity and form an excellent hydraulic barrier. However, some flaws during installation such as seaming adjacent sheets together or flashing penetrations or flaws after installation from subsequent earthwork activities appear inevitable (ASTM 2002; Koerner and Daniel, 1997; Schroeder et al, 1994). Other issues with geomembranes include added cost of materials and installation, requirement for bedding or cushioning layers adjacent to the geomembrane to limit damage, they may introduce planes of weaknesses with adjacent layers, and there is a limited data base regarding their long-term stability.

The degree of complexity of the prescriptive Subtitle C design is an issue, especially when optional and redundant layers are included. Beyond the obvious increase in cost, these type of covers are difficult to design, specify and construct. Further, experience has shown that these types of covers have a doubtful prognosis for meeting long-term design objectives (Daniel, 1994).

Prescriptive covers such as the Subtitle ‘C’ Cover can be very expensive (Dwyer 1998b). Current estimates are that a Subtitle C design may cost on the order of $1.39 per square meter (Dwyer 1998b), which is more than twice as costly as an alternative such as a simple soil cover. For a typical landfill of 20 hectares, the cost savings of a simple soil cover compared to a prescriptive Subtitle C design is expected to be in excess of $17 million. Given this substantial cost saving and the large number of landfills operating in the United States, alternative covers are a very appealing technology.

2.2 Alternative designs

There are two types of alternatives. The first type is a modification of the prescriptive design that retains the essential design principle of a barrier layer within the cover with a low saturated hydraulic conductivity. Two materials that have been used as alternative barrier layer materials are asphalt and paper mill sludge (Rumer and Mitchell, 1995). Another alternative barrier layer, and the most common, is the use of a Geosynthetic Clay Liner (GCL) to replace the compacted soil layer. GCLs are thin layers (typically about 5 mm thick) of low permeability bentonite clay affixed to or sandwiched between geosynthetics. GCLs are manufactured, delivered to the field and installed by simply laying in place without physical seaming of joints. Thus, the principal advantage of the GCL is that it avoids the construction problems associated with the compacted soil layer.

The other type of alternative cover system does not rely upon a barrier layer but instead relies upon water storage within the cover system to prevent water from passing through it. Water is stored in the available porosity of the cover soil until it is removed by evapotranspiration (ET), the combined process of soil water evaporation and plant transpiration. The potential ET (or PET) is a measure of the climatic demand for water. PET is maximized in dry, hot climates, and can be much greater than the precipitation. This suggests that cover systems that rely upon ET may be able to simply evapotranspire all of the precipitation in a dry climate.

The simplest cover system of this type is a monolithic soil profile that has adequate soil water storage capacity to retain all infiltrated water until it can be removed via ET. This type of cover is often termed an "ET cover" or "monolithic soil cover." Previous research has shown that a simple soil cover can be very effective at minimizing percolation and erosion, particularly in dry environments (Nyhan et al., 1990; Hauser et al., 1994; Dwyer, 1998a; Dwyer et al, in press (a); and Dwyer, 2001).

An important advantage of an ET cover is that they are less expensive to construct and maintain than their prescriptive counterparts. The soil used will, for economic reasons, generally come from a nearby borrow site. Use of indigenous materials significantly reduces construction costs, which is probably the single most important issue currently driving the deployment of these covers. A comparison of constructed costs showed that the cost savings for an ET cover versus a cover utilizing a compacted soil layer is in excess of 50 percent (Dwyer, 1998b).

A modification of the ET cover is the capillary barrier, which consists of fine-over-coarse soil layers. The contrasting materials of the fine-over-coarse arrangement serve as a barrier to downward flow (Stormont, 1997). Infiltrating water is held in the fine layer by capillary forces and does not move into the coarse layer until the fine layer near the interface approaches saturation. The presence of the underlying coarse layer essentially increases the storage capacity of the fine soil layer (Stormont and Morris, 1998). Just as with an ET cover, soil water is removed from the fine layer by ET. If the fine-coarse interface is sloped, water in the fine layer can also drain laterally under unsaturated conditions. Advantages of capillary barriers include (Stormont, 1997): the cover layer of a capillary barrier will store more water than a comparable layer without the capillary break; the additional water stored within a capillary barrier will encourage the establishment and development of a surface plant community; and the coarse layer can serve as a biointrusion and/or gas collection layer.

2.2.1. Design procedures for alternatives

EPA regulations permit alternative designs if they can achieve erosion and infiltration protection equivalence to an acceptable conventional cover system. As a practical matter, equivalency is usually demonstrated by means of computer-based simulations of the water balance (e.g., Morris and Stormont, 1998). The Hydrologic Evaluation of Landfill Performance (HELP) program (Schroeder et al., 1994) is the most common tool for assessing equivalency. For example, the State of New Mexico requires HELP simulations to show that an alternative cover design produces the same or less flux rate compared to a prescriptive design subjected to the same climatic and operational conditions (New Mexico Environment Department, 1996).

Reliance on the HELP program is potentially problematic for the assessment of alternatives. A particular shortcoming of HELP is that it assumes a unit gradient for unsaturated flow in cover soils. In other words, HELP does not account for the influence of matric potential gradients on water movement such as water being drawn upward toward the surface in response to surface evaporation. As one would expect, water movement in response to matric potential gradients in the near surface is a critical component in the water balance for alternatives that rely upon ET. HELP also assumes that any layer that is designated as a barrier layer is always saturated, which is clearly not the case (refer to chapter 3 – field data).

Unsaturated flow codes (e.g. HYDRUS, SWIM, UNSAT-H, and VS2DTI) are preferred for use as design tools with alternative cover systems that rely on water storage. These codes more completely simulate the physics of unsaturated water movement than HELP and generally yield more accurate results (Scanlon et al, in press). These numerical water balance models are often used to predict the effectiveness of engineered covers in minimizing percolation through the cover into the underlying waste (Fayer et al, 1992; Khire et al, 1997; Andraski and Jacobson, 2000). Sensitivity analyses have been conducted to determine controlling factors on determining subsurface flow, such as time discretization of precipitation input, vegetation, soil depth, soil texture, hydraulic parameters, liquid and vapor flow, and hysteresis (Fayer and Gee, 1992, Fayer et al, 1992; Magnuson, 1993; Fayer and Gee, 1997).

Fayer and Gee (1992) concluded that the inclusion of vapor flow would yield more accurate results than omitting it in sandy soil in semiarid climates. Fayer et al (1992) concluded UNSAT-H was highly sensitive to variations in saturated hydraulic conductivity. Magnuson (1993) concluded that changes in saturated hydraulic conductivity in the fine soil layer of a capillary barrier significantly changed the output in UNSAT-H simulations while similar changes in saturated hydraulic conductivity in the coarse layer of the same capillary barrier had little affect. Magnuson (1993) found on monolithic soil profiles that UNSAT-H flux results were inversely related to changes in the soil's saturated moisture content. It was concluded that parameter sensitivities can be dependent on the conceptual model and so should be determined on a case-by-case basis. Fayer and Gee (1997) concluded that UNSAT-H could reasonably predict the water balance of a non-vegetated capillary barrier profile, especially when the affect of hysteresis is included in the simulations. It is important to note that these studies summarized were small-scale and were constructed using specialized methods not necessarily applicable to full-scale landfill covers nor did they take into account many ecological changes that would take place on an actual landfill cover such as that from flora and fauna intrusions.

UNSAT-H has been used to design a number of recent alternative landfill cover designs. Several of these designs have been deployed (e.g., Kirtland Air Force Base, Albuquerque, New Mexico shown in figure 2.3; Navajo Nation, Arizona and New Mexico) while many more are awaiting regulatory approval {e.g., Sandia National Laboratories, Albuquerque, New Mexico (Dwyer et al, 1999); Los Alamos National Laboratory, Los Alamos County, New Mexico (DB Stephens, 2002); Las Vegas, Nevada (SCS Engineers, 2001); Rocky Flats, Denver, Colorado (Earthtek, 2002)}.

Figure 2.3. Deployment of ET Cover at Kirtland Air Force Base, Albuquerque, NM

2.3 Comparative studies of cover systems

2.3.1. Field measurements

There is limited data available on the performance of engineered landfill covers. These water balance data were collected from small-scale test plots conducted primarily over the past decade and site-specific field-scale measurements (Table 2.1). It is important to note that although these small-scale tests can provide useful comparative data, these smaller scales did not allow for heterogeneities that can dominate performance such is the case in actual landfill covers. The small scales also did not allow for the evaluation of typical construction methods and equipment in building these cover profiles. The Alternative Cover Assessment Program (ACAP) was established by the Desert Research Institute (DRI, Nevada), Pacific Northwest Laboratory (Hanford, Washington), and the EPA to provide field data on the performance of engineered landfill covers that have been deployed in different types of climates and soils (Wilson et al 1999). There are 21 planned sites to be included in the data set; 9 have been instrumented with limited data collected date. There was no large-scale performance data in arid or semi-arid climates that directly compares various cover designs under the same climatic and soil conditions. This dissertation is intended to fill this void.

Location	Reference	Design	Size	Flux (1)	Comments
Los Alamos National Laboratory, Los Alamos, NM	Nyan et al, 1990	1. Subtitle D 'type' Cover (20 cm sandy loam, 108 cm crushed tuff)	3 m x 10.7 m	10.6 cm	Precipitation = 173.7 cm
		2. Capillary Barrier (71 cm sandy loam over sand and gravel)		2.6 cm	
Los Alamos National Laboratory, Los Alamos, NM	Nyan et al, 1997	1. Subtitle C 'type' Cover (61 cm loam, 30 cm sand, 30 cm bentonite amended tuff – no geomembrane)	1 m x 10 m	0 to 0	5% to 25% slope; no vegetation on covers; 1991 to 1995 monitoring period
		2. Capillary Barrier #1 (15 cm topsoil, 76 cm crushed tuff, 30 cm gravel)		17.40 cm to 3.09 cm	
		3. Capillary Barrier#2 (30 cm loam, 76 cm fine sand, 30 cm gravel)		9.64 cm to 0	
		4. Capillary Barrier #3 (30 cm loam and bentonite, 76 cm fine sand, 30 cm gravel)		5.59 cm to 0	
Wenatchee, WA	Khire et al, 1997; Benson et al, 1994	1. Subtitle D Cover (15 cm topsoil, 60 cm silty clay)	18.3 m x 12.2 m	0.5 cm	1992 to 1995 monitoring period
		2. Capillary Barrier (15 cm topsoil, 75 cm sand)		3.2 cm	

Hill Air Force Base, Utah	Hakonson et al, 1994	1. Subtitle C ‘type’ Cover (120 cm topsoil, 30 cm sand, 60 cm bentonite amended loam – no geomembrane)	5 m x 10 m	0.01 cm	1990 to 1994 monitoring period; covers vegetated with native grasses, capillary barrier#2 also included shrubs; 4% slope; precipitation = 173 cm
		2. Soil Cover (90 cm sandy loam)		41 cm	
		3. Capillary Barrier#1 (150 cm topsoil, 30 cm gravel)		24 cm	
		4. Capillary Barrier#2 (150 cm topsoil, 30 cm gravel)		30 cm	
Omega Hills Landfill, Milwaukee, Wisconsin	Montgomery and Parsons, 1990	1. Subtitle D ‘type’ Cover (15 cm topsoil, 120 cm clay)	6 m x 12 m	6.11 cm	1986 to 1989 monitoring period; 33% slope
		2. Subtitle D ‘type’ Cover (45 cm topsoil, 120 cm clay)		9.67 cm	
		3. Capillary Barrier (15 cm topsoil 30 cm glacial till, 30 cm sand, 60 cm clay)		10.30 cm	
Grede Foundries, Reedsburg, Wisconsin	Verbicher Associates, 1996	1. Subtitle D Cover (15 cm topsoil, 60 cm clay)	None given	108 mm/yr	1992 to 1996 monitoring period; test located on mine tailings pile
		2. Subtitle D ‘type’ Cover (15 cm topsoil, 90 cm native soil, 60 cm clay)		45 mm/yr	

		3. Capillary #1 (15 cm topsoil, 90 cm sand, 60 cm clay)		1.1 mm/yr	
		4. Capillary Barrier#2 (15 cm topsoil, 90 cm sand, 90 cm bentonite amended sand)		1.3 mm/yr	
		5. Capillary Barrier#2 (15 cm topsoil, 90 cm sand, 150 cm bentonite amended sand)		2 mm/yr	
Nuclear Regulatory Commission, Beltsville, MD	O'Donnell et al 1994; Schultz et al 1995	1. Vegetated Soil Cover (400 cm native soil)	13 m x 19 m	127 cm	1990 to 1994 monitoring period
		2. Resistive Barrier with Riprap (Riprap, 30 cm gravel, 45-60 cm clay)		0	
		3. Resistive Barrier with Vegetation (20 cm topsoil, 30 cm gravel, 45-60 cm clay		0	
		4. Capillary Barrier with Vegetation (20 cm topsoil, 30 cm gravel, 45-60 cm clay, 20 cm native soil, 20 cm gravel)		0.13 cm	

Geogrswerder, Germany	Melchoir, 1997	1. Subtitle C 'type' Cover (75 cm topsoil, 25 cm sand, 60 cm compacted soil – no geomembrane) @ 4% slope	10 m x 50 m	138 mm	1987 to 1993 monitoring period
		2. Subtitle C 'type' Cover (75 cm topsoil, 25 cm sand, geomembrane, 60 cm compacted soil) @ 4% slope		3 mm	
		3. Capillary Barrier (75 cm topsoil, 25 cm sand, 30 cm gravel, 30 cm sand, 40 cm compacted soil) @ 4% slope		10 mm	
		4. Subtitle C 'type' Cover (75 cm topsoil, 25 cm sand, 60 cm compacted soil – no geomembrane) @ 20% slope		75 mm	
		5. Subtitle C 'type' Cover (75 cm topsoil, 25 cm sand, geomembrane, 60 cm compacted soil) @ 20% slope		4 mm	
Little Packington Landfill, Birmingham, England	Rust, 1996	1. 50 cm topsoil, 100 cm compacted (engineered) clay @ 10% slope	2 m x 5 m	7.8 mm	1992 to 1994 monitoring period

		2. 50 cm topsoil, 100 cm compacted (non-engineered) clay @ 10% slope		7.4 mm	
		3. 50 cm topsoil, 100 cm compacted (engineered) clay @ 20% slope		2.4 mm	
		4. 50 cm topsoil, 100 cm compacted (non-engineered) clay @ 20% slope		8.3 mm	

(1) Flux is cumulative over monitoring period unless noted as an annual flux.

Table 2.1. Field Data from Landfill Cover Test Plots

2.3.2 Simulation Comparisons with Field Data

Several previous modeling studies have been hypothetical and did not compare modeled results with actual field data (Stothoff, 1997; Kearns and Hendrickx, 1998; Khire et al, 2000). However, some code-comparison studies included some field data for model input (Nichols, 1991; Fayer et al, 1992; Berger et al, 1996; Khire et al, 1997; Wilson et al, 1999; Ogan et al, 1999). There have been a few code comparison studies that have directly compared simulations and field results (Khire et al 1997, Scanlon et al, in press, Roesler and Benson 2002).

Khire et al (1997) compared water balance simulations with field obtained data from the Fall of 1992 through the Spring of 1995 on two resistive barrier test landfill cover sections: one in East Wenatchee, Washington and one in Atlanta, Georgia using UNSAT-H and HELP (Table 2.2). Khire also compared UNSAT-H simulations with field data from a capillary barrier test section in East Wenatchee. In general, Khire concluded that UNSAT-H better predicted flux through earthen covers than HELP while showing HELP consistently over predicted flux. Scanlon et al (in press) compared field results from a capillary barrier landfill cover test section located in Sierra Blanca, Texas (120 km southeast of El Paso) with simulations using multiple computer programs. Field data were collected for this set of comparisons from October 1997 through September 1998 (Table 2.2). Scanlon et al (in press) concluded that all simulations using unsaturated flow programs were relatively accurate while HELP significantly over predicted flux. The measured field data used to compare to the output of these simulations had no measured percolation (i.e. flux was zero), consequently the comparison of predicted fluxes using these programs to a field flux of zero may not be a good evaluation of the accuracy of these programs. Roesler and Benson (2002) performed simulation comparisons using UNSAT-H and HELP with 9 different sites and compared the results with the initial results from some of the early ACAP data collected. Simulation results were not summarized but the conclusions stated that these results did not correlate well with field data even after manipulation of the input parameters was done to attempt to better match the simulation output with the field results. The simulation fluxes in some cases were under predicted while in others, they were over predicted. It should be noted that these were initial results with the earliest field data collected in 1999 while most sites had only a year or less of data.

Report	Site	Cover	Program	Program Reference	Field Percolation (cm)	Simulation Percolation (cm)	Percolation Difference (cm)
Khire (1995)	East Wenatchee, WA	Resistive (15 cm topsoil, 60cm compacted clay)	UNSAT-H	Fayer et al 1995	24.0	17.0	-7.0
			HELP	Schroeder et al 1994		102.0	+78.0
		Capillary Barrier (15cm topsoil, 75 cm sand)	UNSAT-H	Fayer et al 1995	0.5	9.8	+9.3
	Live Oak, Atlanta, Georgia	Resistive (15 cm topsoil, 91.5 cm silt barrier layer)	UNSAT-H	Fayer et al 1995	3.1	1.8	-1.3
			HELP	Schroeder et al 1994		1.8	-1.3
Scanlon et al (in press)	Sierra Blanca, Texas	Capillary Barrier (30 cm topsoil, 170 cm compacted sandy clay loam, 100 cm sand & gravel)	UNSAT-H	Fayer et al 1995	0	0.3	+0.3
			HYDRUS-1D	Simuntek and van Genuchten 1999		0	0
			SHAW	Flerchinger et al 1996		0.3	+0.3
			SoilCover	Wilson et al 1994		0	0
			SWIM	Verburg et al 1996		0	0
			VS2DTI	Healy 1990		0	0
			HELP	Schroeder et al 1994		0.9	+0.9

Table 2.2. Simulation Results versus Field Measured Data

Chapter 3. Field Water Balance Data

3.1 Field Demonstration Description

3.1.1 Overview

A large-scale field test was conducted whereby six different landfill cover designs were built side-by-side (Dwyer 1998d). This physical arrangement allowed for direct comparison of the various designs under the same climatic conditions with similar soils. The landfill test covers were installed and located in Tech Area III at Sandia National Laboratory in Albuquerque, New Mexico. The landfill covers (Figure 1) were constructed in two phases due to annual funding constraints. The Phase I covers, constructed in the summer of 1995, included two prescriptive covers to be used as baselines and the first of four alternative covers. The first baseline cover was a RCRA Subtitle 'D' Soil Cover constructed to meet minimum requirements set forth in the Code of Federal Regulations (40CFR258). This type of cover is generally used to close municipal landfills. The second baseline cover was a RCRA Subtitle 'C' compacted clay cover built to meet minimum guidelines set by the EPA RCRA/CERCLA Landfill Closure Guidance Document (EPA 1991). The Subtitle C type of cover is generally used to close hazardous waste landfills. The first of four alternative covers was referred to as a Geosynthetic Clay Liner (GCL) Cover. The Phase II covers, built in the summer of 1996, included two capillary barrier designs (Capillary Barrier and Anisotropic Barrier), and a monolithic soil profile referred to as an Evapotranspiration (ET) Cover.

The test covers were each 13 m wide by 100 m long (Figure 3.1). The 100 m dimension was chosen because it was representative of many landfills found throughout the Department of Energy (DOE) complex (approximately 1 hectare in surface area). All covers were constructed with a 5% slope in all layers. The 5% slope was chosen because it was within the slope (3 to 5%) recommended by the EPA (1991). The slope lengths were 50 m each (100 m length crowned at the middle with half of the length sloping to the east and the other half sloping toward the west). The western slope components of the covers were monitored under ambient conditions (passive monitoring). A sprinkler system was installed in each of the eastern slope components to facilitate stress testing (active monitoring) of the covers.

The two baseline covers and the first alternative cover (GCL Cover) were termed resistive barriers (Benson 1997). Resistive barriers are cover profiles designed to have a very low saturated hydraulic conductivity and thus block or "resist" the movement of water through them. The remaining three alternatives rely on water storage capacity to prevent water from passing through them. These covers were designed to store water within their soil layers until it could be removed via ET. These covers are generally considered to be appropriate for dry climates.

There is extensive documentation associated with these tests beyond that included here. More detailed information can be found in additional documents on the following topics:

- instrumentation and monitoring (Dwyer et al 1998c);
- instrumentation calibration (Lopez et al 1997, Dwyer et al 1998c);
- test description (Dwyer 1997; Dwyer et al 1998c);
- construction of test covers (Dwyer 2000a, Dwyer et al 1998c);

- construction costs of the test covers (Dwyer 1998b);
- vegetation attributes of the test covers (Dwyer et al, in press, b);
- problems with prescriptive covers (Dwyer 2000b);
- soil properties and testing procedures (UNM 1995, UNM 1996, Anderson and Stormont 1999).

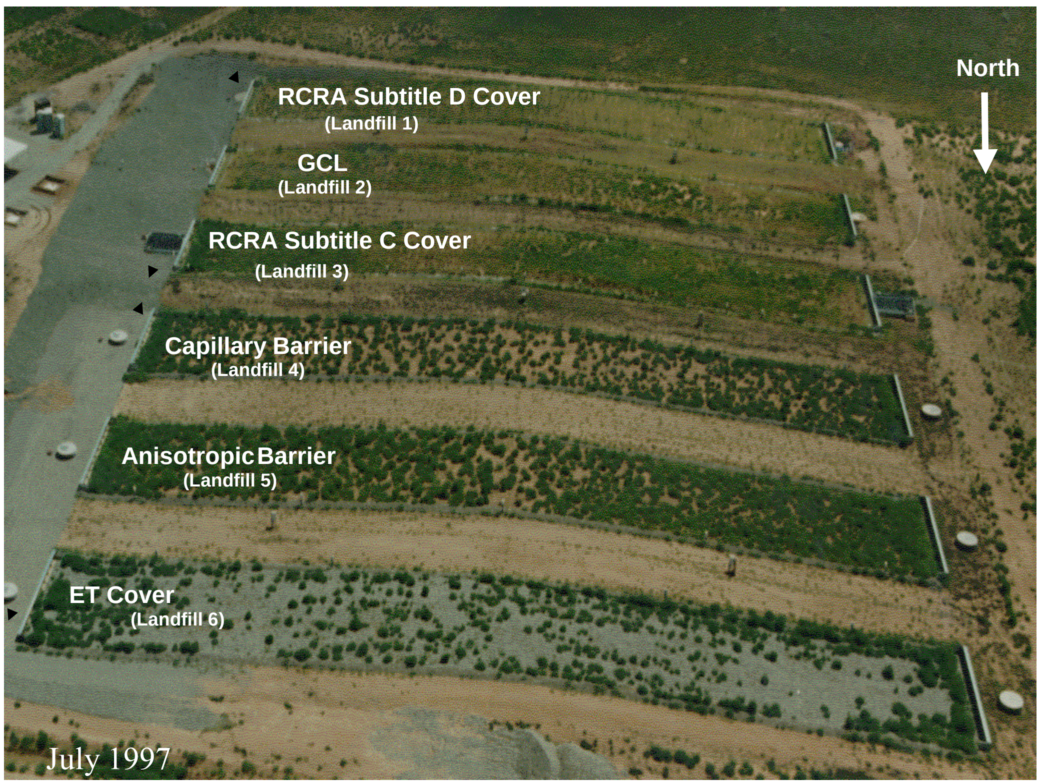


Figure 3.1. Field Test Layout

3.1.2 Baseline Test Covers

3.1.2.1 Baseline Test Cover 1 (Subtitle D Cover) was a basic soil landfill cover installed to meet minimum requirements for RCRA Subtitle 'D' governed landfills per 40CFR258. These requirements apply to municipal solid waste landfills (MSWL).

The installed test cover was 60 cm thick (Figure 3.2). It was constructed of two layers. The top vegetation layer was 15 cm of loosely laid topsoil. The bottom layer was a 45 cm thick compacted soil barrier layer. Laboratory tests with a flexible wall permeameter (ASTM D5084) yielded saturated hydraulic conductivity results on the barrier soil layer between 5.5 x 10^{-6} cm/sec and 5.1 x 10^{-7} cm/sec. The in-situ saturated hydraulic conductivity was determined to be about 4.9 x 10^{-7} cm/sec with a sealed double ring infiltrometer (ASTM D5093) immediately after the installation of the barrier layer (Dwyer et al. 1998c).

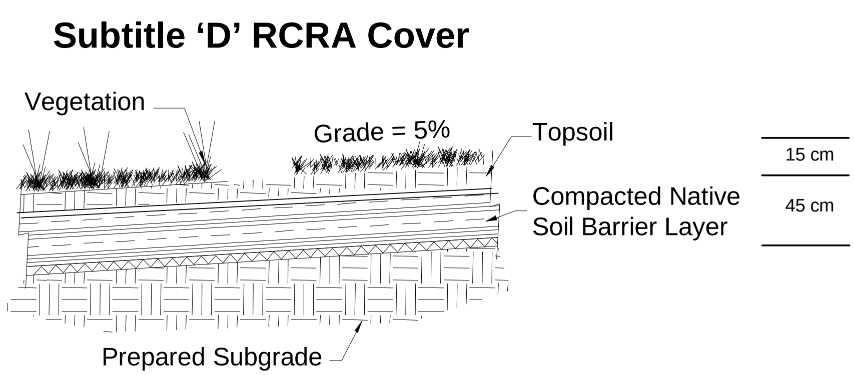


Figure 3.2. Profile of Baseline Test Cover 1 (Subtitle D Cover)

3.1.2.2 Baseline Test Cover 2 (Subtitle C Cover) was a landfill cover designed and constructed in accordance with minimum regulatory requirements for closure of hazardous and mixed waste landfills found in 40CFR Parts 264 and 265 and the EPA Design Guidance for RCRA/CERCLA Landfill Closures (EPA 1991).

The installed cover was 1.5 m thick which was consistent with the recommended EPA design described above. The profile for this cover consisted of three layers (Figure 3.3).

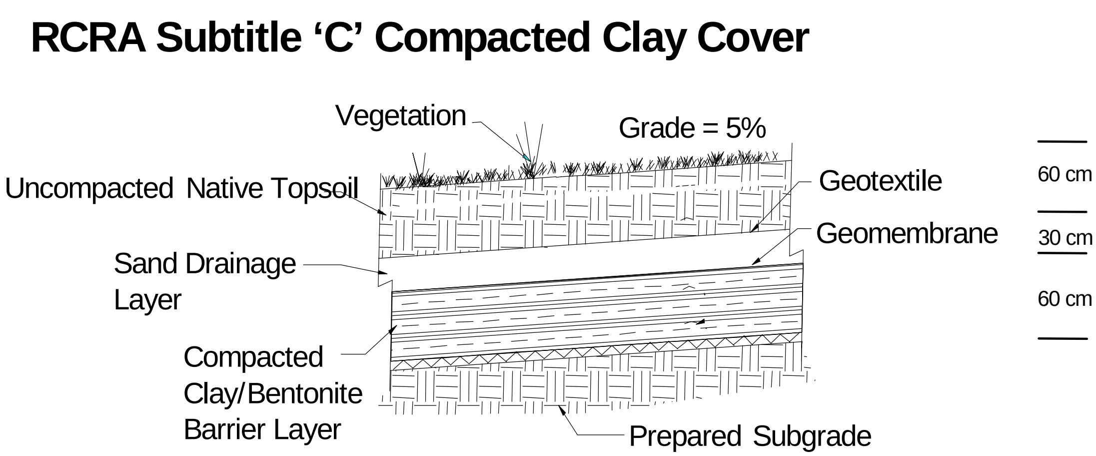


Figure 3.3. Profile of Baseline Test Cover 2 (Subtitle C Cover)

The bottom layer was a 60-cm thick compacted soil barrier layer. Laboratory tests (Dwyer et al. 1998c) revealed that the native soil at the test site required amendment to meet the saturated hydraulic conductivity requirement (maximum of 1 x 10^{-7} cm/sec). The goal of the laboratory testing was to find a combination of native soil and soil amendment, in this case sodium bentonite, that would yield a saturated hydraulic conductivity less than or equal to this value. Laboratory testing using a rigid-wall permeameter (Daniels et al 1985), determined that a mixture of 6% by weight of sodium bentonite blended with the native soil compacted wet of the optimum moisture content to a minimum of 98% of the amended soil's maximum dry density using the standard proctor method (ASTM D698) would be adequate (Dwyer et al. 1998c). All laboratory tests yielded saturated hydraulic conductivity results between 10^{-8} to 10^{-9} cm/sec for this soil mixture. The soil was then specified and installed with compaction 'wet of optimum' as recommended by the EPA (1991) to remold the soil to lower the hydraulic conductivity.

This barrier layer was extremely difficult (Dwyer 2000a) and expensive (Dwyer 1998b) to install partly due to the soil amendment needed to meet the saturated hydraulic conductivity requirement. The most economical means of purchasing the bentonite was to have it trucked in from Wyoming. Approximately 100 tons of bentonite was transported and used in the barrier layer.

The combination of the compaction requirements, soil amendment, and placement ('wet of optimum') was specified in hopes of yielding a maximum hydraulic conductivity of 1 x 10^{-7} cm/sec. The in-situ saturated hydraulic conductivity was measured using a sealed double ring infiltrometer (ASTM D5093) to be 7.9 x 10^{-7} cm/sec. Visible desiccation cracks (Figure 3.4) began to form in the Subtitle C Cover's barrier soil layer within 15 minutes after installation. Desiccation cracking was believed to be the cause for the greater than expected hydraulic conductivity. Desiccation cracking is usually not observed or included in laboratory tests; consequently its effect on hydraulic conductivity is often overlooked.

Figure 3.4. Desiccation Cracking in Subtitle C Cover Barrier Layer (15 minutes after compaction)

A 40-mil linear low-density polyethylene (LLDPE) geomembrane was placed directly on the compacted soil to create a composite barrier layer. In addition, the geomembrane was intended to mitigate damage to the soil barrier layer due to desiccation. The geomembrane was installed in compliance with the manufacturer recommendations with double seams that were pressure tested accompanied by destructive strength testing. Upon completion of the geomembrane placement, eight 1-cm^2 defects (puncture holes) were purposely and randomly placed in this geomembrane (Dwyer et al. 1998c). This number of defects was consistent with that expected in a typical geomembrane installation in a landfill (ASTM 2002, Koerner and Daniel 1997, Schroeder et al 1994).

This project was endorsed by many regulatory agencies (Dwyer 1995) and with this endorsement came involvement from regulators from many of these agencies in the design, construction, and monitoring of the covers. Through a consensus decision amongst the reviewing regulators, it was decided that defects should be included in the geomembrane to best represent the construction of an actual landfill.

The cover's middle layer was a 30-cm thick drainage layer. The purpose of the drainage layer was to minimize the time any infiltrated water was in contact with the underlying barrier layer by quickly routing water that had passed through the vegetation layer laterally to collection drains. This layer was constructed of sand placed directly on the geomembrane.

The top layer was a 60-cm thick vegetation layer composed of uncompacted soil. This layer's primary purpose was to provide a medium for allowed for storage of infiltrated water, vegetation growth, erosion protection, and to protect the underlying layers from freeze/thaw cycles.

3.1.3 Alternative Test Covers

Native soil used in the construction of the alternative landfill test covers came from on-site excavations. Other materials purchased off-site, such as sand and gravel, are common construction materials and readily available (i.e., no exotic grain-size distributions).

Compaction of soil required for the alternative covers was performed 'dry of optimum' rather than 'wet of optimum' as currently recommended by the EPA for the baseline covers (EPA 1991). Dry-side compaction was performed to limit the potential for desiccation cracking in the compacted soil layer. Dry-side compaction also made construction easier and provided for more initial soil water storage capacity due to the lower initial saturation. The constructed densities of the compacted soil layers in the alternative covers were lower than the prescriptive covers. While the intent of the prescriptive covers' compacted soil layers was to lower the hydraulic conductivity thus warranting high-energy compaction, the intent of the alternative cover profiles' compacted soil layers was to allow for both maximum storage capacity and to reproduce undisturbed soil densities. Therefore, construction specifications were altered for these layers by specifying a maximum and minimum soil density and a maximum water content that comprised each layer's acceptable compaction zone (Dwyer et al 1998c).

3.1.3.1 Alternative Test Cover 1 was a Geosynthetic Clay Liner (GCL) Cover (Figure 3.5) identical to the prescriptive Subtitle C Cover, with the exception that the expensive (Dwyer 1998b) and problematic (Dwyer 2000a) clay barrier layer was replaced with a manufactured sheet referred to as a GCL installed in its place. All other aspects of the cover were identical to those in the Subtitle C Cover. The overall thickness of this cover was 90 cm. The cover's component layers from bottom to top were:

1. composite barrier layer (the GCL membrane covered with a geomembrane);
2. 30-cm sand drainage layer;
3. geotextile filter fabric;
4. and 60-cm thick vegetation soil layer.

The GCL product installed was Claymax 500SP (Claymax 1995). It consisted of two non-woven fabrics that sandwiched a thin layer of bentonite. The specified-saturated hydraulic conductivity of the GCL (Claymax 1995) was 5 x 10^{-9} cm/sec. The GCL was simply rolled into place. Seams consisted of 15 cm overlaps. No physical seaming was performed as recommended by the manufacturer. The installed geomembrane also had eight 1-cm^2 randomly placed defects in it similar to those inflicted on the Subtitle C Cover's geomembrane. The GCL itself had no defects placed in it (Dwyer et al, 1998c).

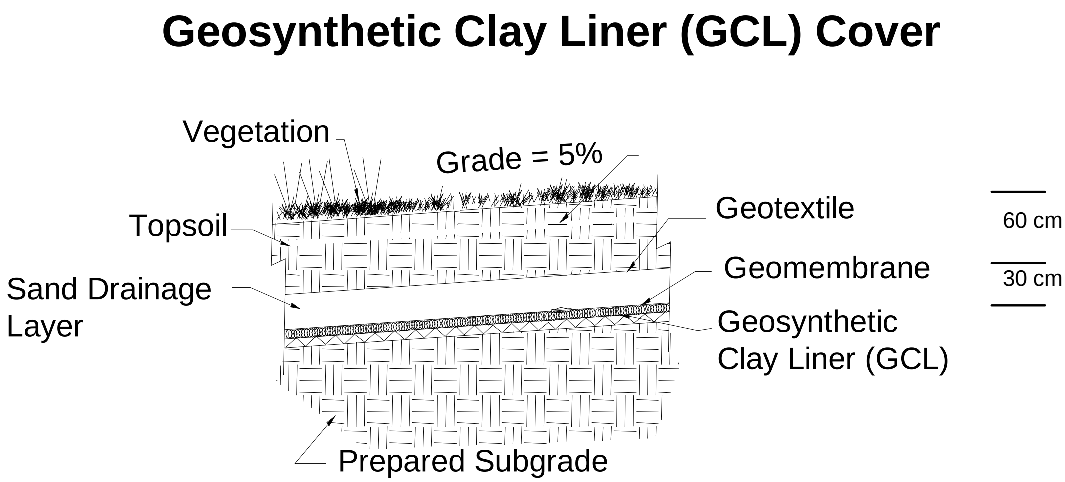


Figure 3.5. Profile of Alternative Test Cover 1 (GCL Cover)

3.1.3.2 Alternative Test Cover 2 is a Capillary Barrier. Capillary barriers, consisting of fine-over-coarse grained soil layers, are another alternative cover system suggested for use in final landfill closures, particularly in dry climates. Water is held in the fine soil by capillary forces until ET, horizontal drainage, or percolation removes the water. A capillary barrier functions because of the contrast in hydraulic conductivity between the fine and coarse soils at similar suction heads that exist near the fine-coarse interface (Stormont 1995). The performance of a capillary barrier can be explained by considering figure 3.6. Beginning at relatively dry conditions, that is, at high suctions, the fine soil has a finite hydraulic conductivity, whereas the hydraulic conductivity of the coarse layer will be immeasurably small. With increasing water content and decreasing suction head, the hydraulic conductivity of the fine layer will increase gradually. The hydraulic conductivity of the coarse layer will remain immeasurably small until its water entry head is overcome. Under these conditions, water will not move from the fine layer into the coarse layer, but increase the water content of the fine layer. Breakthrough into the coarse layer occurs when the suction head at the contact equals the water entry head of the coarse layer. When the suction head decreases below this value, the hydraulic conductivity of the coarse layer will increase rapidly and eventually exceed that of the fine layer

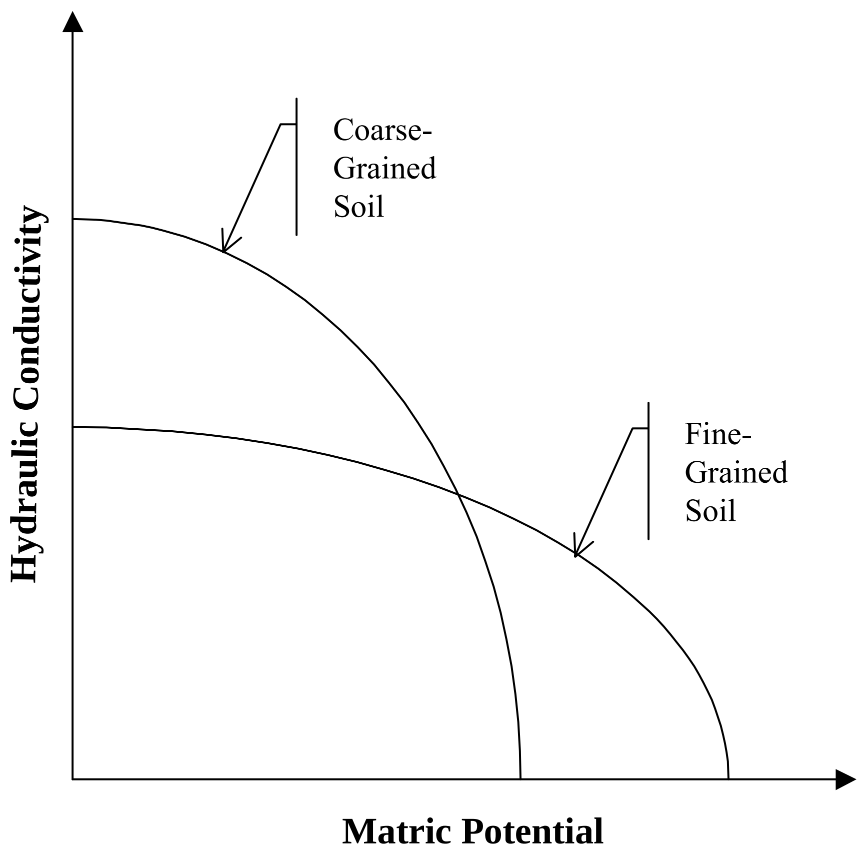


Figure 3.6. Hydraulic Conductivity Functions for Fine- and Coarse Grained Soils

The installed Capillary Barrier cover system consisted of four layers from bottom to top: (1) a lower drainage layer; (2) a barrier soil layer; (3) an upper drainage layer; and (4) a topsoil layer (Figure 3.7). The barrier soil layer and lower drainage layer comprised the capillary barrier by design (Shackleford 1994). In addition, the topsoil and sand drainage layer formed an inadvertent capillary barrier. The lower drainage layer was composed of 30 cm of clean sand, defined as containing less than 5% fines.

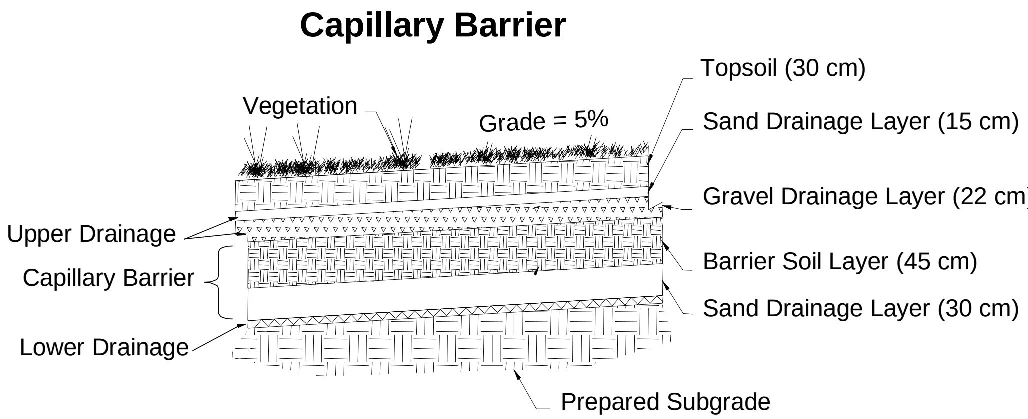


Figure 3.7. Profile of Alternative Test Cover 2 (Capillary Barrier)

The 45-cm barrier soil layer was installed directly on the sand. The upper drainage layers were placed over the barrier soil layer. This upper drainage layer consisted of two materials containing 22 cm of clean pea gravel (10 mm) and 15 cm of clean sand (1 mm). Finally, a 30-cm thick layer of topsoil was placed on the sand. There were no geosynthetics used in this cover profile.

3.1.3.3 Alternative Test Cover 3 (Anisotropic Barrier) was another capillary barrier system that was designed to limit the downward movement of water while encouraging the lateral movement of water. Lateral diversion within a sloped capillary barrier system provided an additional means of removing soil water from the fine-textured soil layer. Lateral diversion is essentially gravity-driven unsaturated drainage within the fine layer. Because the water content in the fine layer is usually greatest near its interface with the underlying coarse-textured soil layer, and the hydraulic conductivity of an unsaturated soil increases with water content, lateral diversion is concentrated near this interface. Laterally diverted water will result in increasing water content in the down dip direction.

This cover system contained four layers: (1) a top vegetation layer; (2) a cover soil layer; (3) an interface layer; and (4) a sub layer (Figure 3.8). The vegetation layer was 15-cm thick. It was comprised of a mixture of local topsoil and pea-gravel. The gravel to soil mixture ratio by weight was 0.25 (25%). Erosion (Ligotke 1994) and water balance studies (Waugh 1994) suggested that moderate amounts of gravel mixed into the cover topsoil would control both water and wind erosion with little effect on the vegetation or the soil-water balance. As wind and water pass over the landfill cover surface, some winnowing of fines from the admixture is expected, creating a vegetated erosion-resistant surface sometimes referred to as a “desert pavement”. This layer encouraged ET, allowed for vegetation growth, and reduced surface erosion. The compacted native soil layer was 60-cm thick. Its function was to allow for water storage and eventual ET and to serve as a rooting medium. The interface layer was 15 cm of fine sand (1 mm) that served as a filter between the overlying soil and the underlying gravel, and served as a drainage layer to laterally divert water to collection areas that had percolated through the cover soil. The sub layer was 15 cm of pea-gravel (10 mm). The native soil overlying the sand layer created one capillary barrier while the sand overlying the pea gravel created a second capillary break.

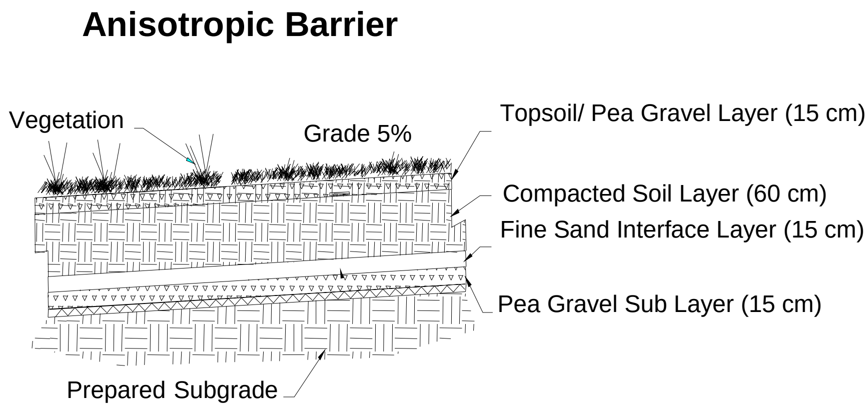


Figure 3.8. Profile of Alternative Test Cover 3 (Anisotropic Barrier)

3.1.3.4 Alternative Test Cover 4 (ET Cover) was a soil cover (Figure 3.9). The installed test cover was 105 cm thick of native soil. The bottom 90 cm of soil was compacted while the top 15 cm of topsoil was loosely placed.

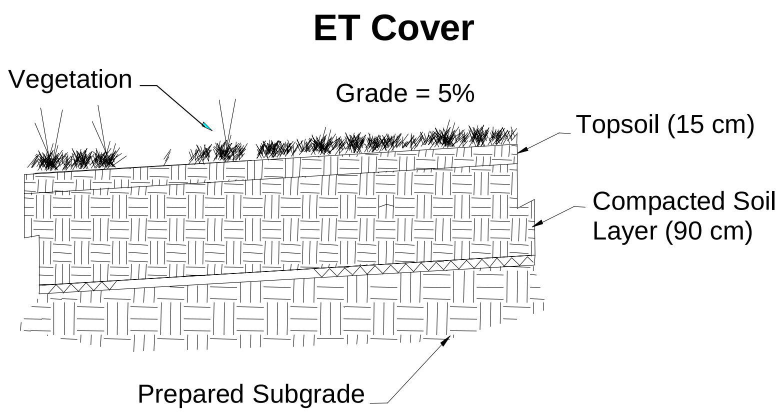


Figure 3.9. Profile of Alternative Cover 4 (ET Cover)

A thin gravel veneer (2 to 4 cm) was placed on the surface after the cover was seeded. The objective of the gravel veneer (Reith and Caldwell 1993) was to enhance the vegetation establishment and minimize erosion. This surface treatment offered several advantages in dry climates. A gravel layer will reduce surface erosion due to runoff and wind erosion. It will also serve to hold seed in place until germination. Furthermore, moisture will be retained in the upper-most layer of soil allowing vegetation such as native grasses to be established. This increases the transpiration capacity available to remove moisture and thus prevent percolation after a summer thunderstorm.

3.1.4 Vegetation

After the covers were constructed, they were drill-seeded with native rangeland vegetation. The seed mix (Table 3.1) was chosen based on acceptable native vegetation that would provide an adequate coverage during both warm and cool growing seasons (Lofton 1997).

Desired Establishment	**Quantity in Mixture[1] (% of total vegetation) (kg/hectare)**	**Seed[2]**
Warm Season Grasses:		
Bouteloua gracillis (Blue Grama)	20	1.1
Hilaria jamesii (Galleta)	10	3.4
Sporabolis cyptandrus (Sand Dropseed)	50	0.6
Cool Season Grasses:		
Oryzopsis hymenoides (Indian Ricegrass)	10	3.4
Stipa comata (Needle & Thread)	10	4.5

(1) Approximate percentage of total species present in number of plants per given area.
(2) Note that differences in weight among the various species can result in large differences in the mass ratio (kg/hectare) of seed required in the seed mixture.

Table 3.1. Seed Mix for Test Covers

3.2 Performance Monitoring and Instrumentation

Continuous water balance data for each test cover and meteorological data were obtained at the project site from May 1997 through June 2002. Passive testing consisted of daily on-site observations to validate system performance and to correct problems as they potentially developed. Continuous data was obtained on soil moisture, percolation, lateral drainage, runoff and erosion, precipitation, wind speed and direction, relative humidity, solar radiation, air and soil temperatures. Periodic measurements of vegetation cover, biomass, leaf area index, and species composition were obtained (Dwyer et al., in press, b).

Active testing included the addition of supplemental irrigation to hydrologically stress the cover systems. Water applied using a sprinkler system was tested for rate and uniformity of application. All water was distributed through electronically controlled flow meters where quantities discharged were controlled and measured.

All water balance measurements were made with automated monitoring systems to provide continuous data. Manual backup systems were available in case of failure in one or more of the automated measurements systems and/or to verify accuracy of the automated systems. A complete description of the instrumentation used, monitoring plan, and automated data acquisition system can be found in Dwyer et al. (1998). The following is a brief description of the measurement systems used.

3.2.1 Soil Moisture: Time Domain Reflectometry (TDR) and an associated data acquisition system were used to provide a continuous record of soil moisture status at various plan locations and depths within each cover profile. Each TDR probe was individually calibrated (Lopez et al. 1997). PVC pipes were installed strategically in the covers to be used as ports to allow for the use of a frequency domain reflectometry probe as a backup measurement system for soil moisture and to verify the accuracy of the TDR system. There were 310 TDR probes placed within the test cover profiles to enable a comprehensive determination of soil moisture both within the plan and depth of each cover. Refer to Appendix C for TDR probe and equipment locations within the test site.

3.2.2 Runoff: Runoff was measured on an event basis. Surface runoff was collected with a gutter system located at the bottom of each slope component of each cover. The collected water was routed to instrumentation that consisted of sinks with flow meters that quantified the volume (Figure 3.10). The data acquisition system allowed for automated data retrieval and storage to an onsite field computer.

3.2.3 Percolation and Interflow*:* Subsurface flows were measured. Lateral drainage from each drainage layer (GCL Cover and Subtitle 'C' Cover) was collected using underdrain systems placed at the base of each slope component of each cover. The water was routed to tipping buckets for measurement. This instrumentation was linked to a data acquisition system that allowed for continual data retrieval and storage. Percolation through the barrier layer within each cover was collected using a geomembrane under a geonet that routed the water to an underdrain collection system. Both percolation and interflow were routed via subsurface drains to tipping buckets (Figure 3.10). Measurement redundancy was built into the system to reduce the probability of losing data because of equipment failure or power loss and to verify correctness of results obtained.

Figure 3.10. Flow Measurement Instrumentation in the Underground Vault

3.2.4 Meteorology*:* A complete weather station was installed at the test site. Precipitation, air temperature, wind speed and direction, relative humidity, and solar radiation were continuously recorded. The meteorological observations were made with automated equipment coupled to the on-site data acquisition system.

3.2.5 Vegetation*:* Attributes of the vegetation on each landfill cover (Dwyer et al, in press, b) were measured annually. Several point frames were used to evaluate percent cover, leaf area index, species count and vegetation biomass. Biomass production was determined by clipping and weighing oven-dried samples collected from subplots within each landfill cover. Species composition was measured using line transects staked within each landfill subplot.

3.3 Field Data

Field data measured from May 1, 1997 through June 30, 2002 is presented here. The measured water balance variables include: precipitation plus applied water if any (P), surface runoff (R), lateral drainage (D), change in soil water storage (ΔS), and percolation (I). Evapotranspiration (E) was then determined for using the following mass balance equation:

$$E = P - I - R - D - \Delta S \qquad \textbf{Equation 3.1}$$

3.3.1 Water Balance Data

Tables 3.2 through 3.7 present the annual water balance data for each landfill cover. The cumulative water balance data (May 1, 1997 through June 30, 2002) for the covers is presented in table 3.8.

Landfill Cover	**Surface Runoff (mm)**	**Percolation (mm)**	**Lateral Drainage (mm)**	**Soil Moisture Change (mm)**	**ET (mm)**
Subtitle D Cover	4.42	3.56	NA	-42.00	301.02
GCL Cover	2.60	0.51	0.03	-48.00	311.86
Subtitle C Cover	5.55	0.04	0.00	-54.00	315.41
Capillary	4.38	0.54	NA	-48.00	310.07

Barrier					
Anisotropic Barrier	2.02	0.05	NA	-75.90	340.82
ET Cover	4.12	0.08	NA	-22.50	285.30

Table 3.2. Field Obtained Water Balance Data for 1997 (precipitation = 267.00 mm)

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	18.55	2.48	NA	-10.50	281.45
GCL Cover	20.77	0.19	0.12	-18.00	288.91
Subtitle C Cover	6.93	0.15	0.20	-12.00	296.70
Capillary Barrier	9.91	0.41	NA	-4.50	286.16
Anisotropic Barrier	19.19	0.07	NA	-12.15	284.88
ET Cover	11.28	0.22	NA	-54.00	334.48

Table 3.3. Field Obtained Water Balance Data for 1998 (precipitation = 291.98 mm)

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	3.33	1.56	NA	-9.00	229.34
GCL Cover	2.21	2.15	0.10	-27.00	247.77
Subtitle C Cover	2.15	0.02	0.00	-57.00	280.06
Capillary Barrier	3.92	0.00	NA	-25.50	246.80
Anisotropic Barrier	0.84	0.14	NA	-18.00	242.25
ET Cover	0.73	0.01	NA	-10.50	234.99

Table 3.4. Field Obtained Water Balance Data for 1999 (precipitation = 225.23 mm)

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	0.27	0.00	NA	19.50	280.15
GCL Cover	0.05	0.00	0.00	42.00	257.87
Subtitle C Cover	0.49	0.00	0.00	72.00	227.43
Capillary Barrier	0.97	0.00	NA	46.50	252.45
Anisotropic Barrier	0.15	0.00	NA	37.65	262.12
ET Cover	0.63	0.00	NA	58.50	240.79

Table 3.5. Field Obtained Water Balance Data for 2000 (precipitation = 299.92mm)

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	0.75	0.00	NA	-1.80	255.07
GCL Cover	0.15	0.02	0.00	-45.00	298.85
Subtitle C Cover	0.55	0.00	0.00	-60.00	313.46
Capillary Barrier	0.88	0.00	NA	-46.50	299.63
Anisotropic Barrier	0.12	0.00	NA	-27.00	280.89
ET Cover	0.38	0.00	NA	-52.50	306.13

Table 3.6. Field Obtained Water Balance Data for 2001 (precipitation = 254.01 mm)

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	0.00	0.74	NA	-7.50	151.08
GCL Cover	0.00	0.00	0.00	12.00	132.32
Subtitle C	0.04	0.00	0.00	12.00	132.28

Cover					
Capillary Barrier	0.04	0.00	NA	63.00	81.28
Anisotropic Barrier	0.01	0.00	NA	10.65	133.66
ET Cover	0.03	0.00	NA	34.50	109.79

Table 3.7. Field Obtained Water Balance Data for 2002 (precipitation = 144.32 mm)

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	27.32	8.34	NA	-51.30	1498.10
GCL Cover	25.77	2.87	0.25	-84.00	1537.58
Subtitle C Cover	15.71	0.21	0.20	-99.00	1565.34
Capillary Barrier	20.11	0.95	NA	-15.00	1476.40
Anisotropic Barrier	22.32	0.26	NA	-84.75	1544.63
ET Cover	17.17	0.30	NA	-46.50	1511.49

Table 3.8. Cumulative Field Obtained Water Balance Data for May 1997 through June 2002

The Subtitle D Cover allowed the most percolation through it (8.34 mm) with the GCL Cover the second worst (2.87 mm). The best performing covers were the Subtitle C Cover, Anisotropic Barrier, and ET Cover all with less than a 0.30 mm total percolation. Precipitation and ET were by far the two largest water balance variables. ET was larger or smaller than precipitation in a given year depending on whether the cover profile was drying or wetting. Lateral drainage occurred in only two covers: the Subtitle C and GCL Covers because they were the only two with lateral drainage layers. Measurements indicated that lateral drainage was very small. These data revealed that layers installed to provide for lateral drainage were largely ineffective. Furthermore, flow through the upper soil layers was unsaturated (figures 3.11 through 3.16), not saturated as the prescriptive design methodologies assume. An unintended advantage of the lateral drainage layer was the creation of a capillary barrier with the overlying soil layer.

The surface runoff numbers were generally within an order of magnitude of each other. The primary reason for the difference in these numbers was the inadequacies of the monitoring system used to quantify them. Instruments utilized to make quantitative measurements occasionally malfunctioned during rainstorms because of the high flow and the fact that water often carried sediments that clogged the system. Visual observation coupled with manual backup measurements indicated that runoff was approximately equal for each cover profile. The actual number for surface runoff could possibly be equated to the largest runoff value of the six covers for any given year because this number was measured with continual working instrumentation. However, the runoff values presented in this chapter were not modified or corrected based on these observations. Corrected values would not change any water balance results other than the runoff quantities and the corresponding ET values.

3.3.2 Percolation

The variable of primary concern was percolation integrated over time to enable determination of the cover's flux. Regulators and design engineers are most concerned with the cover's flux because any water that has entered the waste increases the amount of leachate that can potentially leak from the landfill and harm the surrounding environment. Flux served as the principal basis for the comparison between the performances of the cover profiles (Figures 3.11a,b).

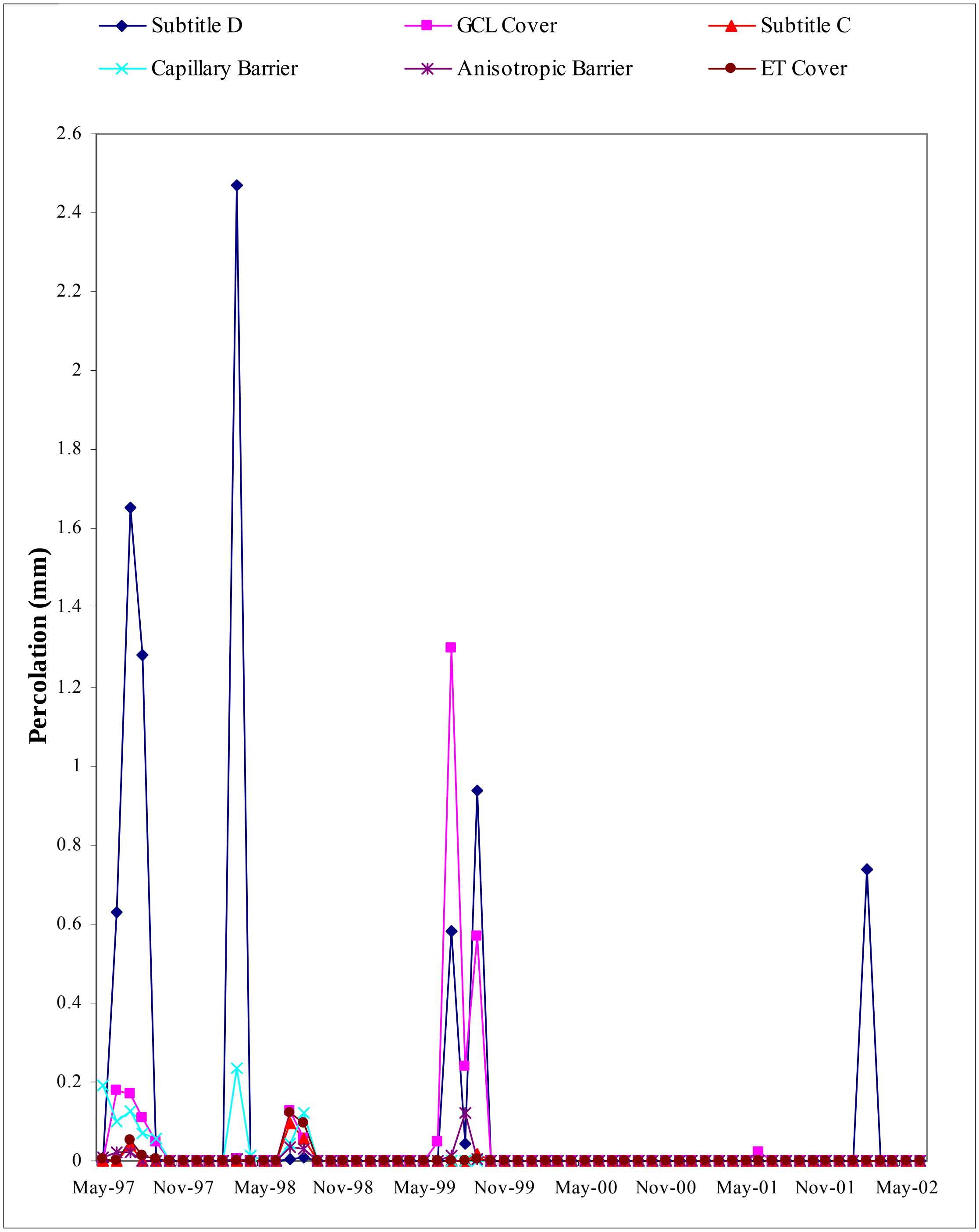


Figure 3.11a. Percolation (Monthly) Measured for the Six Test Covers; Scaled to View all Measurements on the Same Chart

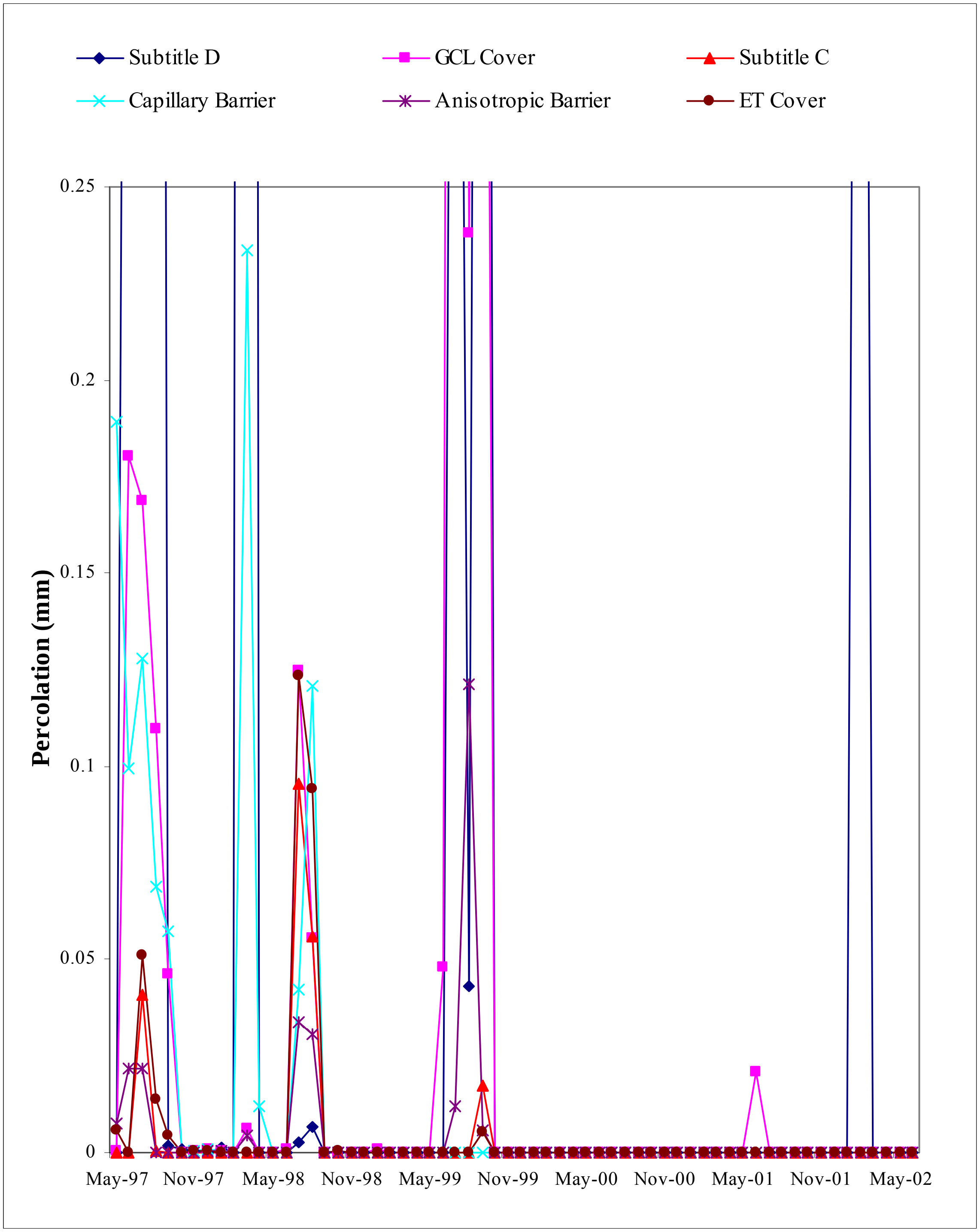


Figure 3.11b. Percolation (Monthly) Measured for the Six Test Covers; Scaled to View Percolation Events Smaller than 0.25 mm

Percolation occurred to some degree in all covers. The Subtitle D Cover had the largest percolation. The Subtitle C Cover, ET Cover, Capillary Barrier, and Anisotropic Barrier had relatively small fluxes. Percolation was most extreme for the covers during the summer of 1997, spring 1998, and summer of 1999. These percolation events coincided with barrier soil layers in the cover profiles reaching their wettest state at a volumetric water content of about 20%.

The summer events of 1997 were the results of construction water remaining in the covers along with a relatively wet period. In addition, vegetation on the covers was just beginning to be established and was without a mature and well-established rooting network to quickly remove water from the soil. The spring 1998 percolation events were the result of a large snowstorm followed by a warming period that quickly melted the snow. Snowstorms appear to be the worst-case infiltration event for the cover profiles due to the slow infiltration rate (melting snow compared with high intensity, short duration thunderstorms that can produce significant runoff) coupled with dormant vegetation that cannot quickly transpire the infiltrated water. There was a series of precipitation events during the summer of 1999 that were close enough to one another that the cover profiles could not dry between storms.

After the summer of 1999, there were very few percolation events recorded in any of the covers. It is believed that the smaller flux rates after the summer of 1999 were attributable to three factors: 1) below average precipitation; 2) the compacted soil layers had adequate time since construction to dry thus increasing these layers' storage capacities, and 3) the establishment of native vegetation. The Subtitle D Cover also had a large percolation event during the month of February 2002 following a snowstorm and subsequent stress test where water was applied to the covers through the sprinkler system. This applied water was added to the precipitation total and was represented in the precipitation totals shown for this year.

3.3.3 Soil Moisture

Soil moisture data presented in figures 3.12 through 3.17 were averaged daily values for all TDR probes located within each respective soil layer (Dwyer et al. 1998c).

3.3.3.1 Subtitle D Cover

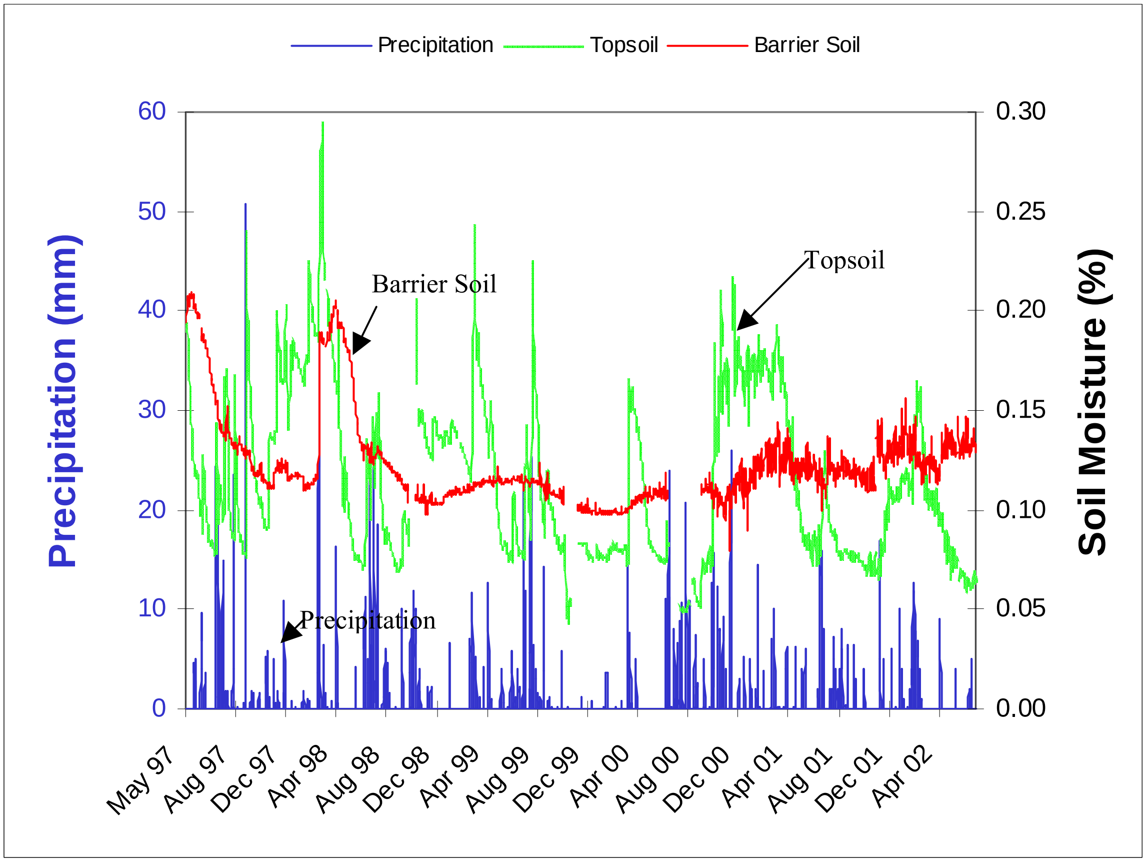


Figure 3.12. Soil Moisture Changes for the Subtitle D Cover

The Subtitle D Cover was a soil cover with a thin topsoil layer (15 cm) and a compacted barrier soil layer (45 cm). The topsoil generally showed immediate response to precipitation events by quickly wetting after a rain or snow event. The drying rates were affected by the potential evapotranspiration (PET), an index that represents the climatic 'demand' for water. PET can be calculated using Penman's equation (Jensen et al., 1990). PET in dry climates is far in excess of available water or precipitation. The results presented in Figure 3.12 were consistent with the expected PET values: during the summer months when PET was highest, the cover profile drying-rate was also highest. Conversely, during the winter months when PET was lowest, the cover drying rates were also lower.

The barrier layer moisture content fluctuations were not as extreme as the topsoil fluctuations. Initially the barrier layer was fairly wet as a result of a relatively wet spring in 1997. The barrier layer quickly accumulated moisture in response to a spring snowstorm in 1998. This event was a significant snowstorm where the snow quickly melted, but not so fast as to result in appreciable runoff. Transpiration was low because the plants were dormant at the time of the storm. The topsoil moisture content reached its wettest peak at nearly 30% in response to this snowstorm (saturated moisture content for the barrier soil is 37%, for the topsoil it is 45%). This event resulted in the largest percolation for the cover of almost 2.5 mm (Figure 3.11) for the month of March 1998. The barrier layer soil moisture content peaked at just over 20%. Other significant percolation events occurred during the summer of 1997. This was a relatively wet period as seen by the number and magnitude of precipitation events compared to other years. This wet period combined with the construction water still present in the cover profile led to a series of sizable percolation events. Percolation in 1997 and 1998 occurred when the barrier layer moisture content reached a volumetric moisture content of approximately 20%.

Beginning in the summer of 1998 through the remainder of the monitoring period, the topsoil layer continued to wet and dry in response to climatic conditions. The barrier layer remained within a much tighter moisture fluctuation, however. This result implied that the storage capacity of the topsoil layer was adequate to absorb and release most of the moisture from precipitation events over this period via ET. As seen in Figure 3.11, there were a number of smaller percolation events after the summer of 1998.

3.3.3.2 Subtitle C Cover

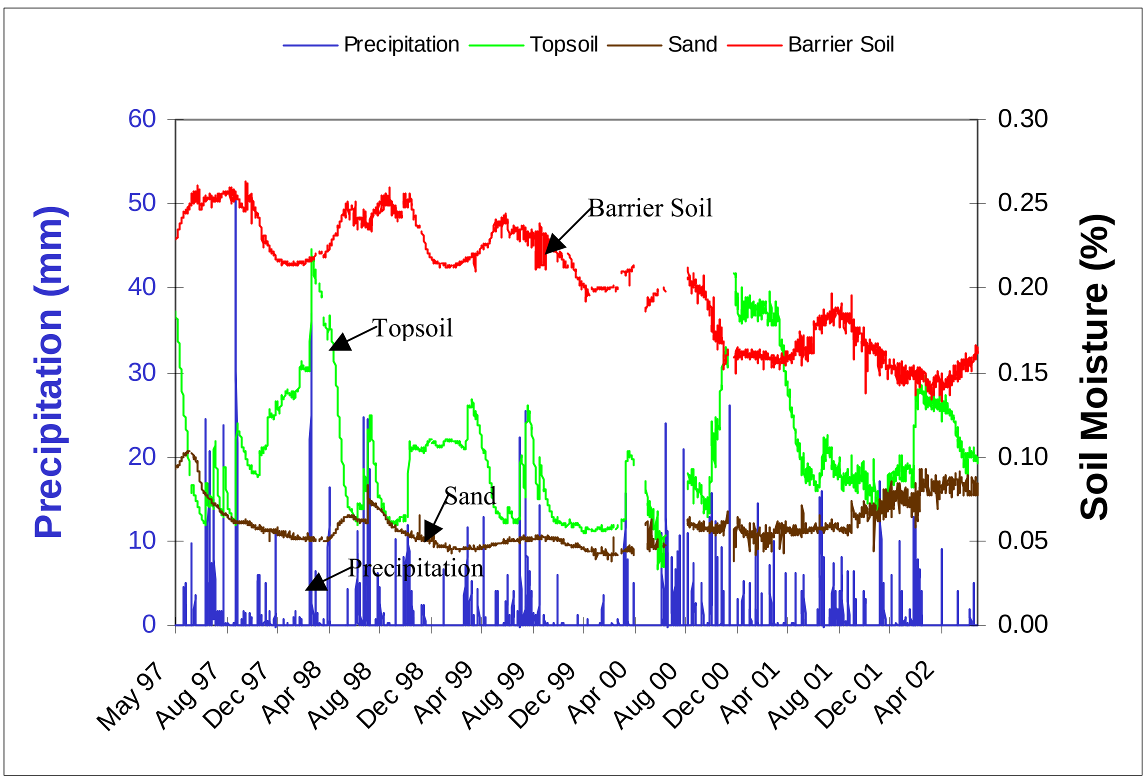


Figure 3.13. Soil Moisture Changes for the Subtitle C Cover

The topsoil layer in the Subtitle C Cover was a relatively thick layer (60 cm). Its wetting and drying trends were similar to that of the topsoil layers in the other cover profiles (figure 3.13). The average water content within the thicker topsoil layers was lower (peaking at just over 20%) compared to the thinner topsoil layers (peaking at about 30%). The sand drainage layer exhibited very little fluctuation in its moisture content, never getting near saturation. The barrier layer experienced a drying trend since it was constructed. The barrier layer soil had periodic fluctuations in its moisture content lagging the topsoil fluctuations by about two months. The number of percolation events and their magnitude were relatively small for the Subtitle C Cover. These events did correlate with the peak moisture contents in the topsoil layer that were at or exceeded 20% for both the summers of 1997 and spring of 1998. The barrier layer in this cover dried much more slowly than that in the Subtitle D Cover because it was deeper in the profile, covered by a geomembrane, and most likely does not contain roots in it that would quickly draw moisture out of the soil.

3.3.3.3 GCL Cover

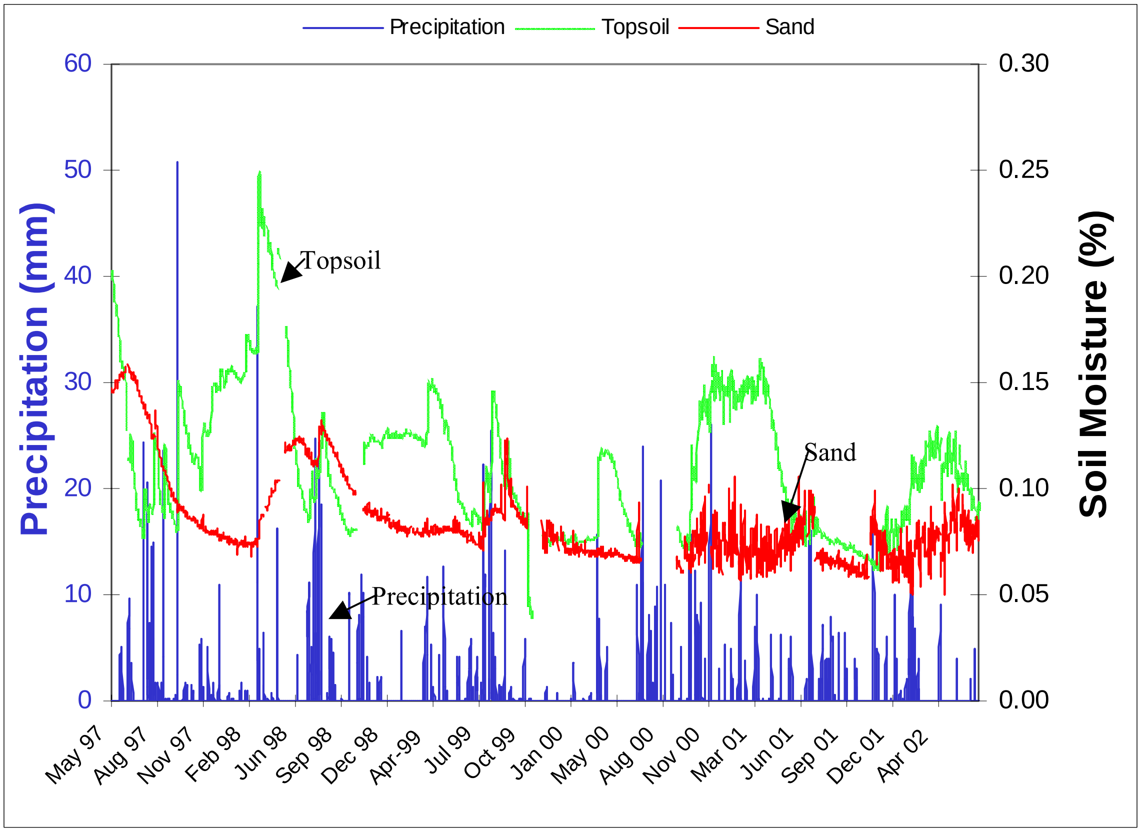


Figure 3.14. Soil Moisture Changes for the GCL Cover

The 60 cm thick topsoil layer in the GCL Cover reacted to precipitation in the same manner as that for the Subtitle C Cover (figure 3.14). The sand layer in the GCL Cover was installed at a higher moisture content than the sand drainage layer in the Subtitle C Cover due to a rainstorm that occurred during installation of this layer. This layer gradually dried until the snowstorm in the Spring of 1998 when it wetted up to nearly 25% before drying and maintaining a relatively tight moisture fluctuation trend around 7%. There were no measurements in the GCL itself.

3.3.3.4 Capillary Barrier

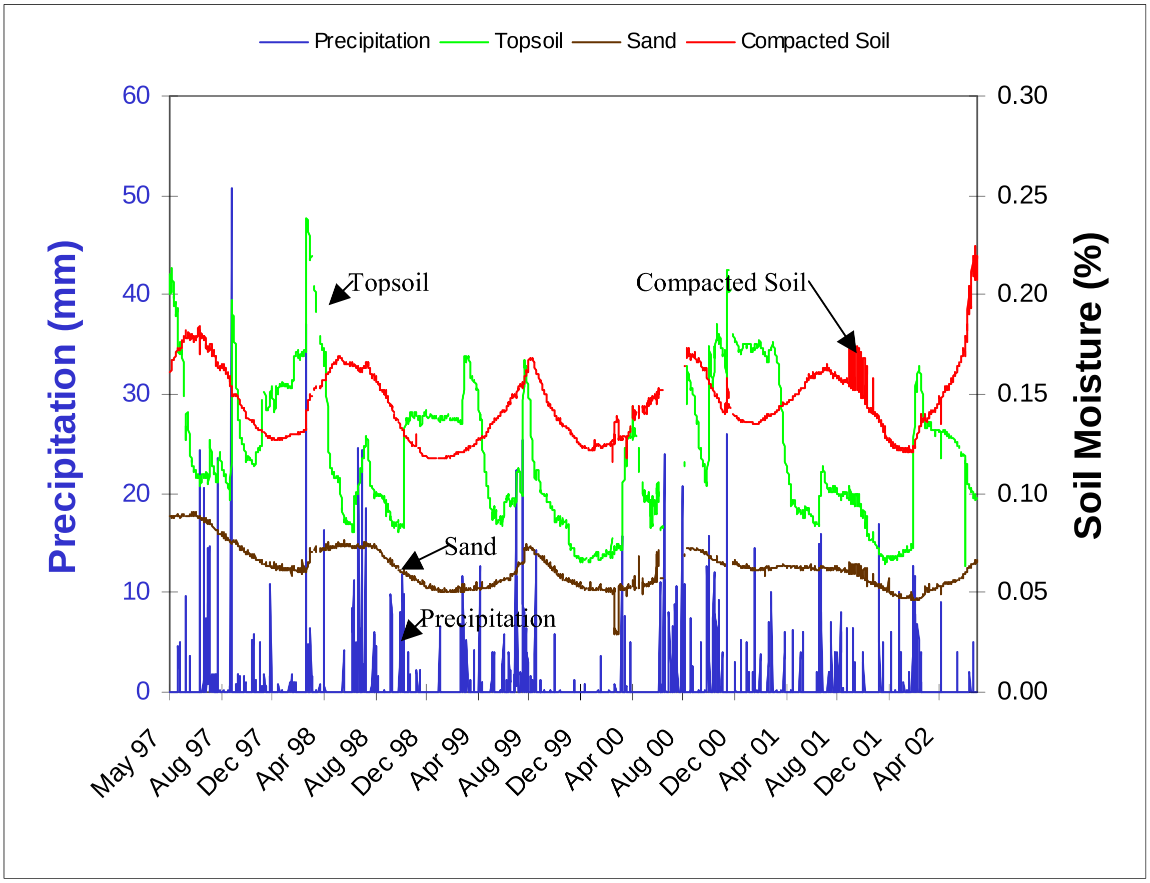


Figure 3.15. Soil Moisture Changes for the Capillary Barrier

The topsoil in this cover was 30 cm thick. The moisture fluctuations although not as extreme as the thin topsoil layer of the Subtitle D Cover had larger differences between the peaks and troughs than the thicker topsoil layers of the Subtitle C and GCL Covers (figure 3.15). The compacted soil layer (barrier) showed moisture fluctuation similar to the topsoil yet the peaks and troughs were not as extreme. There appeared to be about a two to three month lag between a moisture content peak in the topsoil and the corresponding peak in the sand layer directly below this layer. The peak moisture content on the topsoil layer was about 20%, well below saturation. The lower sand layer showed very small fluctuations between peak and trough that occurred gradually. The trends matched that of the compacted soil layer very well. The peaks in the moisture content in the sand and compacted soil generally correlated well with percolation events. The largest percolation event occurred after the snowstorm of 1998.

3.3.3.5 Anisotropic Barrier

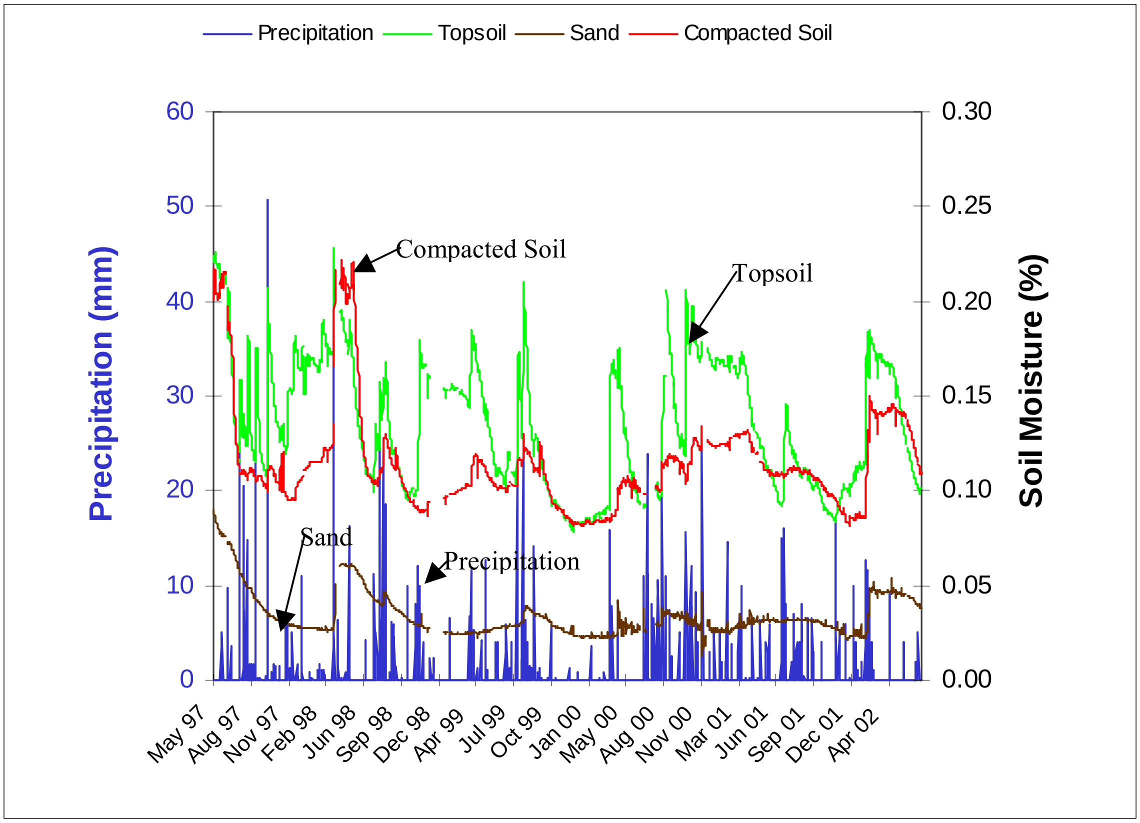


Figure 3.16. Soil Moisture Changes for the Anisotropic Barrier

The topsoil layer in the Anisotropic Barrier was thin (15cm) and responded to precipitation events with rapid fluctuations in moisture and likewise dried out very quickly thereafter (figure 3.16). The underlying compacted soil showed the same trends as the topsoil without the extreme peaks. The moisture content in the compacted soil rose to in excess of 20% following the spring snowstorm of 1998 that resulted in this cover's largest percolation event of about 0.2 mm. The moisture content in the sand layer below this compacted soil layer also reached its highest level of about 7% after this storm. Both the topsoil and compacted soil layers showed another moisture increase following a series of rain events in the summer of 1999 that resulted in a small percolation event. The only other significant wetting trend in the sand layer occurred in the late winter of 2002, but no percolation was recorded at that time.

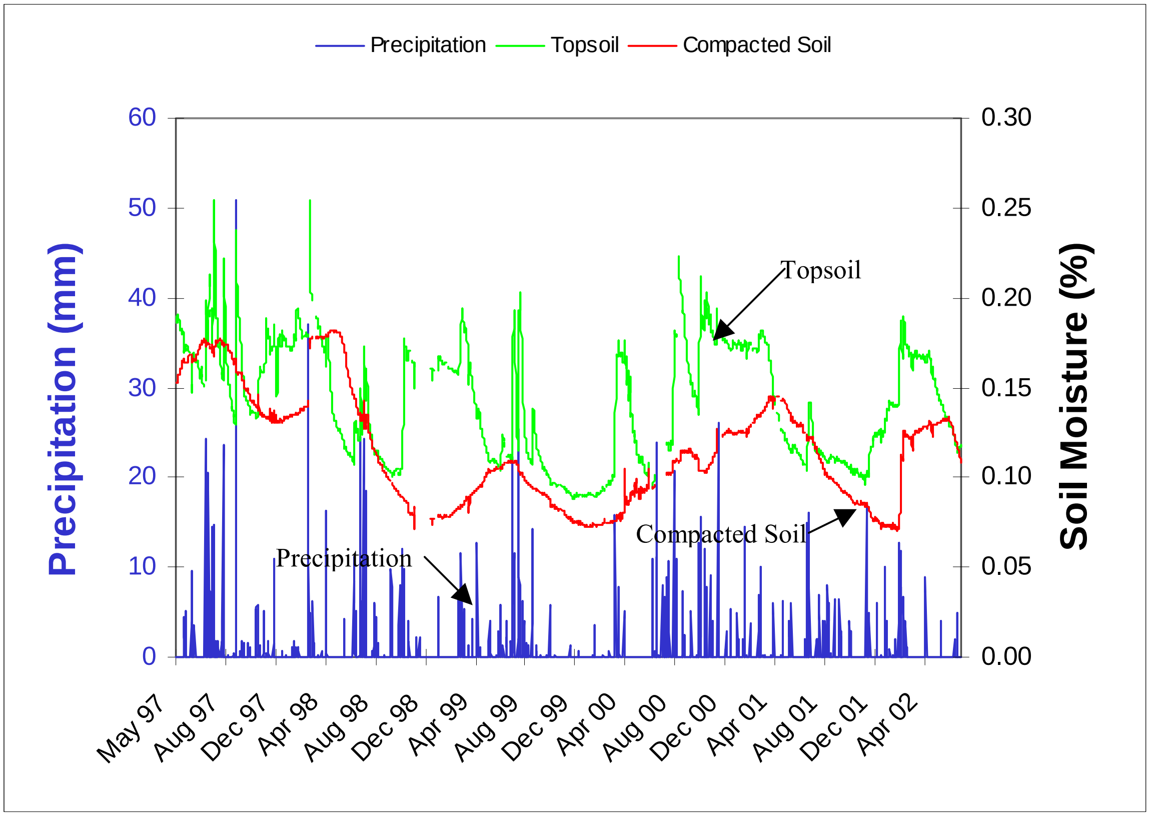


Figure 3.17. Soil Moisture Changes for the ET Cover

3.3.3.6 ET Cover

The topsoil layer in the ET Cover (15 cm) showed the same extremes with wetting and drying that were exhibited in the other covers that contained thin topsoil layers (figure

3.17). The compacted soil in the ET Cover also revealed wetting/drying trends that followed that of the topsoil layer with the wettest reaching about 20% after the snowstorm of 1998. This resulted in the largest percolation event for this cover of just less than 0.1 mm. The ET Cover experienced a small number and magnitude of percolation events. These events correlated well with extreme wetting peaks in the compacted soil at about 20%.

3.3.4 Vegetation Measurements

The vegetation on each landfill cover was quantified by measuring individual and species percent cover, density, and biomass over a five-year period (Dwyer et al, in press, b). The primary variables presented here were those included as input parameters to the computer models (HELP and UNSAT-H). The HELP model required the cover's leaf area index (LAI). The UNSAT-H model required the total percent bare area for each cover as well as the LAI. These parameters are presented in Figures 3.18 and 3.19 and were averaged over the five-year monitoring period.

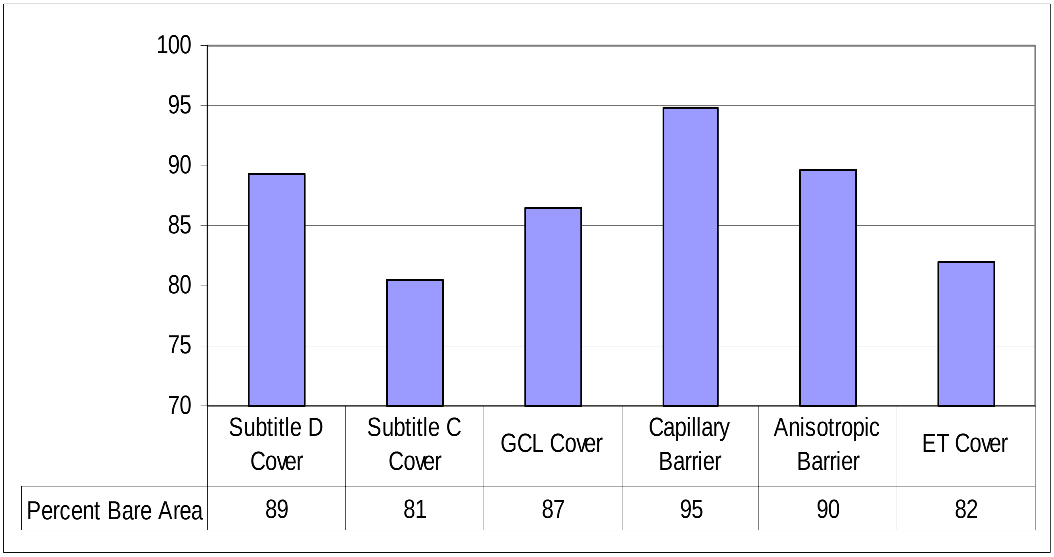


Figure 3.18. Percent Bare Area (Average Value from 1997 through 2001)

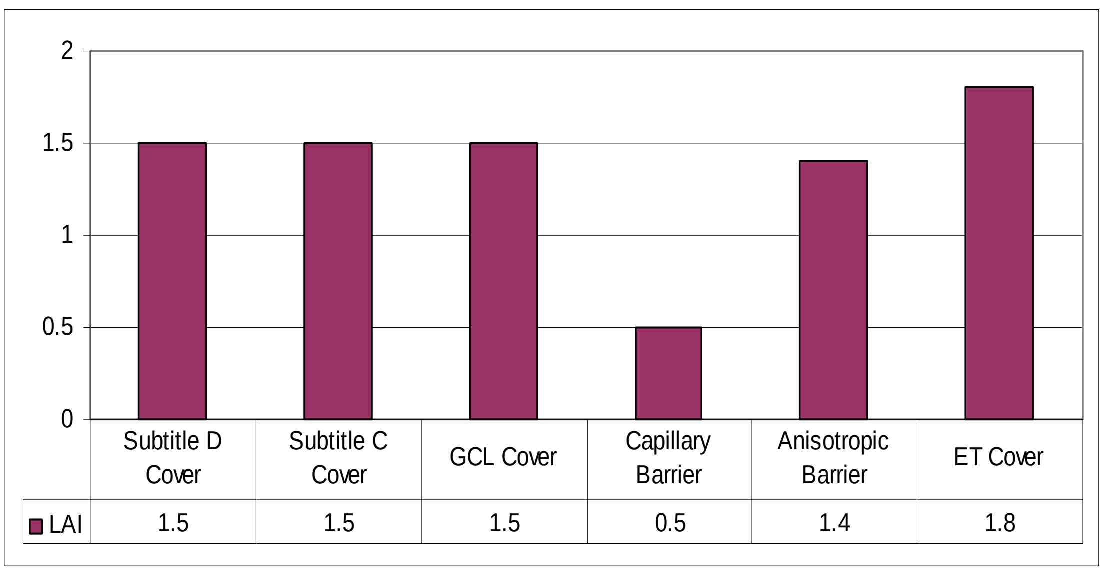


Figure 3.19. Leaf Area Index (Average Value from 1997 through 2001)

The Subtitle D, Subtitle C, and GCL Covers had about the same type and quantity of vegetation on them (Figure 3.20). The Anisotropic Barrier had a gravel topsoil mixture installed to minimize erosion. This treatment did not appear to have adversely affected the plant establishment. In fact, it may have helped. There was a slightly smaller amount of plant cover, but the cover consisted of more native grasses and less shrub (Dwyer et al, in press, b) than the other covers. Grasses are preferred on landfill covers because they stabilize the ground to minimize erosion, transpire the stored soil water, and have relatively shallow thin roots that generally do not result in preferential flow paths (EPA 1991). The ET Cover had the most plant cover. This was largely due to the gravel veneer surface treatment. This thin gravel layer on the surface served to hold seed in place until germination. Furthermore, moisture was retained in the upper-most layer of soil allowing vegetation such as native grasses to be established. This increased the available transpiration capacity. A higher percentage of shrubs and weeds were present on this cover than the others (Dwyer et al, in press, b) thus resulting in a higher LAI. The Capillary Barrier had the lowest percent plant cover and LAI. The thin (30 cm) topsoil layer did not have adequate water storage capacity to maintain native vegetation, especially during dry periods.

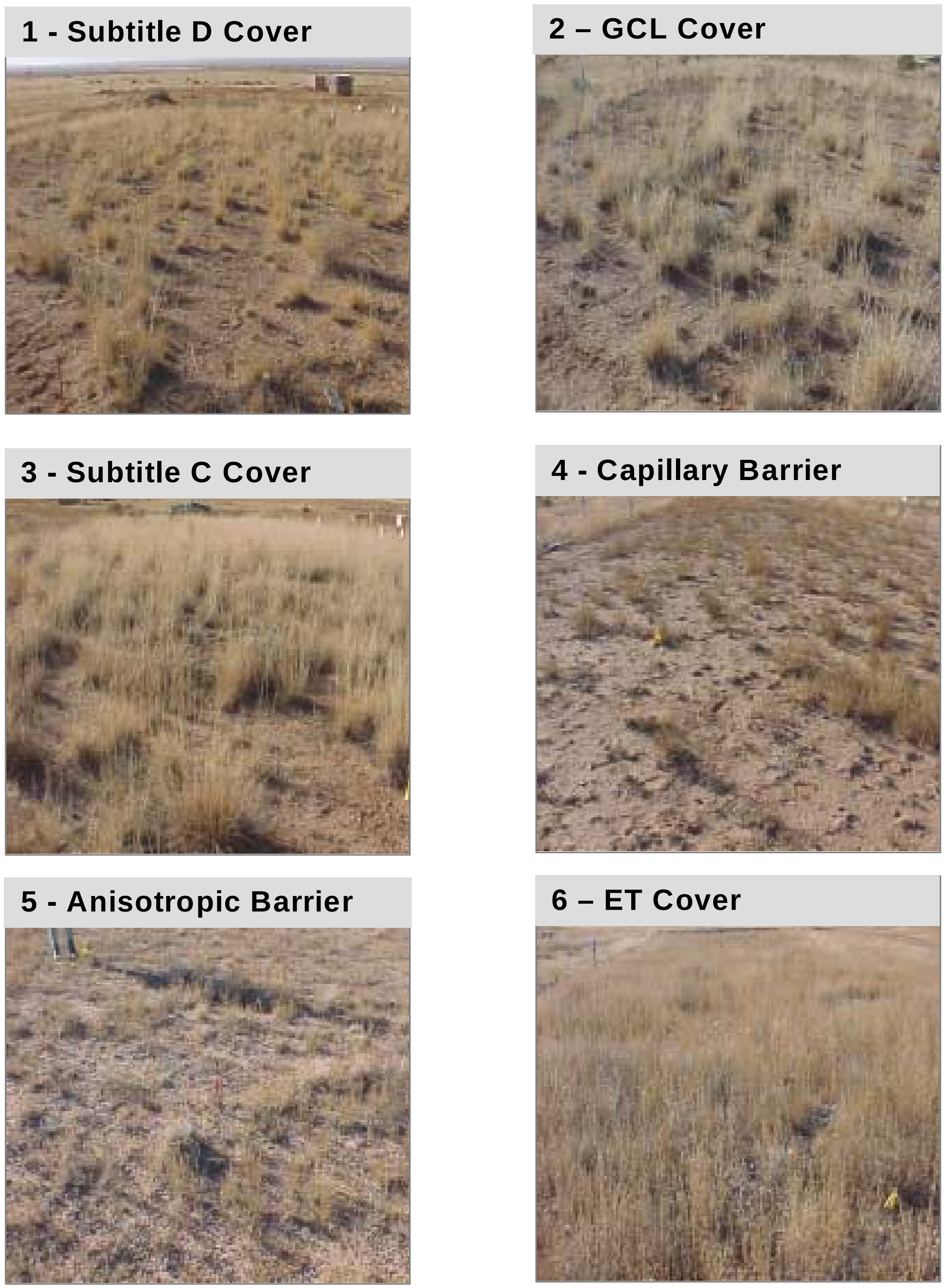


Figure 3.20. Surface Vegetation on Test Covers, Summer 1998

3.4 Discussion

The best performing covers were the Subtitle C Cover, Anisotropic Barrier, and ET Cover: each yielded less than 0.3 mm of cumulative percolation (figure 3.21). The Subtitle D Cover was the worst performing profile; it yielded just over 8 mm of percolation during the monitoring period. This was disturbing considering that this is the cover recommended by the EPA for municipal landfills nationwide. Poor performance of Subtitle D type covers may be a significant contributing factor to why virtually all parts of the country have experienced groundwater contamination due to a leaking landfill (EPA 1988).

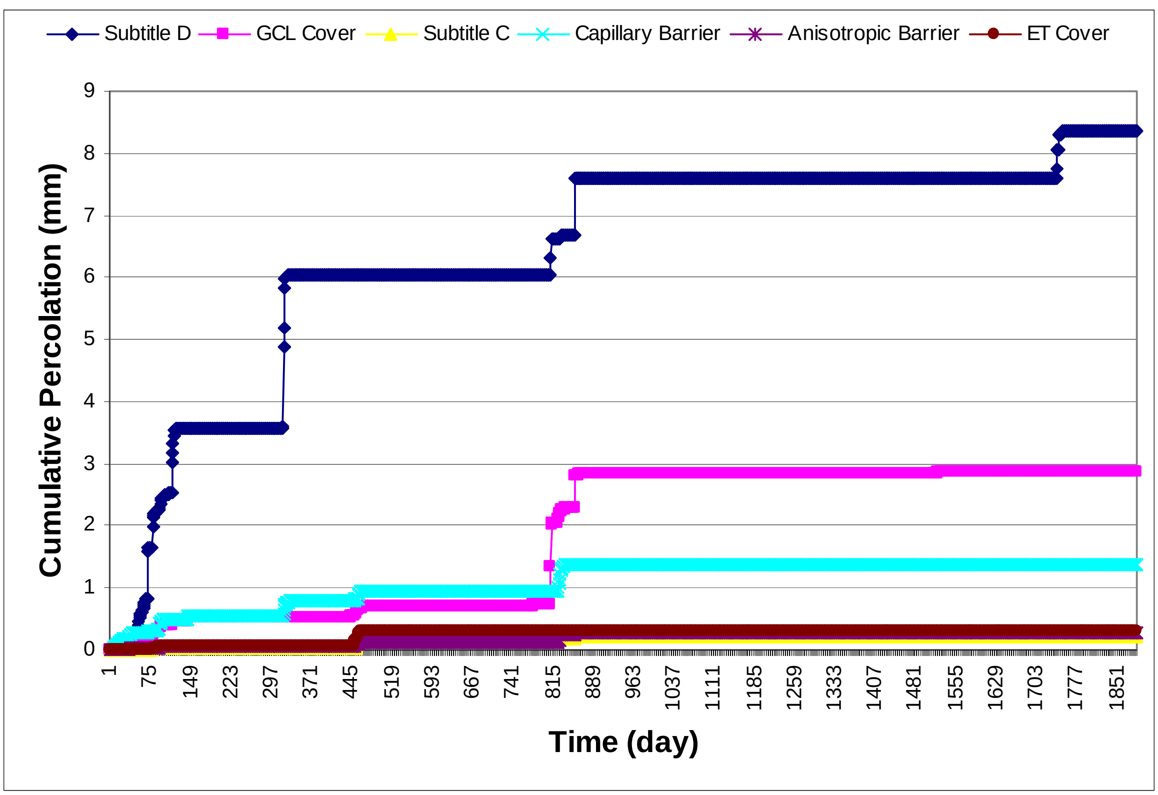


Figure 3.21. Cumulative Percolation for the Six Test Covers

Resistive barriers are prone to failure because the fine-grained barrier layers are easily damaged by weathering and distortion. Cracking due to frost can dramatically increase the layers' saturated hydraulic conductivity, in some cases by as much as four orders of magnitude (Benson et al 1995). The barrier layer in the Subtitle D Cover was within the frost zone (UBC 1997) for the site. Desiccation can create cracks and thus create preferential flow paths (Montgomery and Parsons, 1990; Suter et al, 1993; Benson et al, 1994). Shallow excavation of the Subtitle D Cover during tension infiltrometer testing of the cover during the fall of 2002 revealed extensive cracking in the barrier layer (figure 3.22). Furthermore, root intrusion into the barrier layer can increase the saturated hydraulic conductivity by as many as three orders of magnitude (Waugh et al. 1999).

Figure 3.22. Desiccation Crack in Subtitle D Cover (Barrier Layer)

The GCL Cover had the highest measured flux in 1999. Wet moisture content spikes occurred in the topsoil and sand drainage layers during the periods of measured percolation. However, they were not as extreme or as long in duration as those that corresponded to the percolation events measured in 1997 or 1998. A possible explanation for the data is that the GCL may have experienced degradation. It was the only cover profile that experienced an increased flux rate between 1997 and 1999. Degradation of a GCL may be the result of desiccation cracking and/or ion exchange issues (James et al. 1997, Melchoir 1997, Lin and Benson 2000). The clay within the GCL may have experienced desiccation cracks (James et. al. 1997) that did not fully heal upon resaturation. It was also possible that the GCL may have experienced a reduction in swell potential with an accompanying increase in saturated hydraulic conductivity. The clay in the GCL was sodium montmorillinite. The native soils used in the cover profiles had a relatively high calcium carbonate content (Dwyer et. al. 1999). Wet-dry cycles in the presence of water rich in divalent cations such as Ca^{+2} (James et. Al. 1997, Melchoir 1997) can severely increase the permeability of the GCL. Lin and Benson (2000) showed that after just four wet-dry cycles using water with 0.0125-M $CaCl_2$ the swell potential of the GCL clay layer was reduced by several orders of magnitude while the saturated hydraulic conductivity increased by four orders of magnitude after just 6 wet-dry cycles. The GCL was subjected to more than four wet-dry cycles between its construction in the summer of 1995 and the initiation of water balance monitoring on May 1, 1997.

The percolation events in 1997 and 1998 appeared to be dominated by unsaturated flow through the cover profiles with contribution from preferential flow. The compacted soil layers wetted up to their peak levels prior to these percolation events. These soil moisture content peaks were below the saturated moisture content for the soil, consistent with the concept that flow through the cover was dominated by unsaturated flow. During these percolation events, the barrier soil layers generally reached their wettest peaks at about 20% that corresponded to a matric potential for the given soil conditions of about 100 cm. Preferential flow can easily take place at a suction of 100 cm (Stormont 1999).

A simple calculation can illustrate the likelihood that preferential flow is occurring. The hydraulic conductivity for the Subtitle D Cover was calculated using the van Genuchten (1980) formula (equation 3.2) at the peak barrier soil moisture content of 20% (measured in March 1998) that produced the largest percolation event.

$$\theta = [1+(\alpha h)^n]^{-m} \qquad \textbf{Equation 3.2}$$

where: θ = normalized water content,

h = suction head,

α, n = fitting parameters,

m = 1 – 1/n,

$$K(\theta) = K_s * \theta^{0.5} [1 - (1- \theta^{1/m})^m]^2 \qquad \textbf{Equation 3.3}$$

where: K_s = saturated hydraulic conductivity.

Given; K_s = 1.23E-6 cm/sec, α = 0.033, n = 1.36, m = 0.26 (Table 5.7);

θ = 0.50,

thus, $K(\theta)$ = 3.26E-10 cm/sec.

Using the Darcy Buckingham (Jury et al 1991) formula to calculate the hydraulic conductivity from the measured flux rate (J_w), assuming a unit gradient flow (constant matric potential):

$J_w = K(h)\,\partial H/\partial z$, **Equation 3.4**

where; $\partial H/\partial z = 1$ (unit gradient),

H = total potential,

z = depth,

and h = 100 cm (for measured moisture content = 20%).

J_w = K(h) = 2.5 mm/month = 9.3E-8 cm/sec

Thus the expected hydraulic conductivity of the soil is two orders of magnitude lower than that estimated from the measured flux. One explanation for this difference is that flow is occurring preferentially through regions with a substantially greater hydraulic conductivity than that expected for the bulk of the soil that is, preferential flow.

Preferential flow appeared to play a larger role in total flux in percolation events after the summer of 1999 as evidenced by smaller moisture content peaks in the compacted soil layers prior to recorded percolation events. The calculated hydraulic conductivity (equations 3.2 and 3.3) for the percolation event recorded in February 2002 for the Subtitle D Cover was 4.54E-13 cm/sec. The peak moisture content in the barrier soil layer was 13%, which corresponds to a suction head of 2000 cm (Appendix A). The hydraulic conductivity that corresponded with the measured flux rate for this period was 3.1E-8 cm/sec. The measured value was about five orders of magnitude larger than the calculated value in February 2002 compared to about two and a half orders of magnitude for March 1998. This result suggests that preferential flow had increased with time.

This relative increase in preferential flow corresponded with ongoing ecological changes observed on the cover profiles (i.e., desiccation cracking, root intrusion, earthworm activity, animal intrusion) as well as soil pedogenic processes that led to changed soil properties as shown with the field tension infiltrometer measurements (chapter 6).

Preferential flow through soil profiles is a phenomenon that exists (Beven and Germann, 1982), yet is generally unaccounted for in cover designs or the design tools (computer programs) used in the designs. Flury et al (1994) believe the occurrence of preferential flow is the rule rather than the exception. Hornberger et al (1990) determined that the most significant amount of flow through a soil profile in Orono, Maine was through preferential flow channels. Watson and Luxmore (1986) determined that approximately 96% of water was transmitted through only 0.32% of the soil volume. They concluded that the larger the water flux, the larger the macropore contribution to total water flux. Many other studies (Rawls et al 1993, Edwards et al 1988) have concluded that preferential flow is the largest contributor to water flux through soil profiles.

Biointrusion into the cover profiles by ants (Johnson and Blom. 1997, Gaglio et al. 1998), earthworms (Edwards et al, 1988, Lee, 1985; Mackay and Kladivko, 1985, Waugh et al 1999), or roots (Waugh et al 1999, Reynolds, T. D. 1990) is a contributing factor to preferential flow. Burrowing animals can produce significant preferential flow (Hakonson 1986, Bowerman and Redente 1998, Cadwell et al. 1989, Pratt 2000). Figure 3.23 shows an anthill located on the Anisotropic Barrier. Figure 3.24 shows a cross section of the barrier layer in the Subtitle D Cover with an earthworm hole. Figure 3.25 shows an animal hole in the Anisotropic Barrier.

Figure 3.23. Ant Hill on Anisotropic Barrier

Figure 3.24. Earthworm Hole in Subtitle D Cover, Barrier Soil Layer

Given a wormhole the size of that shown in figure 3.24 (about 1 mm in diameter), the following calculations illustrate just how much preferential flow a single wormhole can produce. Using Poiseulle's Law (Jury et al 1991):

$Q = \pi R^4 \rho_w g(L+d)/(8L\nu)$, **Equation 3.5**

where:

Q = water volume flow rate;

R = radius of wormhole = 0.5mm;

ρ_w = water density = 1 g/cm^3;

L = depth of cover profile = 60 cm for Subtitle D Cover;

d = diameter of soil column (assume 1 wormhole per diameter of 10 cm);

ν= water viscosity = 0.01 g/cm*sec

$Q = 0.3\ cm^3/sec$.

Given the 13 m by 100 m test cover surface area:

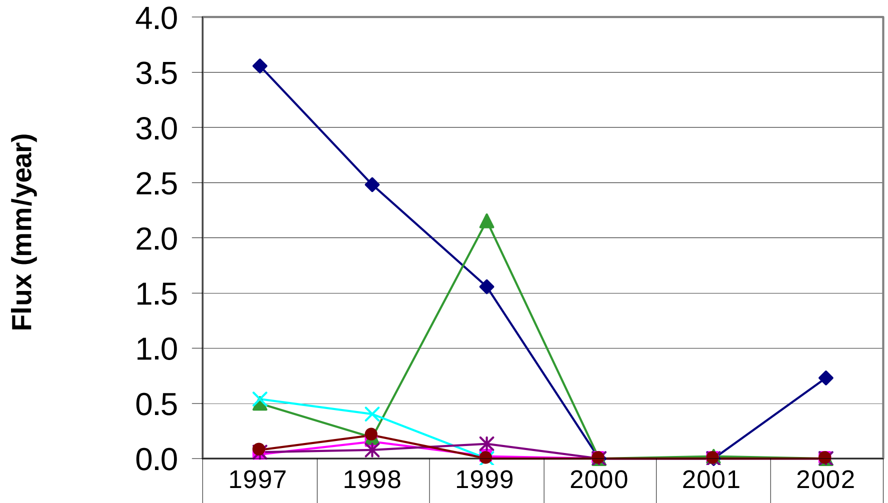
$$Q = (0.3\ cm^3/sec)/(13\ m \times 100\ m) = 0.6\ mm/month.$$

Thus, if all flow occurred through just 4 wormholes, the potential flux would be about the same as the peak flux measured in March of 1998 for the entire test cover surface area (2.5 mm/month).

It is understood that wormholes do not run vertically from top to bottom of a soil profile, but meander through it. Nonetheless it is clear that structural voids can have a dominant effect on water movement through a cover.

Figure 3.25. Burrowing Animal Hole on Anisotropic Barrier

An acceptable flux has not been universally established to date. The newly revised EPA RCRA/CERLA Final Design Landfill Closure Guidance Document (Dwyer et al, in press, a) suggests a range of 0.1 to 1 mm/year as an acceptable flux rate for design purposes. The 0.1-mm/year criteria was suggested for a hazardous waste landfill or a site where small amounts of leachate leaking into the surrounding environment will be harmful while the 1 mm/year was suggested for MSWLs located where leachate that escapes the landfill poses a low risk to the surrounding environment. Given this 0.1-mm/year criteria, only the Subtitle C Cover, Anisotropic Barrier, and ET Cover would be acceptable designs (Table 3.9) based on their measured average annual fluxes.



	1997	1998	1999	2000	2001	2002
Subtitle D Cover	3.56447	2.47911	1.56115	0.00000	0.00000	0.73966
Subtitle C Cover	0.04131	0.15161	0.01756	0.00000	0.00000	0.00000
GCL Cover	0.50628	0.18831	2.15408	0.00018	0.02091	0.00000
Capillary Barrier	0.54412	0.40907	0.00000	0.00008	0.00002	0.00005
Anisotropic Barrier	0.05135	0.06888	0.13937	0.00035	0.00047	0.00021
ET Cover	0.07546	0.21837	0.00538	0.00002	0.00000	0.00000

Figure 3.26. Annual Flux

Cover	Average Annual Flux (mm/yr)
Subtitle D Cover	1.39
GCL Cover	0.48
Subtitle C Cover	0.04
Capillary Barrier	0.16
Anisotropic Barrier	0.04
ET Cover	0.05

Table 3.9. Average Annual Flux

Based on this demonstration over the monitoring period, the best performing profiles were the ET Cover, Subtitle C Cover, and Anisotropic Barrier, which yielded the least amount of cumulative percolation (about 0.3 mm) while simultaneously experiencing a decreasing trend in flux rate (figure 3.26). The decreasing trend was largely attributable to the establishment of native vegetation and thus expedited removal of moisture from the cover profile. The ET Cover was preferable to both the Subtitle C and Anisotropic Barrier because its performance was comparable, but construction was cheaper (Dwyer 1998b) and easier (Dwyer 2000a).

Chapter 4. Design Tool Accuracy

4.1. Forward Modeling

The principal tool available to assist in the design of landfill cover profiles is computer programs used to predict water balance. Many design engineers use these programs with little knowledge of their internal workings or sensitivities. This may be a factor in inadequate designs, which contribute to failure of many landfill closures (Gross et al, 2001). This chapter describes an evaluation of a forward modeling exercise intended to simulate a typical design process. By forward modeling it is meant that simulations were performed without the benefit of field data or lessons learned during collection of this field data to adjust input parameters. The input parameters used with the simulations were based on early field and laboratory measurements completed prior to the construction of the test covers. These simulations are therefore consistent with the procedure used to design and obtain regulatory approval for landfill covers. Results from these simulations were compared to the field data to determine the accuracy of current design tools (i.e. computer programs).

The two programs utilized in the forward simulations were the Hydrologic Evaluation of Landfill Performance (HELP) program (Schroeder et al. 1994) and the UNSAT-H program (Fayer and Jones 1990). HELP was selected because it is the most popular software used by landfill cover designers and is endorsed by the EPA. It is routinely used for prescriptive cover designs as well as alternative cover designs. All six landfill covers installed and tested were modeled using HELP. UNSAT-H was selected because it appeared to be the most popular water balance program presently used for alternative cover designs. Unlike most unsaturated flow programs, UNSAT-H was specifically developed for the evaluation of landfill covers. UNSAT-H was used to model the Subtitle D Cover, Capillary Barrier, Anisotropic Barrier, and ET Cover. UNSAT-H was not used to model the Subtitle C or GCL Covers because they have geomembranes that could not be readily accommodated by the software.

4.1.1 HELP Overview

HELP is a quasi-two-dimensional program developed by the U.S. Army Corp of Engineers for the United States Environmental Protection Agency (EPA). This program not only estimates percolation, surface runoff, soil water storage, lateral drainage, and evapotranspiration for landfill covers but also calculates flow through the underlying waste, leachate collection system, and the liner. Schroeder et al. (1994) provides a detailed description of the algorithm HELP uses to route water into different components of the water balance. A schematic illustration of how HELP handles the water balance in a landfill cover profile is shown in Figure 4.1.

HELP requires that each layer of the landfill cover be specified as a vertical percolation layer, barrier soil liner, lateral drainage layer, or geomembrane liner depending on the function and hydraulic properties of the layer. A vertical percolation layer generally has moderate to high saturated hydraulic conductivity and unsaturated flow of water occurs in the vertical downward direction. A barrier soil layer has a low saturated hydraulic conductivity and is assumed to be fully saturated. A lateral drainage layer has a relatively high hydraulic conductivity and is underlain by a barrier layer. A lateral drainage layer allows for the vertical downward movement of water similar to a vertical percolation layer, as well as lateral saturated flow.

HELP divides precipitation into surface runoff and infiltration based on a modified version of the Soil Conservation Service (SCS) runoff curve number method. The SCS runoff curve number used by HELP is based on the hydraulic conductivity of the surface layer, condition of vegetation (i.e. LAI), and the slope and slope-length of the cover. If the air temperature is less than or equal to 0°C, precipitation is stored as a snowpack. The snowpack is allowed to melt only when the air temperature rises above 0 °C. The infiltrated water either remains in storage or is subjected to ET, lateral drainage, and/or percolation.

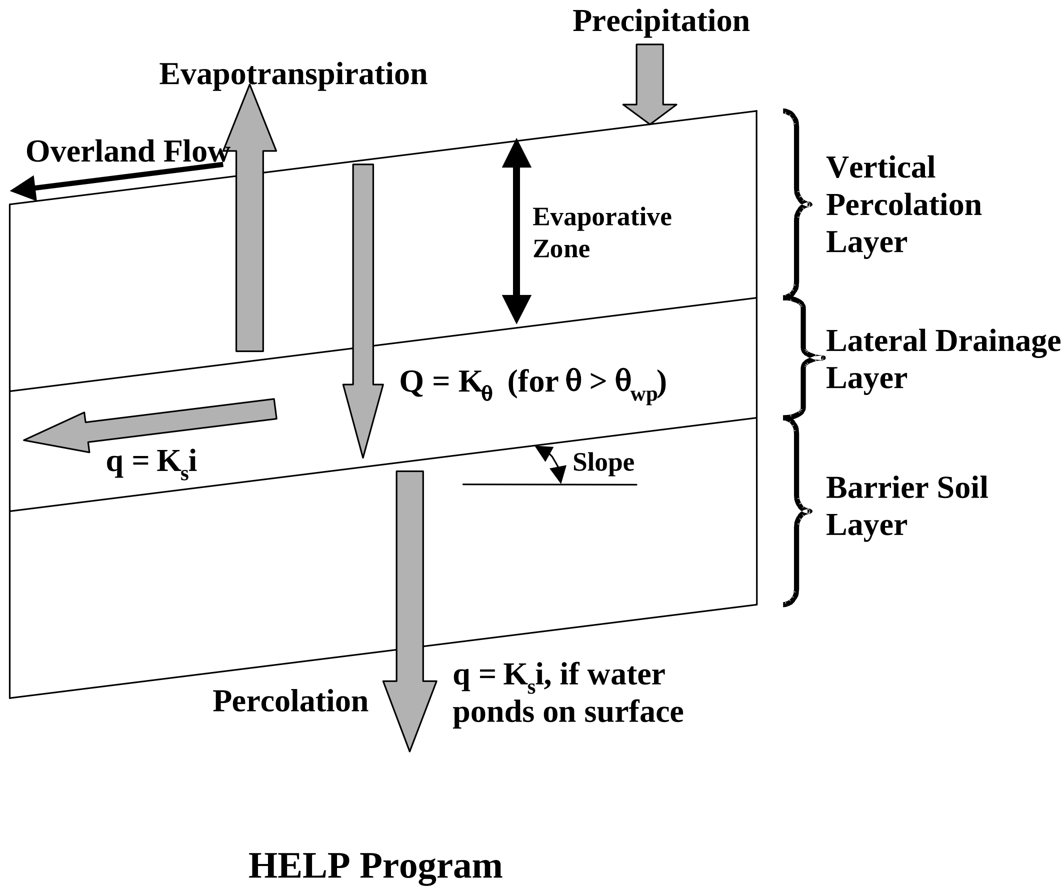


Figure 4.1. Schematic Representation of Water Balance Computations by HELP

Water removal via ET occurs from the evaporative depth of the cover. A vertical percolation layer is the only layer type that allows for water removal via ET. Consequently, the evaporative depth of the cover cannot be greater than the top vertical percolation layer. HELP provides default values for evaporative depth based on the location of the site and the condition of the vegetation. The quantity of water removed by ET is computed using an approach recommended by Ritchie (1972) and was a function of potential evapotranspiration (PET) and the availability of water stored in the soil profile. Potential evapotranspiration is calculated using a modified form of the Penman (1963) equation.

If the layer is a vertical percolation layer, the water stored in the soil layer is routed under a unit hydraulic gradient in the vertically downward direction (Figure 4.1) using the unsaturated hydraulic conductivity (K_θ) computed by Campbell's (1974) equation. ET removes water from the vertical percolation layer if the water content is above the permanent wilting point (θ_{WP}). The permanent wilting point is defined as the lowest amount of water that remains in the soil because a plant is unable to extract it. Field capacity is the amount of water in a wetted soil after it has drained. The size of the reservoir of water in a soil that can be used by plants to maintain life is the moisture range between the permanent wilting point and field capacity.

If the layer is a barrier soil layer, the saturated hydraulic conductivity and the depth of ponded water on the surface of the barrier soil layer are used with Darcy's law to compute percolation (Figure 4.1). The soil's saturated hydraulic conductivity is used because the barrier layer is assumed to be fully saturated.

4.1.2 UNSAT-H Overview

UNSAT-H is a one-dimensional, finite-difference computer program developed at Pacific Northwest Laboratory by Fayer and Jones (1990). UNSAT-H can simulate the water balance of landfill covers as well as soil heat flow (Fayer 2000); however, in this study only the water balance simulations were utilized. UNSAT-H simulates water flow through soils by solving Richards' equation and simulates heat flow by solving Fourier's heat conduction equation. This approach for analyzing water flow in earthen covers is distinctly different from the approach used by HELP.

A schematic illustration on how UNSAT-H computes the water balance is shown in Figure 4.2. UNSAT-H separates precipitation falling on a landfill cover into infiltration and overland flow. The quantity of water that infiltrates depends on the infiltration capacity of the soil profile immediately prior to rainfall (e.g. total available porosity). Thus, the fraction of precipitation shed as overland flow depends on the saturated and unsaturated hydraulic conductivities of the soils characteristic of the final cover. If the rate of precipitation exceeds the infiltration capacity, the extra water is shed as surface runoff. UNSAT-H does not consider absorption and interception of water by the plant canopy, or the effect of slope and slope-length when computing surface runoff.

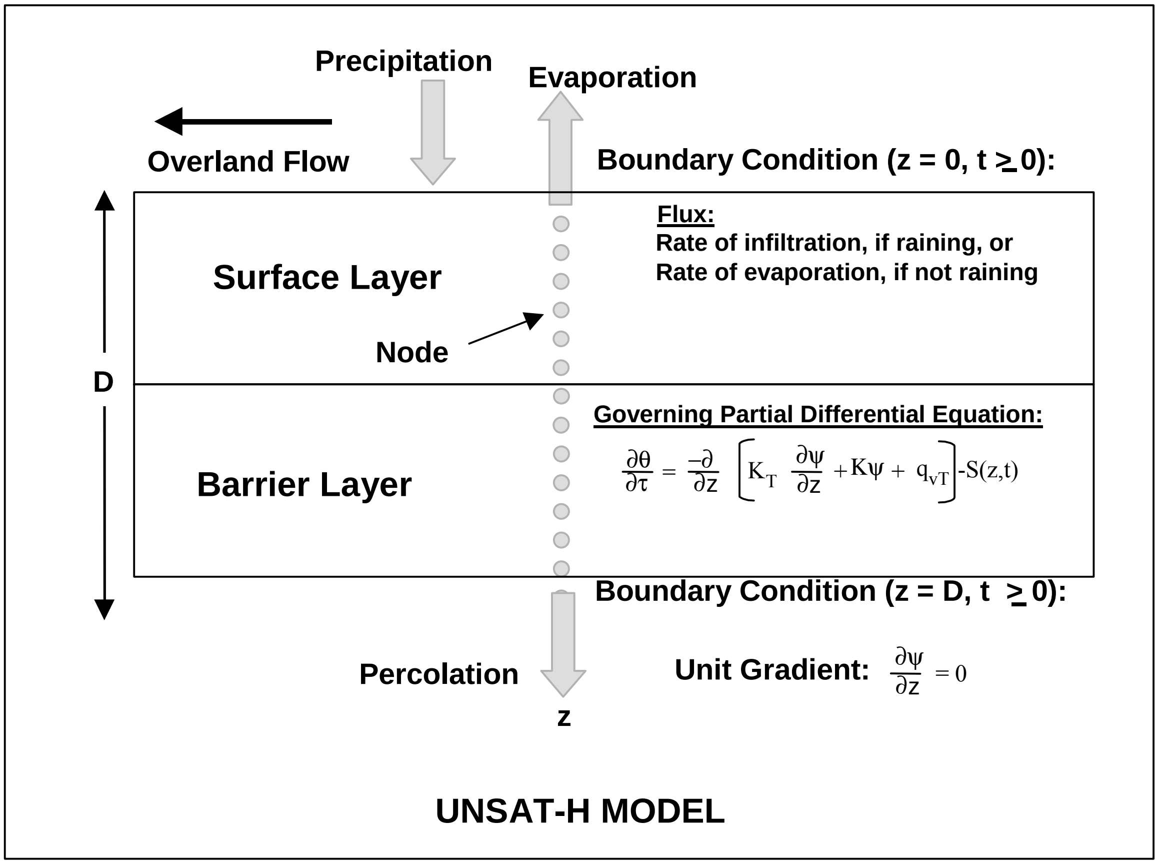


Figure 4.2. Schematic Representation of Water Balance Computation by UNSAT-H (modified from Khire 1995)

Water that has infiltrated a soil profile during an UNSAT-H simulation moves upward or downward as a consequence of gravity and matric potential (Figure 4.2). Evaporation is computed using Fick's law. Water removal by transpiration of plants is treated as a sink term in Richards' equation (Figure 4.2). Potential evapotranspiration is computed from the daily wind speed, relative humidity, net solar radiation, and daily minimum and maximum air temperatures using a modified form of Penman's equation given by Doorenbos and Pruitt (1977). Soil water storage is computed by integrating the water content profile. Flux from the lower boundary is via percolation (Figure 4.2). UNSAT-H, being a one-dimensional program, does not compute lateral drainage.

4.2 Input Parameters

The input parameters used for the forward modeling simulations were determined from laboratory and field testing as well as expert opinion obtained prior to the construction of the test covers. The weather data for the simulation period was conservative in that the annual precipitation volume used was above the historical average for the test site. The use of relatively high precipitation is a common design approach.

4.2.1 HELP Input Parameters

Sets of input parameters for the HELP forward simulations were developed for all six test covers. HELP is a user-friendly computer program that contains default values for most input parameters included within the software. To simulate a typical design, many of these default parameters were utilized. Input parameters required for the HELP program include the site location (nearest city), weather data (daily precipitation, temperature, and solar radiation), evapotranspiration data (LAI, evaporative zone depth, and growing season), soil data (total porosity, field capacity, wilting point saturated hydraulic conductivity, and initial moisture conditions), runoff data (SCS runoff curve information, slope and slope length), installation information about geosynthetics used if any (i.e., installation quality and number of defects in geomembrane), and finally a cover profile description (depth of layer, and type of layer such as barrier or vertical percolation layer).

4.2.1.1 Weather Data

Albuquerque, NM was used as the design site. The intent of the forward simulations was to be compared to the measured field water balance data to assess design tool accuracy. Consequently, the simulations were for a five-year duration consistent with the number of years of field data collected. The weather from 1998 (http://weather.nmsu.edu/map/map.htm) was used for two consecutive years in front of the selected model years to establish appropriate antecedent conditions. Weather data from 1998 was used because it was a near average precipitation year. An additional year (also 1998 weather) beyond the five-year simulation period was included to allow for transient data to dissipate. The simulation period included weather from 1997, which was a relatively wet year, modeled consecutively for 5 years to simulate a non-conservative design.

4.2.1.2 Vegetation Data

The onset and termination of the plant growing season (allowable transpiration period) for the site was set to the default values for Albuquerque, NM of 98 and 299, respectively. A LAI of 1.2 was used for all covers. This is the default value for Albuquerque and relates to a poor stand of grass. A maximum evaporative zone depth of 100 cm was used although the actual evaporative zone depth for each cover is dependent on the cover profile (only vertical percolation layers allow for evaporation). A placement quality of 2 was used for the geomembranes in the Subtitle C and GCL Covers that corresponded to an installation rating of excellent. Each geomembrane had 8 defects, which corresponds to about 13 defects per hectare. The defects were assumed to be 1-cm^2 holes in the geomembrane.

4.2.1.3 Runoff Data

The SCS runoff curve number was computed by the HELP program based on the slope length of 50 m, slope of 5%, runoff was possible over 100% of the landfill area, the respective soil texture for each cover, and a quality of surface vegetation of "poor stand of grass".

4.2.1.4 Soil Properties and Model Geometries

Default parameters were used for the soil hydraulic properties. Tables 4.1 through 4.6 present the soil properties and model geometries used in the simulations. These cover profiles correlate to figure 3.2 (Subtitle D Cover), figure 3.3 (Subtitle C Cover), figure

3.5 (GCL Cover), figure 3.7 (Capillary Barrier), figure 3.8 (Anisotropic Barrier), and 3.9 (ET Cover).

Topsoil layers were modeled as vertical percolation layers. All sand and gravel layers were modeled as lateral drainage layers. The compacted soil layers in the Subtitle D and C Covers were modeled as barrier layers. The compacted soil layers in all other covers were modeled as vertical percolation layers. The difference in model layers for the compacted soil layers used was due to the design intent for each respective cover: the Subtitle D and C Covers' compacted soil layers were designed to serve as barriers while the compacted soil layers in the ET Cover and capillary barriers were designed to store water and allow for unsaturated water movement.

Layer Type	Depth (cm)	Soil Default	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	15	Loamy Sand	0.437	0.105	0.047	0.0017
Barrier Soil	45	Loam, compacted	0.419	0.307	0.18	1.9E-5

Table 4.1. Subtitle D Cover: HELP Input Parameters

Layer Type	Depth (cm)	Soil Default	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol / vol)	Sat. Hyd. Cond. (cm/sec)	Defects
Vertical Percolation	60	Loamy Sand	0.437	0.105	0.047	0.0017	
Lateral Drainage	30	Coarse Sand	0.417	0.045	0.018	0.01	
Geo-membrane		Low density				4.0E-13	13 per hectare

Liner		Poly-ethylene					
Barrier Soil	60	Barrier Soil	0.427	0.418	0.367	1.0E-7	

Table 4.2. Subtitle C Cover: HELP Input Parameters

Layer Type	Depth (cm)	Soil Default	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Sat. Hyd. Cond. (cm/sec)	Defects
Vertical Percolation	60	Loamy Sand	0.437	0.105	0.047	0.0017	
Lateral Drainage	30	Coarse Sand	0.417	0.045	0.018	0.01	
Geo-membrane Liner		Low density Poly-ethylene				4.0E-13	13 per hectare
Barrier Soil		GCL	0.75	0.747	0.4	5.0E-9	

Table 4.3. GCL Cover: HELP Input Parameters

Layer Type	Depth (cm)	Soil Default	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	30	Loamy Sand	0.437	0.105	0.047	0.0017
Lateral Drainage	15	Coarse Sand	0.417	0.045	0.018	0.01
Lateral Drainage	23	Gravel	0.397	0.032	0.013	0.3
Compacted Soil	45	Loam, compacted	0.419	0.307	0.18	1.9E-5
Lateral Drainage	30	Coarse Sand	0.417	0.045	0.018	0.01

Table 4.4. Capillary Barrier: HELP Input Parameters

Layer Type	Depth (cm)	Soil Default	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	15	Loamy Sand	0.437	0.105	0.047	0.0017
Compacted Soil	60	Loam, compacted	0.419	0.307	0.18	1.9E-5
Lateral Drainage	15	Coarse Sand	0.417	0.045	0.018	0.01
Lateral Drainage	15	Gravel	0.397	0.032	0.013	0.3

Table 4.5. Anisotropic Barrier: HELP Input Parameters

Layer Type	Depth (cm)	Soil Default	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	15	Loamy Sand	0.437	0.105	0.047	0.0017
Barrier Soil	90	Loam, compacted	0.419	0.307	0.18	1.9E-5

Table 4.6. ET Cover: HELP Input Parameters

4.2.2 UNSAT-H Input Parameters

A set of input parameters was developed for UNSAT-H for the Subtitle D Cover, Capillary Barrier, Anisotropic Barrier, and ET Cover. These parameters were developed based on field and laboratory measurements, values from the literature, and expert opinion obtained prior to the installation of the test covers.

4.2.2.1 Model Geometry

The model geometry was based on the respective depth of each cover (Tables 4.7 through 4.10). The nodal spacing was set at 1 cm based on expert opinion (Fayer 2002; Webb 2002). The 1 cm spacing of nodes was deemed to be small enough to produce accurate results and was kept consistent so that nodal spacing between covers would not be an issue. The cover profiles modeled correspond to figure 3.2 (Subtitle D Cover), figure 3.7 (Capillary Barrier), figure 3.8 (Anisotropic Barrier), and 3.9 (ET Cover).

4.2.2.2 Boundary Conditions

The flow of water across the surface and lower boundary of the cover profile of interest was determined by boundary condition specifications. For infiltration events, the upper boundary used was set to a maximum hourly flux of 1 cm/hr. The surface boundary condition during evaporation was modeled as a flux that required daily weather data. Weather data from 1997 (http://weather.nmsu.edu/map/map.htm) for the Albuquerque International Airport was used. The precipitation recorded during this year was above the historical average for Albuquerque. This wet year was modeled five consecutive years to produce the design series of events (Dwyer et al 1999). The weather conditions used were consistent with those used for the HELP forward simulations. The UNSAT-H program partitions PET into potential evaporation (E_p) and potential transpiration (T_p). Potential evaporation is estimated or derived from daily weather parameters (Fayer 2000). Potential transpiration is calculated using a function (Equation 4.1) that is based on the value of the assigned LAI and an equation developed by Ritchie and Burnett (1971) for cotton and grain sorghum:

$$T_p = PET\ [a + b(LAI)^c] \quad \text{where } d \le LAI \le e \qquad \textbf{Equation 4.1}$$

where:

a,b,c,d,and e are fitting parameters;

a = 0.0, b = 0.52, and c = 0.5, d = 0.1, and e = 2.7 (Fayer 2000)

4.2.2.3 Vegetation Data

This set of parameters includes the leaf area index (LAI), rooting depth and density, root growth rate, as well as, the suction head value that corresponds to the soil's field capacity, wilting point, and water content above which plants do not transpire because of anaerobic conditions. A LAI of 1.2 was used for all covers based on an average recommendation for this region (Schroeder et al 1994). This value was consistent with that used with the HELP forward simulations. The onset and termination of the growing season for the site was Julian days 75 and 299, respectively based on expert opinion (Lofton 1997). The percent bare area was assumed to be 85% for all covers based on visual observation of undisturbed areas near the test site. The maximum rooting depth was assumed to be 100 cm. This value was thought to be realistic since the grasses present in the area such as Indian rice grass and blue gramma often exceed 100 cm

(Foxx et al 1984, Weaver 1920). The rooting depth for each cover was set to the lesser of 100 cm or depth of first sand or gravel layer in the cover profile. The root length density (RLD) was assumed to follow an exponential function:

$$RLD = a \exp(-bz) + c \qquad \textbf{Equation 4.3}$$

where:

a,b, and c are fitting parameters

Z = depth below surface

The parameters used for the RLD functions are: a = 0.315, b=0.0073, and c = 0.076. These values were measured for bunchgrass (Fayer 2000). These parameters are appropriate for deep rooting grass such as that found at the test site (Weaver 1920). Rooting depth was assumed to grow from the surface to its maximum depth linearly within the growing season of the first year modeled.

A suction head value of 15,000 cm was the head value used corresponding to the wilting point while 330 cm was the head value used corresponding to field capacity. A value of 30 cm was used as the head value corresponding to the water content above which plants do not transpire because of anaerobic conditions (Dwyer et al 1999). The maximum water content a soil can hold after all downward drainage resulting from gravitational forces is referred to as its field capacity. Field capacity is often arbitrarily reported as the water content at about 330-cm of matric potential head (Jury *et al*. 1991). Below field capacity, the hydraulic conductivity is often assumed to be so low that gravity drainage becomes negligible and the soil moisture is held in place by suction or matric potential. Not all of the water stored in the soil can be removed via transpiration. Vegetation is generally assumed to reduce the soil moisture content to the permanent wilting point, which is typically defined as the water content at 15,000 cm of matric potential head (Cassel and Nielsen 1986). Evaporation from the soil surface can further reduce the soil moisture below the wilting point to the residual saturation, which is the water content ranging from below 15,000 cm to an infinite matric potential.

4.2.2.4 Soil Properties

The soil hydraulic properties were obtained from laboratory testing of soils collected near the test site prior to the installation of the test covers. Saturated hydraulic conductivity values and moisture characteristic curves were based on the soil densities specified in the test cover design documents (Dwyer et al 1998c). The saturated hydraulic conductivity of the soils were obtained using a falling head permeameter (ASTM D5856). Unsaturated soil properties were obtained from data using pressure plates and water columns, depending on the suction values to develop moisture characteristic curves for each soil layer. These moisture characteristic curve data were then used as input into the RETC code (van Genuchten et al 1991) to compute van Genuchten parameters. The Mualem conductivity function was assumed to describe the unsaturated hydraulic conductivity of the soils. The van Genuchten ‘m’ parameter for this function was assumed to be'1-1/n'. The initial soil conditions were suction head values that corresponded to the average moisture content between each soil layer's field capacity and permanent wilting point determined form each respective soil layer's moisture characteristic curve.

	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Saturated Hydraulic Conductivity (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (Vol/Vol)	θ_r (Vol/Vol)	α (1/cm)	n	
Topsoil	15	1.54 @ 2.7	3.218	0.43	0.4	0.06	0.04	1.94	1000.
Barrier Soil	45	1.87 @2.7	0.036	0.31	0.29	0.11	0.01	2.43	1000.

Table 4.7. Subtitle D Cover: UNSAT-H Input Parameters

	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Sat. Hyd. Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suctio n Value (cm)
					θ_s (Vol/Vol)	θ_r (Vol/Vol)	α (1/cm)	n	
Topsoil	30	1.54@2.7	3.218	0.43	0.4	0.06	0.04	1.94	1000.
Sand	15	1.6@2.63	86.4	0.39	0.35	0.05	0.13	2.4	50.
Pea Gravel	23	1.7@2.53	4680.	0.33	0.33	0.03	2.8	2.5	25.
Compacted Soil	45	1.87@2.7	0.00839	0.31	0.29	0.11	0.01	2.43	1000.
Sand	30	1.6@2.63	86.4	0.39	0.35	0.05	0.13	2.4	50.

Table 4.8. Capillary Barrier: UNSAT-H Input Parameters

	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Sat. Hyd. Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (Vol/Vol)	θ_r (Vol/Vol)	α (1/cm)	n	
Topsoil	30	1.54@2.7	2.574	0.376	0.35	0.05	0.03	2.04	1000.
Compacted Soil	45	1.66@2.7	0.3816	0.385	0.36	0.08	0.03	2.14	1000.
Sand	30	1.6@2.63	86.4	0.39	0.35	0.05	0.13	2.4	50.
Pea Gravel	23	1.7@2.53	4680.	0.33	0.33	0.03	2.8	2.5	25.

Table 4.9. Anisotropic Barrier: UNSAT-H Input Parameters

	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Sat. Hyd. Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (Vol/Vol)	θ_r (Vol/Vol)	α (1/cm)	n	
Topsoil	30	1.54@ 2.7	3.218	0.43	0.4	0.06	0.04	1.94	1000.
Compacted Soil	45	1.87@ 2.7	0.00839	0.31	0.29	0.11	0.01	2.43	1000.

Table 4.10. ET Cover: UNSAT-H Input Parameters

4.3 Modeling Results

4.3.1 Water Balance

The field data (Chapter 3) are summarized in table 4.11. This format is consistent with presentation of the forward modeling simulations (tables 4.11 through 4.13) to allow for direct comparison. These results depict averages of the measured data obtained from 1998 through 2001. 1997 and 2002 were not used in the averages because field data was only collected for a portion of those years. The average precipitation value measured from 1998 through 2001 was 267.78 mm.

Landfill Cover	Lateral Drainage (mm)	Surface Runoff (mm)	Percolation (mm)	Change in Soil Storage (mm)	ET (mm)
Subtitle D Cover	NA	5.73	1.01	-0.45	261.50
GCL Cover	0.05	5.79	0.59	-12.00	273.35
Subtitle C Cover	0.05	2.53	0.04	-14.25	279.41
Capillary Barrier	NA	3.92	0.10	-7.50	271.26

Anisotropic Barrier	NA	5.07	0.05	-4.88	267.53
ET Cover	NA	3.25	0.06	-14.63	279.10

Table 4.11. Field Data: Average Annual Water Balance Values

Landfill Cover	Surface Runoff (mm)	Percolation (mm)	Change in Soil Storage (mm)	ET (mm)
Subtitle D Cover	7.26	84.47	6.16	257.06
Capillary Barrier	1.84	0.02	5.74	347.32
Anisotropic Barrier	0.02	0.00	12.96	341.73
ET Cover	7.24	30.31	16.45	300.99

Table 4.12. UNSAT-H: Average Annual Forward Modeling Results

Table 4.12 depicts the results of the forward modeling simulations using UNSAT-H with the design input parameters. These are the averaged annualized values over the five-year forward simulation period. The precipitation was 355.20 mm modeled five consecutive years. This value is 33% larger than the average measured precipitation that produced the field data.

Landfill Cover	Lateral Drainage (mm)	Surface Runoff (mm)	Percolation (mm)	Change in Soil Storage (mm)	ET (mm)
Subtitle D Cover	NA	0.25	70.12	0.67	284.16
GCL Cover	0.00	0.28	0.01	2.11	352.80
Subtitle C Cover	0.00	0.29	0.31	1.31	353.30
Capillary Barrier	NA	0.25	11.02	2.89	341.03

Anisotropic Barrier	NA	0.25	67.97	3.01	283.96
ET Cover	NA	0.25	69.84	0.67	284.43

Table 4.13. HELP: Average Annual Forward Modeling Results

The results of the modeling simulations using HELP version 3 with the design input parameters are presented in Table 4.13. These are the average annual values over the five-year forward simulation period. The average annual precipitation was 355.20 mm modeled five consecutive years. The lateral drainage values predicted for the Subtitle C and GCL Covers were zero.

4.3.2 Runoff

For ease of comparison the individual water balance variables for runoff, change in soil moisture, percolation, and ET are presented in Figures 4.3 through 4.6. Percent variance is defined as the difference between the simulation and measured value divided by the measured value expressed as a percentage. To simplify presentation of the data, percent variances between 100% and 1000% are denoted as >100%, while percent variances larger than 1000% are denoted as >>100%.

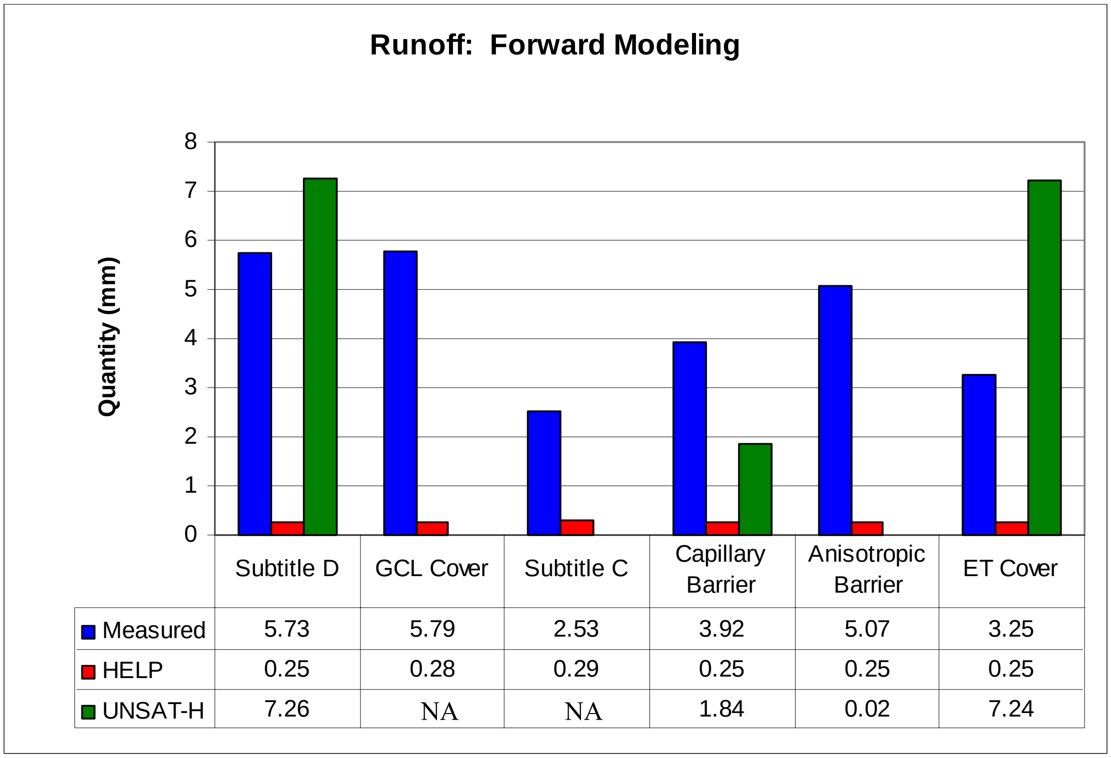


Figure 4.3. Comparison of Runoff Values for Simulations and Field Data

Program	Subtitle D Cover	GCL Cover	Subtitle C Cover	Capillary Barrier	Anisotropic Barrier	ET Cover
HELP	-5.48 (-96%)	-5.51 (-95%)	-2.24 (-88%)	-3.67 (-94%)	-4.82 (-95%)	-3.00 (-92%)
UNSAT-H	1.53 (27%)	NA	NA	-2.08 (-53%)	-5.05 (-100%)	3.99 (>100%)

Table 4.14. Runoff: Variance from Measured Value in mm (Percent Variance)

The data acquisition system used to measure runoff was the only instrumentation that experienced problems. Occasionally, the system would stop working due to the sediment in the runoff clogging the flow meters. Manual backup measurements coupled with visual observations during runoff events assume that the actual runoff values for all covers should be about the same as that for the Subtitle D and GCL Covers.

Nevertheless, the programs did not do a consistent nor accurate quantification of runoff. Scanlon et al (in press) reported that no water balance program accurately represents runoff.

The runoff values from the two programs used were calculated differently. UNSAT-H indirectly calculates runoff as the precipitation rate that exceeds the soil profile's infiltration rate. This method is obviously not representative of the field-measured data. The runoff values are higher for the Subtitle D and ET Covers because their infiltrations rates are relatively slow due to the tighter compaction of the barrier soils and thus smaller storage capacities and slower redistribution rates. Soils in the Capillary and Anisotropic Barriers have higher storage capacities due to moderate compaction of the soil layers and thus have higher redistribution rates allowing for higher infiltration rates. The HELP program calculated runoff using the SCS curve-number method, as described in Section 4 of the National Engineering handbook (USDA, SCS, 1985). HELP was consistent in its prediction of runoff from cover to cover, but was substantially lower than the measured values in all cases because it does not consider storm durations or intensities.

4.3.3 Change in Soil Moisture

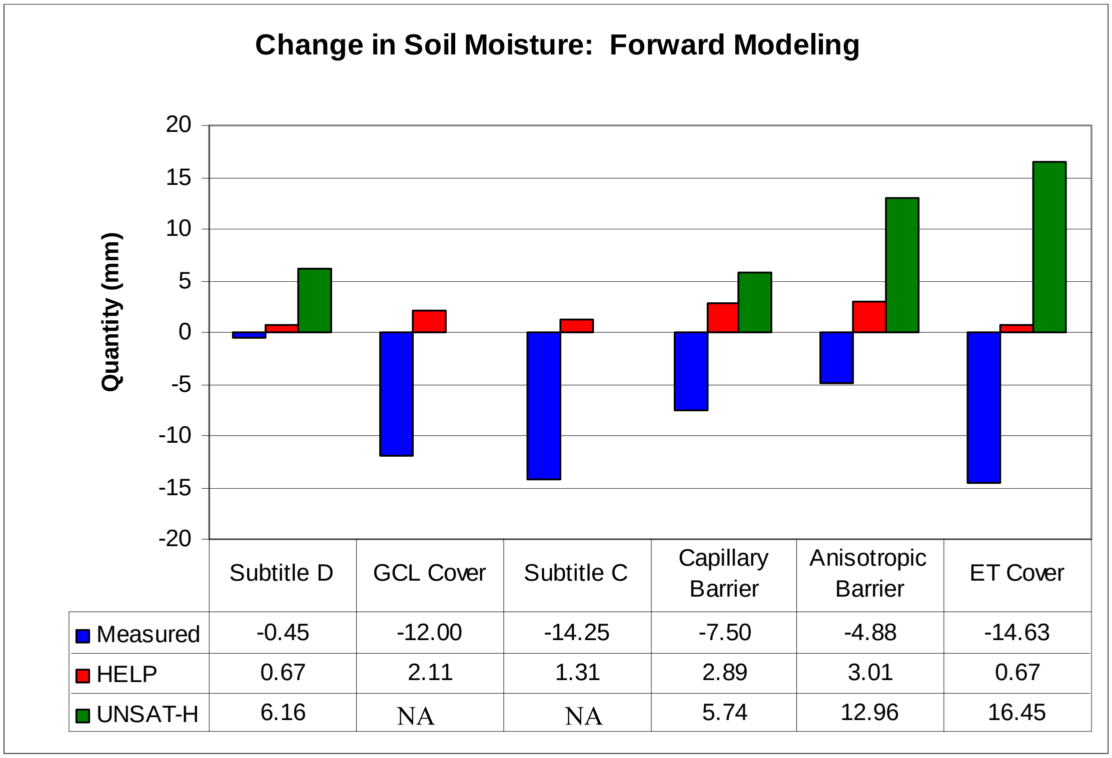


Figure 4.4. Comparison of Change in Soil Moisture Values for Simulations and Field Data

Program	Subtitle D Cover	GCL Cover	Subtitle C Cover	Capillary Barrier	Anisotropic Barrier	ET Cover
HELP	1.12 (<-100%)	14.11 (<-100%)	15.56 (-100%)	10.39 (<-100%)	7.89 (<-100%)	15.3 (<-100%)
UNSAT-H	6.61 (<<-100%)	NA	NA	13.24 (<-100%)	17.84 (<-100%)	31.08 (<-100%)

Table 4.15. Change in Soil Moisture: Variance from Measured Value in mm (Percent Variance)

The field data in all cases showed the cover profiles drying over time. Both programs predicted the covers would gain stored moisture. This difference may be in part because the design precipitation used was substantially more (33%) than the measured precipitation.

Infiltration is the process of water entry into the cover profile. The instantaneous infiltration rate, or infiltrability, is a function of several factors, including the time from the onset of precipitation, the initial water content of the soil, the hydraulic properties of the surface soil, and the hydraulic properties of the soil layers deeper in the profile (Hillel 1980). At the start of an infiltration event, the instantaneous rate is maximized. In time, the rate decreases asymptotically to a value approaching the saturated hydraulic conductivity of the most impeding layer within the wetted portion of the profile. Generally, this process can be explained in two stages. In the first stage, infiltration is controlled by the water supply or precipitation. In the second stage, infiltration is controlled by the soil profile conditions. UNSAT-H determines infiltration by calculating the ability of the soil profile to redistribute water downward (figure 4.2). Initially infiltration is equal to the precipitation rate. Moisture is then redistributed through the soil profile as the total potential (gravitational plus matric potential) between nodes attempts to equilibrate. At the same time, ET is removing moisture from the system. HELP on the other hand calculates infiltration differently based on the type of soil layer used. A vertical percolation layer such as the topsoil layer assumes vertical downward flux of unsaturated flow driven solely by gravity. Matric potential is not considered. Upward flux is a function of ET only. A lateral drainage layer treats the downward vertical movement of water similarly to the vertical percolation layer, except that it allows for saturated lateral drainage and does not allow for removal of water by

ET. The barrier soil layer assumes that the layer is under constant saturation. ET is not allowed to remove water from the barrier layer.

4.3.4 Percolation

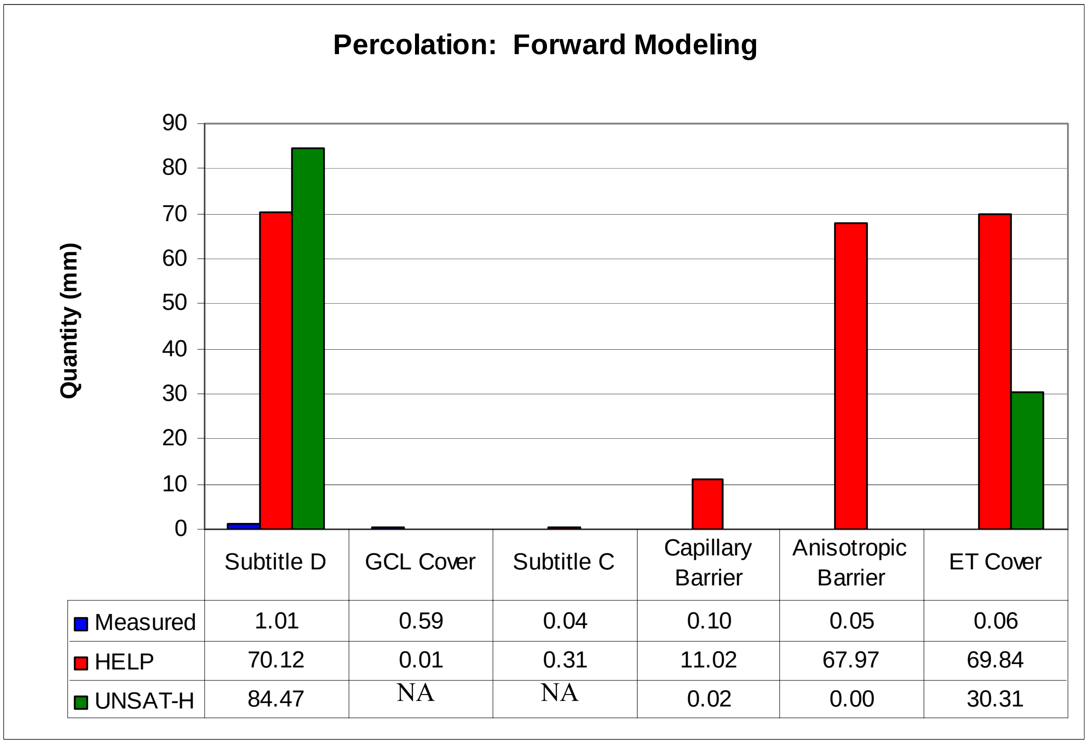


Figure 4.5. Comparison of Percolation Values for Simulations and Field Data

Program	Subtitle D Cover	GCL Cover	Subtitle C Cover	Capillary Barrier	Anisotropic Barrier	ET Cover
HELP	69.11 (>>100%)	-0.58 (-98%)	0.27 (>100%)	10.92 (>>100%)	67.92 (>>100%)	69.78 (>>100%)
UNSAT-H	83.46 (>>100%)	NA	NA	-0.08 (-80%)	-0.05 (-100%)	30.25 (>>100%)

Table 4.16. Percolation: Variance from Measured Value in mm (Percent Variance)

Percolation results from the redistribution of water through a soil profile in response to gradients in the energy state of the water. Other mechanisms that might induce water redistribution, such as geothermal gradients and barometric pressure fluctuations, have been shown to be minor contributors to water flow in most instances (Jones 1978, Gee and Simmons 1979). Water redistribution is dependent on the soil profile hydraulic properties.

Percolation was expected to be slightly higher than the measured values because the design precipitation quantity was about 33% larger than actually experienced. As it turned out, HELP significantly overestimated percolation in all covers that do not have geomembranes within their profile. This overestimation of flux through the cover was a minimum of two orders of magnitude. The HELP program did a relatively good job of predicting flow through the GCL and Subtitle C Covers. The values were low from the HELP forward simulations because of the inclusion of geosynthetics that have very low saturated hydraulic conductivities. The geomembranes had an "equivalent hydraulic conductivity" of 4E-13 cm/sec (Giroud and Bonaparte 1989) based on vapor diffusion through a geomembrane. In addition, another set of equations was used to calculate leakage through the geomembrane that was a function of the number and type of defects in the geomembrane and the quality of the liner contact with the soil (Giroud and Bonaparte 1989). The soil in the Subtitle C Cover had an input parameter of 1E-7 cm /sec while the GCL had a 5E-9 cm/sec saturated hydraulic conductivity input value.

UNSAT-H estimated the average annual percolation through the Subtitle D Cover, which at over 84 mm compared to the 1 mm measured, was the highest for any simulation. The UNSAT-H simulation results for the ET Cover did not fair much better producing over 30 mm of average annual percolation compared with a very low measured value of only 0.06 mm. The soil properties for the compacted soil layers in these profiles were the first set of unsaturated soil properties obtained on the project prior to the design and construction of the test covers. In order to produce a realistic assessment of current design methods, these soil properties were used because designers generally collect a single set of soil properties prior to design of a cover profile for a given soil.

The water holding capacity for the topsoil for both the Subtitle D and ET covers was 7% while the water holding capacity of the compacted soil layers was 9%. These holding capacities are low for the given soils. A simple estimate of water holding capacity for a given soil is the difference between the field capacity and the wilting point moisture contents. The relatively small storage capacity of the profile was believed to be the primary reason for the large percolation prediction. The percolation results from the UNSAT-H forward simulations showed a significant contrast between a soil cover and a capillary barrier. The two capillary barrier profiles each had predicted flux rates below the measured values. The Anisotropic Barrier actually had no percolation predicted.

4.4 Discussion

The intent of this chapter was to assess current design tool accuracies as well as the associated design methodologies that accompany these computer simulations. The accuracy of input parameters is obviously critical for acceptable output results. The forward simulations had known shortcomings with the input parameters used. Many default parameters were utilized with the HELP forward simulations rather than site specific data to emulate design methodologies commonly used by practitioners today. Weather data used was conservative as is prudent in any design approach to allow for some factor of safety. Soil properties used for the UNSAT forward simulations were those obtained from a nearby borrow site prior to the construction of the test covers. Input parameters were not adjusted based on field measurements or lessons learned during the monitoring of the covers. However, it was the programs' handling of physical processes that was shown to be the key weakness or strength in accurately predicting water balance variables for landfill cover profiles.

Neither program accurately predicted surface runoff. This was consistent with findings by Scanlon et al (in press). The UNSAT-H program indirectly predicted surface runoff as a result of the precipitation rate in excess of the cover profile's infiltration rate. The program can easily be manipulated to yield desired surface runoff results by altering the precipitation rate for the simulation. This however, affects the prediction of other water balance variables such as the infiltration of precipitation into the profile. The HELP Program directly calculated runoff, but does so using the SCS Curve Number procedure that does not take into account a storm's intensity or duration. This effect is most severe in dry climates where storms are of high intensity and short in duration. Therefore, HELP will routinely under-predict runoff. This under-prediction of surface runoff leads to more water infiltration and thus more flux through the cover.

HELP's shortcomings with respect to unsaturated flow through the cover profile were inconsistent with it accurately predicting water balance variables, especially percolation for capillary barriers or monolithic soil covers. HELP only allowed unsaturated vertical flow in two of the four layer choices (vertical percolation and lateral drainage layer). This unsaturated flow was a function of gravity only. Matric potential gradients, which can be several orders of magnitude larger than gravitational potential gradients, were not considered. UNSAT-H better estimated unsaturated flow than HELP primarily because of its inclusion of a soil's matric potential. The largest contrast between the two programs was seen with the simulation results of the two capillary barrier covers. Both the Anisotropic and Capillary Barrier had low measured percolation values. HELP drastically overestimated percolation because of its inability to deal with a capillary barrier and omission of matric potential with unsaturated flow was the reason for this. UNSAT-H percolation results were actually slightly less than the measured values. For the Anisotropic Barrier, no flux was predicted because of its relatively large storage capacity within the 75 cm fine layer when enhanced by the capillary break formed by the underlying coarse layer. The Capillary Barrier, even with a much smaller surface topsoil layer of 30 cm also enhanced by the underlying coarse layer, had only 0.02 mm of percolation predicted to flow through it. This was about 20% of the value measured.

HELP appeared to be relatively accurate at predicting flow that was controlled by a calculated effective hydraulic conductivity for a geomembrane when the number and size of defects were known. The potential weakness here is that in the real world, often the size or number of defects in a geomembrane is not known. HELP assumes the defects are 1 cm^2 in surface area. Large gashes in geomembranes that are created and then covered up by earthwork equipment operators after the installation of a geomembrane can occur. HELP is not an adequate design tool for any other type of cover profile. UNSAT-H, on the other hand, is suspect as a design tool. The flux through the monolithic soil profiles (i.e. Subtitle D and ET Covers) were significantly overestimated while the flux through the two capillary barrier profiles although much closer to the measured values, were underestimated.

Chapter 5. Water Balance Simulations with As-Built Properties and Field Monitored Conditions

5.1 Introduction

There have been a relatively small number of simulation comparisons with field applications largely due to the lack of available field data (Nichols, 1991; Berger et al, 1996; Khire et al, 1997; Ogan et al, 1999; Wilson et al, 1999; Scanlon et al in press). These efforts have shown mixed results with respect to the ability of simulations to accurately predict the water balance, and in particular, percolation through a cover.

A detailed comparison of computer simulations using the HELP (Schroeder et al 1994) and UNSAT-H (Fayer 2000) programs are presented here. The simulations were performed with the best available information using data collected during the field-monitoring period (i.e., as actual climate, soil, and vegetation data as input to the simulations).

5.2 Input Parameters

The input parameters used in this set of computer simulations were obtained through laboratory and/or field-testing of the actual soils used in the cover profiles in their "as-built" conditions. In other words, the soil data represents the soil layers' initial soil conditions. Vegetation parameters used were those obtained from field measurements made on the covers at the test site (Dwyer et al in press, b) or expert opinion. Weather data was measured on site with a weather station (Dwyer et al 1998c).

5.2.1 HELP Input Parameters

Albuquerque, NM was used as the design site. Weather measured on site was used as the weather input data files for daily precipitation, temperature, and solar radiation. Data from the on-site weather station was collected beginning in late 1996, while the setup of the instrumentation used to collect water balance data on the test covers was not completed until May 1, 1997. HELP does not allow for partial year calculations, therefore the entire data set for 1997 was used as the file for that year. After the model was run, the output from January 1 to April 30, 1997 was deleted to allow for comparison of the field data beginning in May of 1997.

The ET input file contains information about the city of interest (site latitude, growing season start and end days, LAI, evaporative zone depth, average wind speed and average quarterly humidity). A maximum evaporative zone depth of 100 cm was used. Average LAI values from field measurements (Table 3.3) for each cover were used as input to the ET file. The onset and termination of the growing season for the site is Julian days 75 and 299, respectively based on expert opinion (Lofton 1997). Default values for the site latitude, average wind speed and average quarterly humidity were used.

A placement quality of excellent was used for the geomembranes in the Subtitle C and GCL Covers. Each geomembrane had 8 defects in them. This was comparable to the average number of defects found in field-emplaced geomembranes (ASTM 2002; Koerner and Daniel, 1997; Schroeder et al, 1994). The defects were holes in the geomembrane 1 cm^2 in area. The runoff curve number was computed by the HELP program based on the slope length of 50 m, slope of 5%, runoff was possible over 100% of the landfill area, the respective soil texture for each cover, and a quality of surface vegetation of based on the measured LAI for each cover.

The initial moisture contents were the average values measured for each soil layer with the TDR system on May 1, 1997. Most of the saturated hydraulic conductivity values used for the various soil layers were determined in the laboratory using a falling head permeameter (ASTM D5856). The exceptions were the barrier layers for the Subtitle D and C Covers. These saturated hydraulic conductivities were measured in the field using a sealed double ring infiltrometer (ASTM D5093). The saturated hydraulic conductivity of the GCL was measured in the laboratory using a constant head permeameter at 1.0E-8 cm/sec (GRI GCL-2). This was an order and half magnitude less than claimed by the manufacturer (Claymax 1995).

Tables 5.1 through 5.6 show the soil properties and model geometries used in the simulations. These cover profiles correlate to figure 3.2 (Subtitle D Cover), figure 3.3 (Subtitle C Cover), figure 3.5 (GCL Cover), figure 3.7 (Capillary Barrier), figure 3.8

(Anisotropic Barrier), and 3.9 (ET Cover). The wilting point and field capacity moisture contents used correspond with the 15,000 cm and 330 cm suction head values for each soil (Appendix A).

Layer Type	Depth (cm)	Initial Moisture Content (vol/vol)	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	15	0.19	0.45	0.16	0.09	1.0E-3
Barrier Soil	45	0.37	0.37	0.19	0.1	1.23E-6

Table 5.1. Subtitle D Cover: HELP Input Parameters

Layer Type	Depth (cm)	Initial Moisture Content (vol/vol)	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Cond. (cm/sec)	Defects	Quality
Vertical Percolation	60	0.186	0.45	0.16	0.09	1.0E-3	NA	NA
Lateral Drainage	30	0.121	0.37	0.03	0.02	1.82E-2	NA	NA
Geo-membrane Liner	NA	NA	NA	NA	NA	4.0E-13	12.9/hectare	1
Barrier Soil	60	0.37	0.37	0.19	0.1	9.7E-7	NA	NA

Table 5.2. Subtitle C Cover: HELP Input Parameters

Layer Type	Depth (cm)	Initial Moisture Content (vol/vol)	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Cond. (cm/sec)	Defects	Quality
Vertical Percolation	60	0.203	0.45	0.16	0.09	1.0E-3	NA	NA
Lateral Drainage	30	0.145	0.37	0.03	0.02	1.82E-2	NA	NA
Geo-membrane Liner	NA	Low density Polyethylene	NA	NA	NA	4.0E-13	12.9/hectare	1
Barrier Soil	0.5	GCL	0.75	0.747	0.4	1.0E-8	NA	NA

Table 5.3. GCL Cover: HELP Input Parameters

Layer Type	Depth (cm)	Initial Moisture Content (vol/vol)	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	30	0.193	0.45	0.16	0.09	1.0E-3
Lateral Drainage	15	0.088	0.37	0.03	0.02	1.82E-2
Lateral Drainage	23	0.03	0.37	0.028	0.026	4.42
Compacted Soil	45	0.41	0.41	0.18	0.09	4.0E-4
Lateral Drainage	30	0.088	0.37	0.03	0.02	1.82E-2

Table 5.4. Capillary Barrier: HELP Input Parameters

Layer Type	Depth (cm)	Initial Moisture Content (vol/vol)	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	15	0.224	0.45	0.16	0.09	1.0E-3
Compacted Soil	60	0.218	0.41	0.18	0.09	4.0E-4
Lateral Drainage	15	0.09	0.37	0.03	0.02	1.82E-2
Lateral Drainage	15	0.03	0.37	0.028	0.026	4.42

Table 5.5. Anisotropic Barrier: HELP Input Parameters

Layer Type	Depth (cm)	Initial Moisture Content (vol/vol)	Porosity (vol/vol)	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
Vertical Percolation	15	0.189	0.45	0.16	0.09	1.0E-3
Compacted Soil	90	0.153	0.37	0.19	0.1	4.34E-5

Table 5.6. ET Cover: HELP Input Parameters

5.2.2 UNSAT-H Input Parameters

A set of input parameters was developed for simulations using UNSAT-H for the Subtitle D Cover, Capillary Barrier, Anisotropic Barrier, and ET Cover. These parameters were developed based on field and laboratory measurements, values from the literature, and expert opinion.

5.2.2.1 Model Geometry

The model geometry was based on the respective depth of each cover. The nodal spacing was set at 1 cm as a reasonable value based on expert opinion (Fayer, 2002; Webb, 2002). The cover profiles modeled correlate to figure 3.2 (Subtitle D Cover), figure 3.7 (Capillary Barrier), figure 3.8 (Anisotropic Barrier), and 3.9 (ET Cover).

5.2.2.2 Boundary Conditions

The upper boundary is connected to the atmosphere to allow for infiltration and evaporation. Consequently, the upper boundary conditions are dependent on climatic conditions that were obtained from a weather station located at the test site. The upper boundary condition was set to a maximum infiltration flux rate of 1 cm/hr. Weather files for 1997 were obtained from May 1 through December 31, while those for 2002 were data from January 1 through June 30. All other years contain data from January 1 through December 31 of that year. The UNSAT-H program partitions PET that was calculated from weather data into potential evaporation (PE) and potential transpiration (PT) using a function that was based on the value of the assigned LAI and an equation developed by Ritchie and Burnett (1971) detailed in Chapter 4 (Equation 4.1). The fitting parameters used in the calculation of PET were: a = 0.0, b = 0.52, and c = 0.5, d = 0.1 and e = 2.7 (Fayer 2000).

The lower boundary condition was a unit gradient. With the unit gradient, the calculated drainage flux depends on the hydraulic conductivity of the lower boundary node. The unit gradient corresponds to gravity-induced drainage and is most appropriate when drainage is not impeded. To better represent test conditions, a gravel layer was modeled below the Subtitle D and ET Covers to simulate a seepage face. The seepage face lower boundary was determined to be the best condition to represent a soil profile with a bottom lysimeter (Scanlon et al, in press). The under drain collection system installed below the covers created a capillary barrier. This additional gravel layer was used to simulate that condition. Modeling this condition was not required below the capillary barriers since their bottom layers already consisted of a coarse layer.

5.2.2.3 Vegetation Data

This set of parameters includes the leaf area index (LAI), rooting depth and density, and root growth rate. An average LAI (table 3.3) for the monitoring period was determined for each test cover. These values were consistent with that used with the HELP simulations presented in this chapter. The onset and termination of the growing season for the site was Julian days 75 and 299, respectively, again consistent with the HELP simulations. An average percent bare area (table 3.2) was calculated for each test cover. The maximum rooting depth was assumed to be 100 cm. This value was selected because the grasses present in the area such as Indian rice grass and blue gramma often exceed 100 cm (Foxx et al 1984, Weaver 1920). The rooting depth for each cover was set to the lesser of 100 cm or depth to first sand or gravel layer in the cover profile. The parameters used for the RLD functions (Equation 4.2) were: a = 0.315, b=0.0073, and c = 0.076 (Fayer 2000).

5.2.2.4 Soil Properties

The hydraulic properties of the soils were measured in the laboratory at the soil layers' as-built densities within each cover profile. The saturated hydraulic conductivity of the Subtitle D and C Cover barrier soil layers' were measured in the field using a sealed double ring infiltrometer (ASTM D5093). All other saturated hydraulic conductivities of the soils used in the test cover profiles were obtained using a falling head permeameter (ASTM D5856). The desorption moisture characteristic curves (suction versus moisture content) for the soils were obtained from data using pressure plates and water columns depending on the suction values (Appendix A). This moisture characteristic curve data was then used as input to the RETC code (van Genuchten et al 1991) to compute each soil's van Genuchten parameters (tables 5.7 to 5.10). The

Mualem conductivity function was assumed to describe the unsaturated hydraulic conductivity of the soils. Soil suction values were used to describe the initial soil conditions. The initial suction values used corresponded with the moisture contents measured on May 1, 1997 with the TDR system for each soil layer as determined from each respective layer's moisture characteristic curve (Appendix A). These measured moisture contents are presented in Tables 5.1 through 5.6.

Layer	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	15	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	700.
Barrier Soil	45	1.7 @2.7	0.004426	0.37	0.3587	0.06	0.033	1.36	1000.
Pea Gravel (1)	23	1.65@2.64	15,912.	0.374	0.374	0.017	2.5075	2.47	11.

(1) Modeled to simulate the bottom lysimeter

Table 5.7. Subtitle D Cover: UNSAT-H Input Parameters

Layer	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	30	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	1000.
Sand	15	1.66@2.64	65.52	0.37	0.34	0.026	0.0597	2.81	16.
Pea Gravel	23	1.65@2.64	15,912.	0.374	0.374	0.017	2.5075	2.47	11.
Compacted Soil	45	1.6@2.7	1.43856	0.41	0.3951	0.06	0.0508	1.36	10,000.
Sand	30	1.66@2.64	65.52	0.37	0.34	0.026	0.0597	2.81	16.

Table 5.8. Capillary Barrier: UNSAT-H Input Parameters

Layer	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	30	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	1000.
Compacted Soil	45	1.6@2.7	1.43856	0.41	0.3951	0.06	0.0508	1.36	1000.
Sand	30	1.66@2.64	65.52	0.37	0.34	0.026	0.0597	2.81	16.
Pea Gravel	23	1.65@2.64	15,912.	0.374	0.374	0.017	2.5075	2.47	11.

Table 5.9. Anisotropic Barrier: UNSAT-H Input Parameters

Layer	Thickness (cm)	Dry Density (g/cm3) @Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	30	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	2643.
Compacted Soil	45	1.7@2.7	0.1563	0.41	0.3587	0.06	0.033	1.36	2643.
Pea Gravel (1)	23	1.65@2.64	15,912.	0.374	0.374	0.017	2.5075	2.47	11.

(1) Modeled to simulate the bottom lysimeter

Table 5.10. ET Cover: UNSAT-H Input Parameters

5.3 Results

5.3.1 Water Balance

The combined annual water balance results as well as the simulation variances from the measured values are summarized in tables 5.11 through 5.24. Data for 1997 includes May 1 through December 31, while 2002 includes data for January 1 through June 30. All other years include data from January 1 through December 31.

Landfill Cover	Field Data				
	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	4.42	3.56	NA	-42.00	301.02
GCL Cover	2.60	0.51	0.03	-48.00	311.86
Subtitle C Cover	5.55	0.04	0.00	-54.00	315.41
Capillary Barrier	4.38	0.54	0	-48.00	310.07
Anisotropic Barrier	2.02	0.05	NA	-75.90	340.82
ET Cover	4.12	0.08	NA	-22.50	285.30
UNSAT-H Results					
Subtitle D Cover	17.04	0.61	NA	15.45	244.54
Capillary Barrier	0.13	51.54	NA	19.66	205.81
Anisotropic Barrier	4.00	0.22	NA	77.11	196.10
ET Cover	5.89	0.66	NA	55.55	215.51
HELP Results					
Subtitle D Cover	0.25	25.76	NA	9.39	242.60
GCL Cover	0.25	0.00	0.00	-79.77	357.52
Subtitle C Cover	0.25	0.00	0.00	-62.05	339.80
Capillary Barrier	0.25	34.49	NA	-14.93	258.19
Anisotropic Barrier	0.25	15.66	NA	-71.89	333.98
ET Cover	0.25	4.19	NA	-42.32	315.88

Table 5.11. 1997 Water Balance: As-Built Soil Conditions with Actual Weather Data

Landfill Cover	HELP		UNSAT-H	
	Variance from Measured Data (mm)	Percent Variance from Measured Data	Variance from Measured Data (mm)	Percent Variance from Measured Data
Subtitle D Cover	22.19	>100%	-2.95	-83%
Subtitle C Cover	-0.51	-100%	NA	NA
GCL Cover	-0.04	-98%	NA	NA
Capillary Barrier	33.94	>>100%	51.00	>>100%
Anisotropic Barrier	15.61	>>100%	0.17	>100%
ET Cover	4.11	>>100%	0.58	>100%

Table 5.12. 1997 Percolation: Simulation Variance from Measured

Landfill Cover	Field Data				
	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	18.55	2.48	NA	-10.50	281.45
GCL Cover	20.77	0.19	0.12	-18.00	288.91
Subtitle C Cover	6.93	0.15	0.20	-12.00	296.70
Capillary Barrier	9.91	0.41	NA	-4.50	286.16
Anisotropic Barrier	19.19	0.07	NA	-12.15	284.88
ET Cover	11.28	0.22	NA	-54.00	334.48
UNSAT-H Results					
Subtitle D Cover	4.45	0.10	NA	-8.72	307.90
Capillary Barrier	0.00	21.85	NA	5.59	275.93
Anisotropic Barrier	2.67	2.94	NA	36.18	261.85
ET Cover	3.68	0.10	NA	2.51	297.27
HELP Results					
Subtitle D Cover	0.00	29.70	NA	-11.91	286.29
GCL Cover	0.00	0.00	0.00	-0.34	304.45
Subtitle C Cover	0.00	0.01	0.00	1.34	302.75
Capillary Barrier	0.00	39.67	NA	-15.51	279.93
Anisotropic Barrier	0.00	2.70	NA	-1.48	302.88
ET Cover	0.00	7.10	NA	-10.35	307.34

Table 5.13. 1998 Water Balance (Initial Soil Conditions with Actual Weather Data)

Landfill Cover	HELP		UNSAT-H	
	Variance from Measured Data (mm)	Percent Variance from Measured Data	Variance from Measured Data (mm)	Percent Variance from Measured Data
Subtitle D	27.22	>>100%	-2.38	-96%

Cover				
Subtitle C Cover	-0.19	-100%	NA	NA
GCL Cover	-0.15	-97%	NA	NA
Capillary Barrier	39.26	>>100%	21.44	>>100%
Anisotropic Barrier	2.63	>>100%	2.87	>>100%
ET Cover	6.88	>>100%	-0.22	-54%

Table 5.14. 1998 Percolation: Simulation Variance from Measured

Landfill Cover	**Field Data**				
	Surface Runoff (mm)	**Percolation (mm)**	**Lateral Drainage (mm)**	**Soil Moisture Change (mm)**	**ET (mm)**
Subtitle D Cover	3.33	1.56	NA	-9.00	229.34
GCL Cover	2.21	2.15	0.10	-27.00	247.77
Subtitle C Cover	2.15	0.02	0.00	-57.00	280.06
Capillary Barrier	3.92	0.00	NA	-25.50	246.80
Anisotropic Barrier	0.84	0.14	NA	-18.00	242.25
ET Cover	0.73	0.01	NA	-10.50	234.99
UNSAT-H Results					
Subtitle D Cover	2.59	0.04	NA	-11.95	243.71
Capillary Barrier	0.00	10.61	NA	-25.81	249.19
Anisotropic Barrier	1.37	8.29	NA	-16.88	241.53
ET Cover	2.24	0.04	NA	-21.73	253.66
HELP Results					
Subtitle D Cover	0.00	12.17	NA	0.03	222.14
GCL Cover	0.00	0.01	0.00	32.78	201.80
Subtitle C Cover	0.00	0.02	0.00	34.24	200.34
Capillary Barrier	0.00	34.97	NA	0.45	199.18

Anisotropic Barrier	0.00	2.42	NA	-13.76	245.95
ET Cover	0.00	6.37	NA	-0.90	229.12

Table 5.15. 1999 Water Balance (Initial Soil Conditions with Actual Weather Data)

Landfill Cover	**HELP**		**UNSAT-H**	
	Variance from Measured Data (mm)	**Percent Variance from Measured Data**	**Variance from Measured Data (mm)**	**Percent Variance from Measured Data**
Subtitle D Cover	10.61	>100%	-1.52	-97%
Subtitle C Cover	-2.14	-100%	NA	NA
GCL Cover	0.00	2%	NA	NA
Capillary Barrier	34.97	>>100%	10.61	>>100%
Anisotropic Barrier	2.28	>>100%	8.15	>>100%
ET Cover	6.37	>>100%	0.03	>100%

Table 5.16. 1999 Percolation: Simulation Variance from Measured

Landfill Cover	**Field Data**				
	Surface Runoff (mm)	**Percolation (mm)**	**Lateral Drainage (mm)**	**Soil Moisture Change (mm)**	**ET (mm)**
Subtitle D Cover	0.27	0.00	NA	19.50	280.15
GCL Cover	0.05	0.00	0.00	42.00	257.87
Subtitle C Cover	0.49	0.00	0.00	72.00	227.43
Capillary Barrier	0.97	0.00	NA	46.50	252.45
Anisotropic Barrier	0.15	0.00	NA	37.65	262.12
ET Cover	0.63	0.00	NA	58.50	240.79
UNSAT-H Results					
Subtitle D Cover	5.33	0.02	NA	17.68	289.13
Capillary	2.86	12.41	NA	42.11	254.63

Barrier					
Anisotropic Barrier	3.94	12.02	NA	28.48	267.66
ET Cover	6.62	0.02	NA	34.90	270.57
HELP Results					
Subtitle D Cover	0.00	18.51	NA	3.87	290.03
GCL Cover	0.00	0.02	0.00	57.56	254.82
Subtitle C Cover	0.00	0.04	0.00	53.58	258.77
Capillary Barrier	0.00	47.11	NA	5.55	259.75
Anisotropic Barrier	0.00	1.26	NA	74.66	236.46
ET Cover	0.00	6.51	NA	47.01	258.88

Table 5.17. 2000 Water Balance (Initial Soil Conditions with Actual Weather Data)

Landfill Cover	**HELP**		**UNSAT-H**	
	Variance from Measured Data (mm)	**Percent Variance from Measured Data**	**Variance from Measured Data (mm)**	**Percent Variance from Measured Data**
Subtitle D Cover	18.51	>>100%	-0.02	Err[1]
Subtitle C Cover	0.02	>>100%	NA	NA
GCL Cover	0.04	>>100%	NA	NA
Capillary Barrier	47.11	>>100%	12.41	>>100%
Anisotropic Barrier	1.26	>>100%	12.02	>>100%
ET Cover	6.51	>>100%	-0.02	Err[1]

[1] not divisible by zero

Table 5.18. 2000 Percolation: Simulation Variance from Measured

Landfill Cover	**Field Data**				
	Surface Runoff (mm)	**Percolation (mm)**	**Lateral Drainage (mm)**	**Soil Moisture Change (mm)**	**ET (mm)**

Subtitle D Cover	0.75	0.00	NA	-1.80	255.07
GCL Cover	0.15	0.02	0.00	-45.00	298.85
Subtitle C Cover	0.55	0.00	0.00	-60.00	313.46
Capillary Barrier	0.88	0.00	NA	-46.50	299.63
Anisotropic Barrier	0.12	0.00	NA	-27.00	280.89
ET Cover	0.38	0.00	NA	-52.50	306.13
UNSAT-H Results					
Subtitle D Cover	1.55	0.01	NA	-11.07	266.09
Capillary Barrier	0.00	14.17	NA	-32.63	274.90
Anisotropic Barrier	1.31	7.21	NA	-20.03	268.04
ET Cover	3.08	0.01	NA	-31.50	285.22
HELP Results					
Subtitle D Cover	0.00	2.28	NA	-2.47	257.29
GCL Cover	0.00	0.04	0.01	42.56	214.48
Subtitle C Cover	0.00	0.07	0.01	45.22	211.79
Capillary Barrier	0.00	49.88	NA	-4.99	212.22
Anisotropic Barrier	0.00	17.66	NA	-52.01	291.45
ET Cover	0.00	8.59	NA	-26.28	274.80

Table 5.19. 2001 Water Balance (Initial Soil Conditions with Actual Weather Data)

Landfill Cover	**HELP**		**UNSAT-H**	
	Variance from Measured Data (mm)	**Percent Variance from Measured Data**	**Variance from Measured Data (mm)**	**Percent Variance from Measured Data**
Subtitle D Cover	2.28	>>100%	-0.01	Err [(1)]
Subtitle C Cover	0.02	101%	NA	NA
GCL Cover	0.07	NA	NA	NA

Capillary Barrier	49.88	>>100%	14.17	>>100%
Anisotropic Barrier	17.66	>>100%	7.21	>>100%
ET Cover	8.58	>>100%	-0.01	Err[1]

[1] not divisible by zero

Table 5.20. 2001 Percolation: Simulation Variance from Measured

Landfill Cover	**Field Data**				
	Surface Runoff (mm)	**Percolation (mm)**	**Lateral Drainage (mm)**	**Soil Moisture Change (mm)**	**ET (mm)**
Subtitle D Cover	0.00	0.74	NA	-7.50	151.08
GCL Cover	0.00	0.00	0.00	12.00	132.32
Subtitle C Cover	0.04	0.00	0.00	12.00	132.28
Capillary Barrier	0.04	0.00	NA	63.00	81.28
Anisotropic Barrier	0.01	0.00	NA	10.65	133.66
ET Cover	0.03	0.00	NA	34.50	109.79
UNSAT-H Results					
Subtitle D Cover	26.18	0.00	NA	-4.37	116.05
Capillary Barrier	0.00	39.50	NA	-7.89	106.02
Anisotropic Barrier	0.92	54.07	NA	-12.41	95.26
ET Cover	1.18	0.00	NA	41.14	95.61
HELP Results					
Subtitle D Cover	0.00	0.00	NA	48.82	39.98
GCL Cover	0.00	0.03	0.01	60.09	28.68
Subtitle C Cover	0.00	0.05	0.01	60.55	28.20
Capillary Barrier	0.00	13.28	NA	47.65	27.87
Anisotropic Barrier	0.00	0.84	NA	27.82	60.14
ET Cover	0.00	3.73	NA	29.77	55.31

Table 5.21. 2002 Water Balance (Initial Soil Conditions with Actual Weather Data)

Landfill Cover	HELP		UNSAT-H	
	Variance from Measured Data (mm)	Percent Variance from Measured Data	Variance from Measured Data (mm)	Percent Variance from Measured Data
Subtitle D Cover	-0.74	-100%	-0.74	-100%
Subtitle C Cover	-0.05	-100%	NA	NA
GCL Cover	-0.03	-100%	NA	NA
Capillary Barrier	13.28	Err [1]	39.50	Err[1]
Anisotropic Barrier	0.84	Err[1]	0.00	0
ET Cover	3.73	Err[1]	0.00	0

[1] not divisible by zero

Table 5.22. 2002 Percolation: Simulation Variance from Measured

Landfill Cover	Field Data				
	Surface Runoff (mm)	Percolation (mm)	Lateral Drainage (mm)	Soil Moisture Change (mm)	ET (mm)
Subtitle D Cover	27.32	8.34	NA	-51.30	1498.10
GCL Cover	25.77	2.87	0.25	-84.00	1537.58
Subtitle C Cover	15.71	0.21	0.20	-99.00	1565.34
Capillary Barrier	20.11	0.95	NA	-15.00	1476.40
Anisotropic Barrier	22.32	0.26	NA	-84.75	1544.63
ET Cover	17.17	0.30	NA	-46.50	1511.49
UNSAT-H Results					
Subtitle D Cover	57.13	0.77	NA	-2.98	1467.40
Capillary Barrier	2.99	150.08	NA	1.03	1366.48
Anisotropic Barrier	14.21	84.75	NA	92.45	1330.44

ET Cover	22.69	0.84	NA	80.87	1417.45
HELP Results					
Subtitle D Cover	0.25	88.42	NA	47.72	1338.33
GCL Cover	0.25	0.11	0.02	112.88	1361.75
Subtitle C Cover	0.25	0.18	0.02	132.88	1341.65
Capillary Barrier	0.25	219.41	NA	18.21	1237.14
Anisotropic Barrier	0.25	40.54	NA	-36.67	1470.86
ET Cover	0.25	36.48	NA	-3.08	1441.33

Table 5.23. Cumulative Water Balance (Initial Soil Conditions with Actual Weather Data)

Landfill Cover	**HELP**		**UNSAT-H**	
	Variance from Measured Data (mm)	**Percent Variance from Measured Data**	**Variance from Measured Data (mm)**	**Percent Variance from Measured Data**
Subtitle D Cover	80.08	>100%	-7.57	-91%
Subtitle C Cover	-2.76	-96%	-2.87	-100%
GCL Cover	-0.03	-14%	-0.21	-100%
Capillary Barrier	218.45	>>100%	149.13	>>100%
Anisotropic Barrier	40.28	>>100%	84.49	>>100%
ET Cover	36.18	>>100%	0.54	>100%

Table 5.24. Cumulative Percolation: Simulation Variance from Measured (+ over predicted, - under predicted)

5.3.2 Percolation

Measured percolation was compared with that estimated with the computer simulations to assess each program's accuracy (Tables 5.11 through 5.24). The cumulative results of the field measured percolation as well as the predicted percolation values from the HELP and UNSAT-H simulations are presented in table 5.23 and figure 5.1.

The predicted cumulative percolation with both HELP and UNSAT-H for both capillary barrier profiles (Capillary Barrier and Anisotropic Barrier) was substantially higher than the field measured amounts (Tables 5.24 and Figure 5.1). The HELP predicted cumulative percolation amount for the Subtitle D and ET Covers was much higher than the field measured quantity, while UNSAT-H predicted the cumulative percolation for the Subtitle D and ET Covers to be less than the field measured quantity. HELP and UNSAT-H each under predicted the cumulative percolation for the two covers with geomembranes in their profile (Subtitle C and GCL Covers).

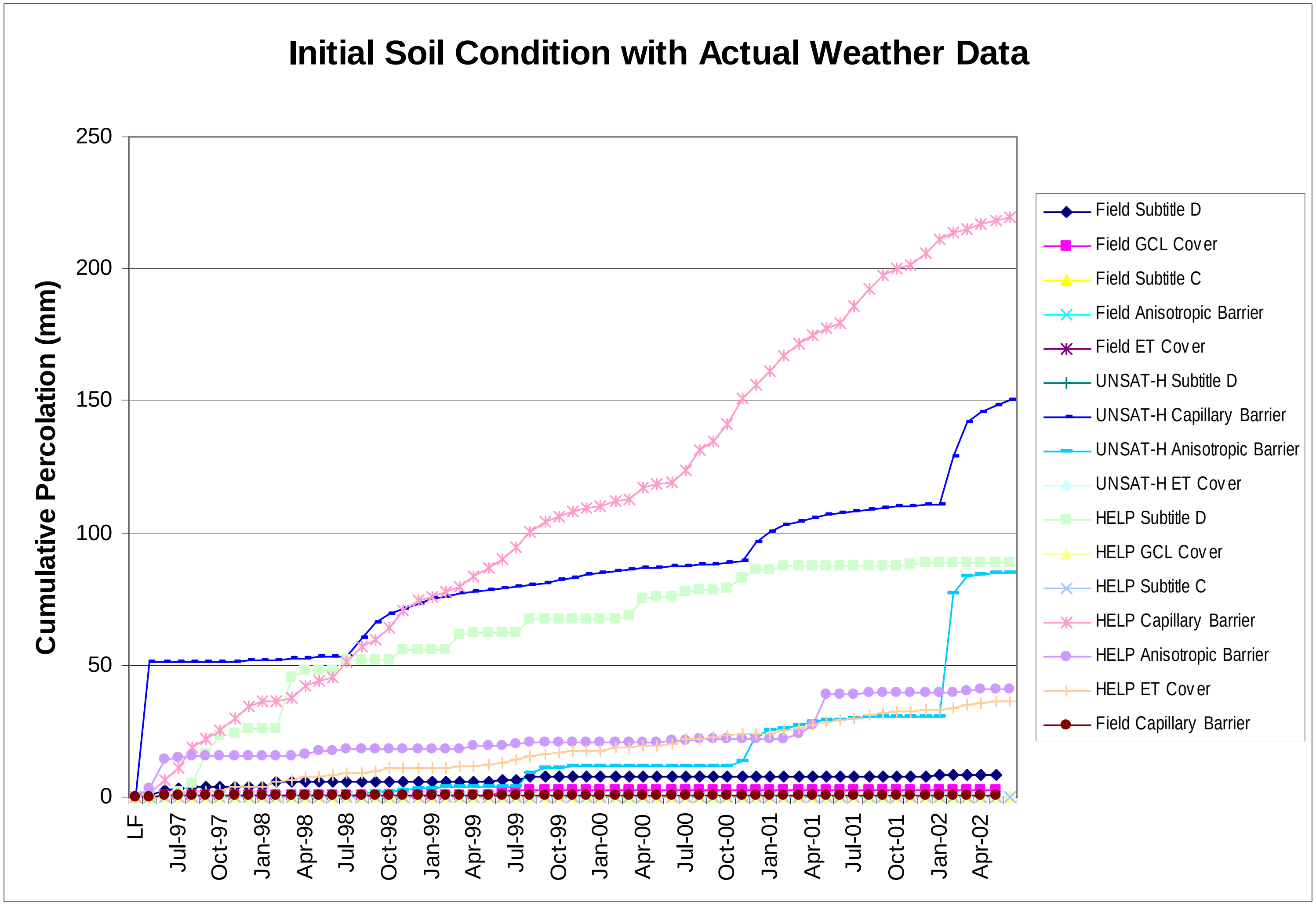


Figure 5.1a. Cumulative Percolation (Scaled to Show all Totals on Same Chart)

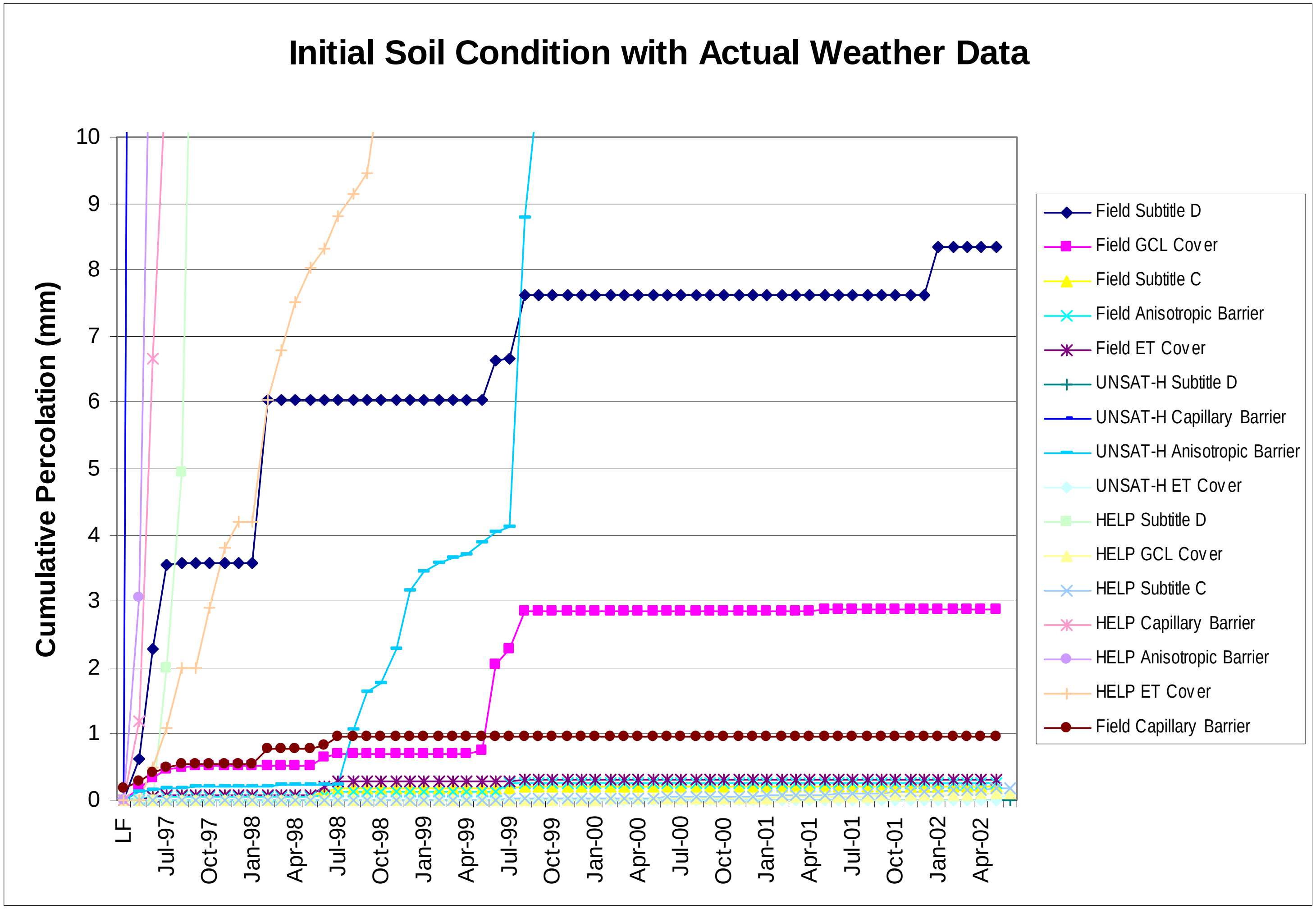


Figure 5.1b. Cumulative Percolation (Expanded Scale to Show Cumulative Totals less than 10 mm)

5.3.2.1 Percolation: Subtitle D Cover

The measured volume of percolation for the Subtitle D Cover was the highest of the six test covers over the monitoring period. The HELP program significantly overestimated the percolation while the UNSAT-H program underestimated it. The profile's HELP model geometry consisted of the top 15 cm being a vertical percolation layer. This layer allowed for the vertical movement of unsaturated water driven solely by gravity. The vertical percolation layer also allowed for water storage between the assigned wilting point and field capacity of the soil. The bottom 45 cm was a barrier layer assumed to be at constant full saturation. The barrier layer does not allow for water removal via ET. The HELP program allowed for water removal from the cover profile only from the 15 cm thick topsoil layer by ET. There was more infiltration into this layer from precipitation than water removed by ET. Consequently, a head formed on the barrier layer that predictably produced percolation after each significant precipitation event or series of events as shown in figure 5.2.

The UNSAT-H program predicted a cumulative percolation of only 0.77 mm through the cover compared to the 8.34 mm measured. The program allowed for water storage within the entire cover profile as well as removal of water via transpiration from the entire profile. In addition, the program allowed for upward fluxes due to matric potential gradients induced by surface evaporation.

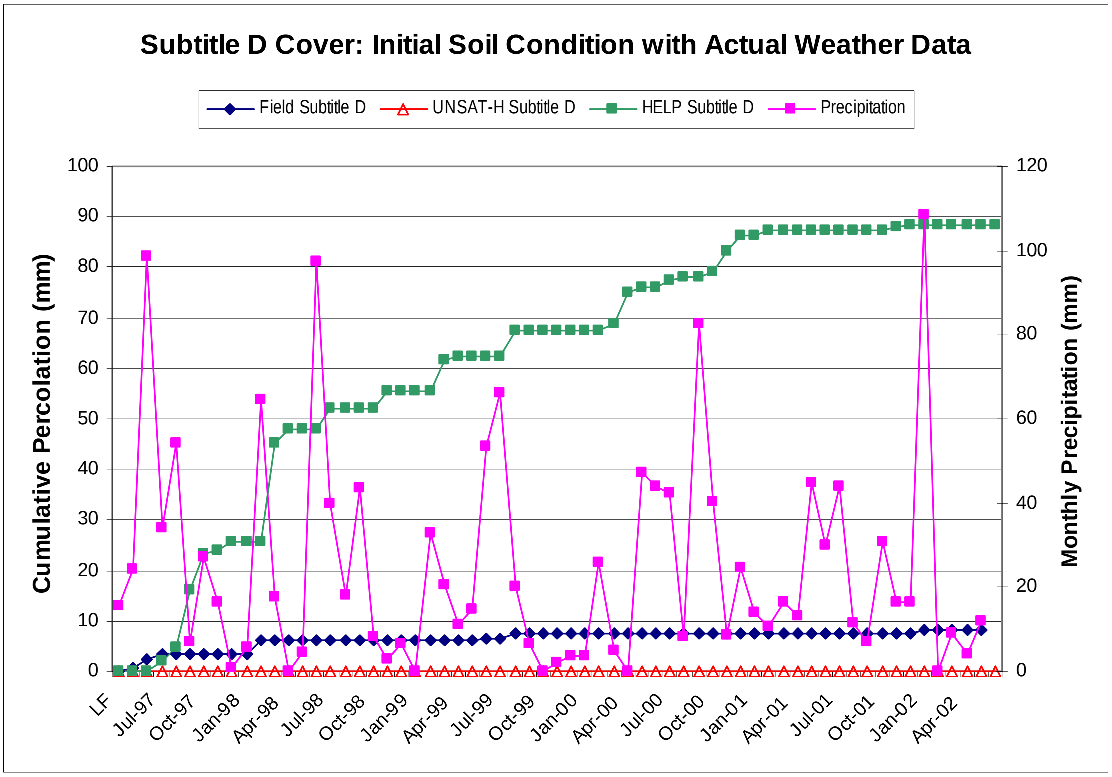


Figure 5.2. Percolation, Subtitle D Cover

5.3.2.2 Percolation: Subtitle C Cover

This was one of the best performing covers in the field. The profile was modeled using HELP with a 60 cm vertical percolation top layer that allowed for water removal via ET and unsaturated vertical downward flux of water driven by gravity. The layer also allowed for water storage. The 30 cm middle sand layer was modeled as a lateral drainage layer that treated the downward unsaturated flux similar to the topsoil layer but also allowed for lateral saturated drainage. Lateral drainage was predicted to be zero for all years. The composite barrier layer was modeled as a geomembrane liner over a barrier soil layer in perfect contact. The geomembrane was modeled with 8 defects in it

(Table 5.2). The barrier soil layer was assumed to be at constant full saturation. The calculated "effective hydraulic conductivity" for this geomembrane was 4E-13 cm/sec.

The measured and predicted percolations were both very small. The measured cumulative percolation was just over 0.2 mm for the entire monitoring period. The HELP program over the entire monitoring period appeared to be very accurate in simulating the cover's low flux rate predicting a total of about 0.18 mm. Although the cumulative percolation values were very close, the measured quantities came in three events while the HELP estimated flux was a gradual accumulation (figure 5.3). The three field events followed large summer thunderstorm events. This cover profile was not modeled with UNSAT-H because of the difficulties associated with modeling the geomembrane.

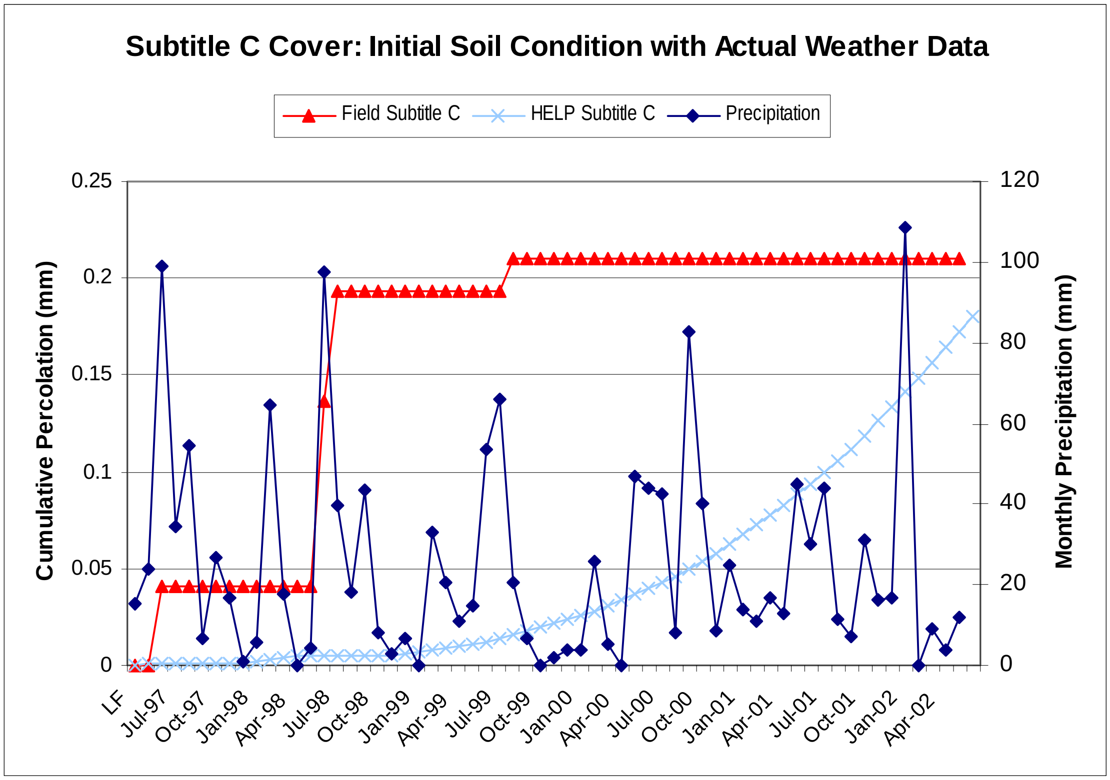


Figure 5.3. Percolation, Subtitle C Cover

5.3.2.3 Percolation: GCL Cover

The GCL cover was the only cover that showed an increase in the measured annual flux rate from 1997 through 1999. This increase was believed to be the result of degradation in the GCL as discussed in chapter 3. As expected, the HELP program predicted a very low flux rate as a result of the calculated "effective hydraulic conductivity" for the geomembrane and the low saturated hydraulic conductivity value used as the input parameter for the GCL. Degradation of the GCL is not accounted for in the program.

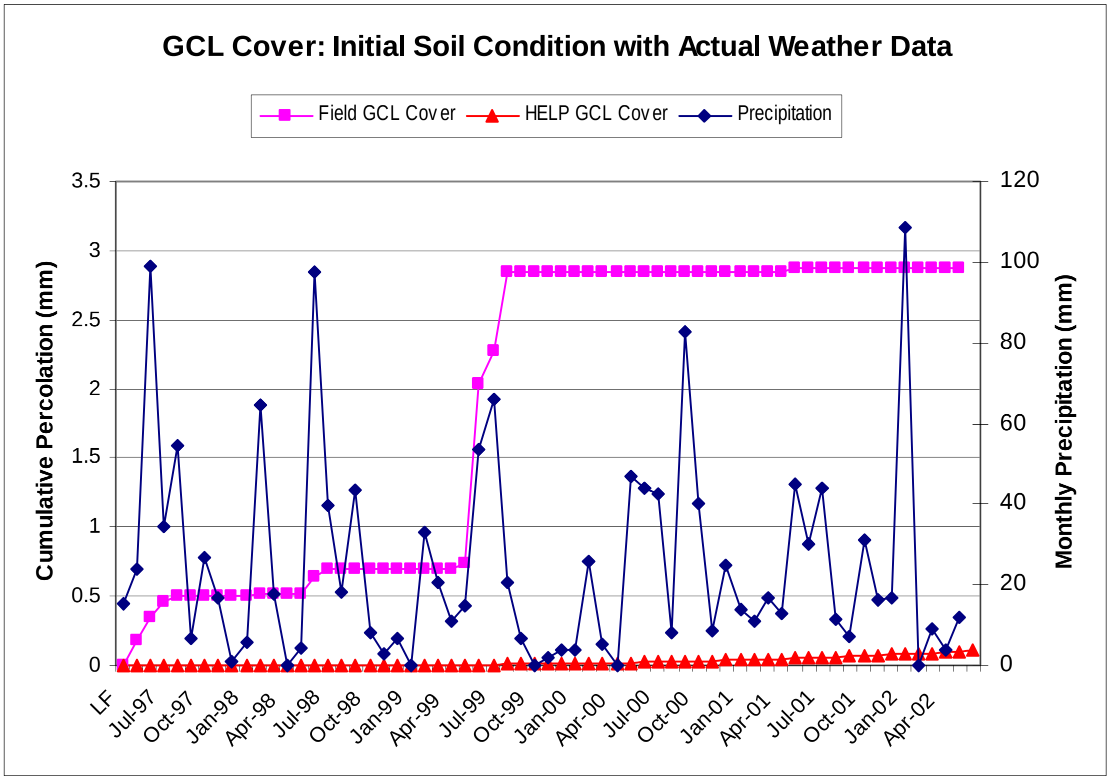


Figure 5.4. Percolation, GCL Cover

5.3.2.4 Percolation: Capillary Barrier

The Capillary Barrier had just less than 1 mm of total percolation measured in the field over the entire monitoring period. Both HELP and UNSAT-H drastically overestimated the percolation through this cover. It was expected that HELP would overestimate percolation due to its unsatisfactory handling of unsaturated flow (in particular, the calculation of hydraulic gradient does not include the soil's matric potential). The HELP program only allowed for water removal from the top 30 cm due to ET. Transpiration was low due to the low plant cover (LAI = 0.5). Consequently, percolation was predicted to result after virtually all precipitation events. The UNSAT-

H program surprisingly greatly overestimated the percolation by 2.5 orders of magnitude. The large percolation events were predicted after large precipitation events predominantly outside of the plant-growing season. The growing season is generally mid-March through the end of October. The low transpiration capacity due to the LAI = 0.5 and only a little over 5% plant cover did not allow for the topsoil layer to dry between storms thus allowing moisture to build-up and eventually pass through the cover profile even during the growing season.

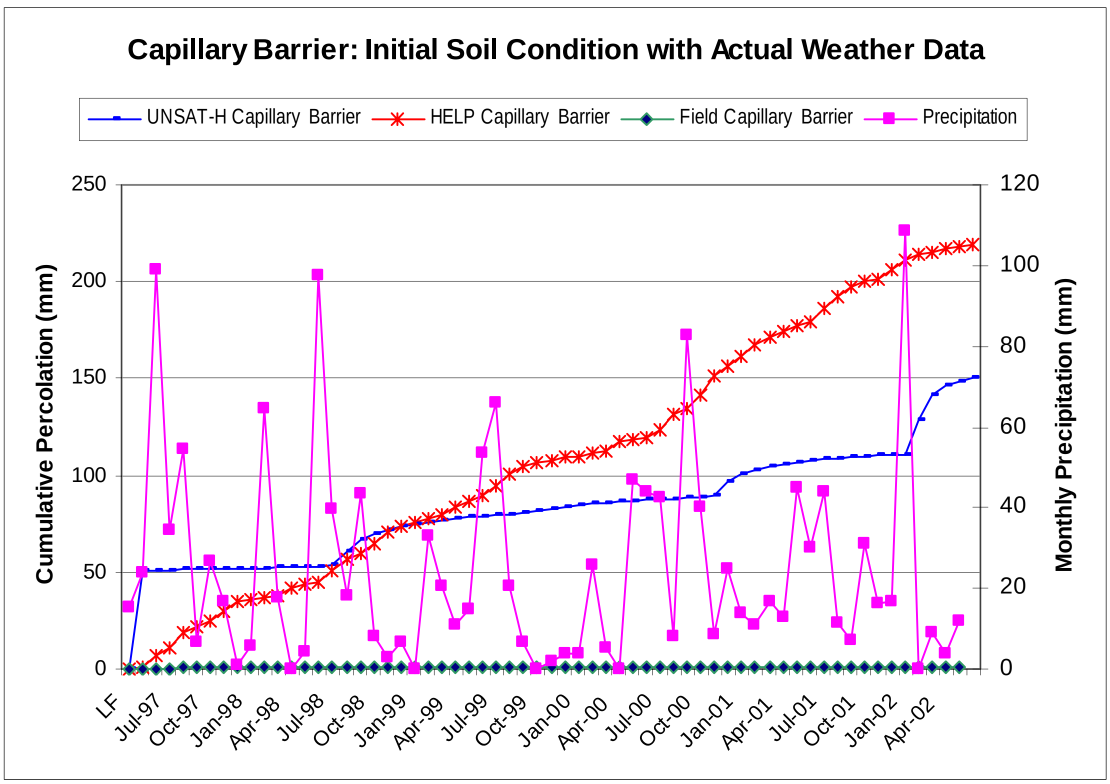


Figure 5.5. Percolation, Capillary Barrier

5.3.2.5 Percolation: Anisotropic Barrier

The Anisotropic Barrier was one of the best performing covers in the field having only 0.26 mm of percolation recorded over the monitoring period (Figure 5.6). As expected the HELP program over predicted percolation. High percolation rates were also predicted with the UNSAT-H program. In fact, this profile was the only one modeled using UNSAT-H that had a higher percolation rate predicted by it than that with the HELP program. Two extremely large percolation events were predicted after large precipitation events outside of the growing season. The largest predicted percolation event followed a spring snowstorm in February 2002 where there was zero percolation measured in the field.

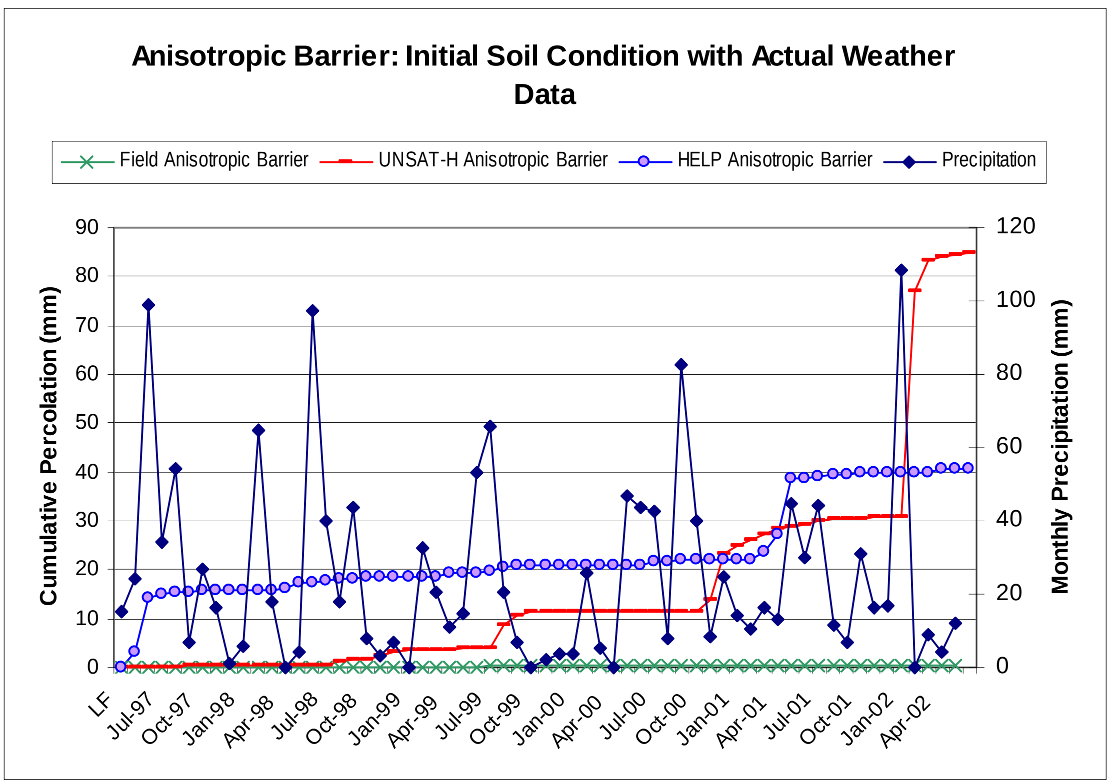


Figure 5.6. Percolation, Anisotropic Barrier

5.3.2.6 Percolation: ET Cover

The ET Cover was one of the best performing cover profiles yielding 0.30 mm of measured percolation over the entire monitoring period. The ET Cover was modeled using HELP with two layers, both vertical percolation layers. The 15 cm topsoil layer was loosely placed soil similar to that used for the compacted 90 cm soil layer. Although they were the same soil, they had different soil parameters due to the different installation densities. In chapter 4, this cover profile was modeled as a 15 cm vertical percolation layer over a 90 cm barrier soil layer. That model geometry yielded a substantial flux rate in large part because moisture removal from the profile was allowed via ET only from the upper 15 cm. This model geometry allowed ET removal of moisture from the entire profile as well as allowing storage capacity within the entire profile as opposed to the profile with a barrier soil layer that assumed constant saturation and no storage capacity for infiltrated moisture. This geometry, however, also yielded large amounts of percolation that occurred after every measurable precipitation event.

The cumulative percolation predicted with UNSAT-H was 0.84 mm; this was more than the amount measured (0.3 mm). The only event that produced percolation through the ET Cover with the UNSAT-H predictions was the late winter snowstorm in February 2002. This storm occurred outside of the model's assigned growing season and consequently transpiration was not operative.

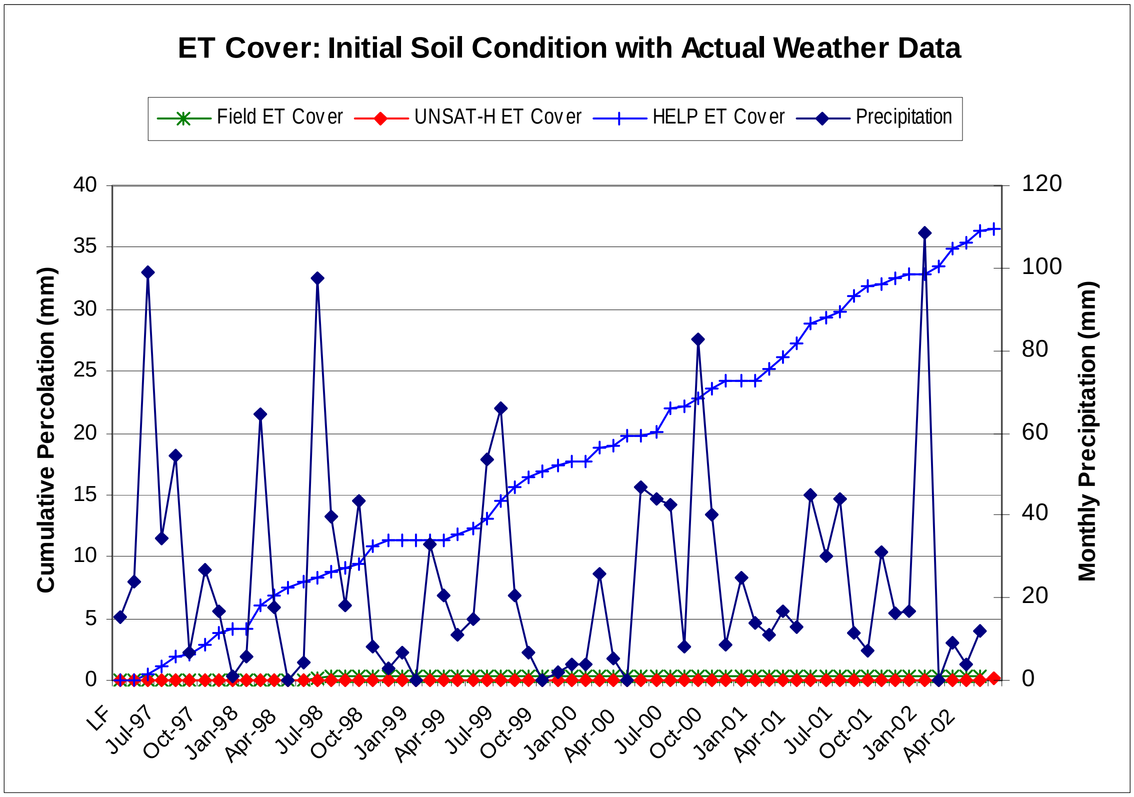


Figure 5.7. Percolation, ET Cover

5.4 Discussion

The weather and vegetation characteristics used as input parameters for the simulations were measured over the same period of time as the water balance measurements were obtained on the test covers. The soil input parameters were measured at the initial or as-built condition of the covers. Weather parameters were measured at the site. Surface vegetation characteristics were measured for each cover at the site and averaged over the monitoring period. Soil samples used for laboratory testing were taken from actual soils installed in the various layers of the covers installed. The soils were carefully tested in the laboratory for their unsaturated soil properties and saturated hydraulic conductivities at the “as-built” densities for the various soil layers (Anderson 2001). The barrier soil layers in the Subtitle D and C Covers were field-tested using a sealed double ring infiltrometer to determine their saturated hydraulic conductivity.

Most of Albuquerque’s precipitation comes in the form of summer thunderstorms that produce surface runoff (chapter 3) because they are generally short in duration with high intensities. The SCS Runoff method used in HELP does not take into account a storm’s intensity nor does it consider its duration. Consequently, HELP is not accurate at predicting surface runoff and consistently under predicts it (section 5.3.1). Runoff was calculated as zero in most years. Runoff is not directly calculated with UNSAT-H but rather indirectly calculated as the precipitation rate that exceeds the maximum soil infiltration rate. It does not account for surface condition or slope. Fayer (2000) states that overland flow is a rare event at the Hanford site where the program was developed. Surface runoff predictions resulting from the UNSAT-H simulations were erratic primarily due to its indirect calculation. In some cases they were over predicted, others were under predicted, while still others were coincidentally close (section 5.3.1).

Lateral drainage was calculated through the drainage layer only by the HELP program. UNSAT-H is a one-dimensional program and therefore cannot calculate lateral drainage. As seen in chapter 3, saturation in lateral drainage layers never occurred. Results from the HELP simulations were generally good for lateral drainage layers predicting no lateral drainage while only trace amounts (0.03 mm) were actually measured.

The HELP program allowed for water removal via ET only from a vertical percolation layer. Consequently, any water that had migrated below a vertical percolation layer eventually resulted in the model predicting its outcome as lateral drainage or in these simulations as percolation. UNSAT-H on the other hand, allowed for the removal of water via transpiration from all layers containing roots combined with surface evaporation thus increasing matric potential gradients near the surface producing an upward flux. When comparing the variances of the predicted values to the measured values for the water balance variables for the different covers (section 5.3.1), ET was relatively well predicted. However, small variances in values such as ET, which was the largest calculated water balance variable (section 5.3.1) or even surface runoff can translate to the under or over prediction of the cover's flux rate by several orders of magnitude

The results are mixed at best for the accuracy of the HELP or UNSAT-H programs at predicting flux through each cover profile. The HELP program grossly over estimated percolation in all covers that did not contain a geomembrane. It appeared to be relatively accurate in predicting the performance of the Subtitle C Cover. Flow through this cover is primarily a function of the defects assigned to the geomembrane in the HELP program as well as the number and size of defects in the field (Bonaparte et al 1989). The simulation results for the GCL cover were less than that measured in the field. The transmissivity of a given soil layer is defined as the hydraulic conductivity of that layer multiplied by its thickness. Transmissivity appeared to be critical for a composite barrier layer to produce very low flux rates if degradation exists. In other words, percolation is more likely from a composite barrier layer comprised of a geomembrane and thin (5 mm) GCL than one comprised of a geomembrane and much thicker (60cm) compacted soil when degradation exists in the GCL or compacted soil, respectively. The HELP program does not consider degradation of the GCL nor of the geomembrane.

The UNSAT-H simulation of the ET Cover produced a relatively accurate prediction of cumulative percolation through this cover. This simulation predicted 0.84 mm while 0.3 mm was measured in the field. All other UNSAT-H simulations produced very large variances compared to the field fluxes. UNSAT-H predicted 0.77 mm of percolation through the Subtitle D Cover while it produced the most percolation in the field while significantly over predicting flux through both capillary barriers. In analyzing the difference in results between the Subtitle D and ET Covers (both are soil covers of varied depths), the van Genuchten parameters were about the same and did not appear to have much role in the difference in the calculated fluxes. The only significant difference in input parameters was that the saturated hydraulic conductivity value used was much lower in the compacted soil layer of the Subtitle D Cover than the ET Cover (tables 5.7 and 5.10). The barrier layer saturated hydraulic conductivity value was measured in the field with a sealed double ring infiltrometer while the value for the ET Cover soil was measured in the laboratory with a falling head permeameter. The UNSAT-H program is very sensitive to this parameter since the unsaturated hydraulic conductivity is a scalar product of the saturated hydraulic conductivity. The simulations for the Capillary Barrier and Anisotropic Barrier resulted in large over-predictions of percolation through the covers. The Capillary Barrier was modeled where roots penetrated only the upper topsoil layer (30 cm). Consequently, removal of moisture via transpiration was only possible from this layer. This fact combined with the small LAI and percent plant cover led to little water removal via transpiration. This topsoil layer was relatively thin and had limited water storage capacity as a result. Large amounts of percolation were predicted after each precipitation event that exceeded 80 mm. The total water holding capacity for this topsoil layer was only 210 mm. The water holding capacity is an approximate term, defined as the soil storage capacity (moisture content associated with the soil's field capacity less that of the wilting point) multiplied by the layer thickness (Hillel 1998).

The Anisotropic Barrier was the only cover that had more percolation calculated with the UNSAT-H program than the HELP program. This cover had a thicker fine soil layer than the entire Subtitle D Cover and thus had more total water storage capacity (Anisotropic Barrier had 6.6 cm of capacity while the Subtitle D Cover had 5.1 cm). The unsaturated soil properties were similar (tables 5.7 and 5.9), the vegetation characteristic were similar (Subtitle D Cover had a LAI of 1.5 while the Anisotropic Barrier had a 1.4 with the percent bare almost identical at just over 89%), transpiration was allowed from a rooting depth of 60 cm for Subtitle D Cover to 75 cm for the Anisotropic Barrier; the only significant difference was the saturated hydraulic conductivity of the compacted soil between the two cover profiles. The saturated hydraulic conductivity in the compacted soil layer of the Subtitle D Cover was 0.004426 cm/hour while that of the Anisotropic barrier was 1.43856 cm/hour. This difference in saturated hydraulic conductivity apparently accounts for the significant difference in percolation predictions. The UNSAT-H results are highly sensitive to this value.

For the aforementioned reasons and lack of accuracy (very large variances), it is concluded that the HELP program was not an effective tool to predict the water balance in a landfill cover profile. It appeared to be relatively accurate only for the prediction of flux through a geomembrane where the number of defects in the geomembrane controls the flow through that cover profile in the field and in the model. In reality however, it is not necessarily practical to assume the size and number of defects are known. The UNSAT-H program better predicted the movement of water within a cover profile's soil layers allowing for matric and gravitational potential gradients to drive flux up and/or down. However, it was very dependent on the input parameters used as seen in the difference in flux rate prediction for covers with very low saturated hydraulic conductivities versus covers with higher values. As shown, the UNSAT-H program was very sensitive to the soil's saturated hydraulic conductivity, yet this value can change many orders of magnitude in just a couple of years. A study funded by the Department of Energy of a closed Uranium Mill Tailings Remedial Action (UMTRA) site at Burrell, PA (Waugh et al, 1999) showed that the hydraulic conductivity in a compacted soil layer changed up to three orders of magnitude in a matter of a few years due to phenomena such as root penetration, wet/dry cycles, and earthworm intrusion. Because there is no way to accurately predict changes in material properties over time, UNSAT-H results based on a single set of parameters is deemed to be unreliable to quantify the performance of a landfill cover for a given design life.

Even with the most accurate of input parameters, neither program accounts for preferential flow, which was shown in chapter 3 to likely be a significant contributor to total percolation measured in the field. These programs can be used to give a design engineer an idea of how a cover might perform in the field and can be used to compare between designs, but they cannot be used to accurately predict percolation.

Chapter 6. Water Balance Simulations with Field Measured Soil Hydraulic Properties

6.1 Overview

Chapter 5 compared field measured water balance data from the landfill profiles with computer simulations of these covers using soil properties based on initial (as-built) conditions of the covers. Soil hydraulic properties are conventionally thought to be constant in time. Many studies however, have shown them to be dynamic and evolving (Lin and Benson 2000, Waugh et al 1999, James et al 1997, Melchoir 1997, Benson et al 1995, Suter et al 1993, Hakonson et al 1992). Soil hydraulic properties frequently exhibit variation over time because of soil disturbance, shrink-swell phenomena of fine-textured soil, the effect of particle dispersion and soil crusting, and changes in the concentration and ionic composition of the soil solution (van Genuchten and Simunek, 1995).

An investigation of a final cover on a Uranium Mill Tailings Disposal Site (Waugh and Smith 1997) reported that the clay barrier layer's hydraulic conductivity increased by three orders of magnitude from its as-built condition of $1.4E10^{-7}$ cm/sec in 1987 to $1.2E10^{-4}$ cm/sec in 1996. The study noted that root intrusion, insect and earthworm intrusion, density changes, and desiccation all contributed to increase the saturated hydraulic conductivity of the clay barrier layer. As the ecological status of the cover changes, so will performance factors such as water infiltration, water retention, ET, soil erosion, gas diffusion, and biointrusion.

Because some changes in soil hydraulic properties should be expected, and these changes will undoubtedly affect the water movement within the covers, a field study was conducted to evaluate soil properties after dynamic ecosystem changes have altered the hydraulic properties of the soil profiles. Furthermore, these new data were then used as input parameters with HELP and UNSAT-H to determine whether this data set would produce results that better replicated field observed data.

The soil parameters used in chapter 5 that were measured immediately after construction of the test covers in 1995 and 1996 will herein be referred to as the initial condition of the landfill covers' soil. The soil parameters measured with the tension infiltrometer during the summer of 2002 will herein be referred to as the final condition of the landfill covers' soil. It is assumed here that the differences in the initial and final properties are largely the consequence of soil structure changes in response to dynamic ecological factors. However, it is recognized that the differences between the two soil hydraulic properties data sets could be due in part to other factors, notably the different experimental methods used to obtain the values (Dorsey et al, 1990).

6.2 Tension Infiltrometer

Tension infiltrometers have been suggested as useful tools to measure the hydraulic properties of soil in the field in an undisturbed state (Perroux and White, 1988; Ankeny et al., 1991; Reynolds and Elrick, 1991; Logsdon et al., 1993). In addition, Everts and

Kanwar (1993) suggest that the tension infiltrometer can be a useful tool for quantifying macropore effects on infiltration in the field. Water held under tension infiltrates into a dry soil through a highly permeable nylon membrane. The time dependent infiltration rate is used to calculate unsaturated hydraulic conductivities and related hydraulic properties.

6.3 Field Hydraulic Measurements

Hydraulic measurements on the upper fine soil layers of the landfill cover test plots were made during the summer of 2002 using a tension infiltrometer (Figure 6.1). Field measurements on the Subtitle C Cover barrier soil layer were not made because it was buried below a geomembrane, and it was not possible to remove a portion of the geomembrane without it adversely affecting the ongoing demonstration.

Figure 6.1. Tension Infiltrometer

Three different tensions (generally, one less than 100 mm, one between 100 to 200 mm, and one greater than 200 mm) were utilized for each measurement location. Soil density (ASTM D2922-91) and moisture measurements (ASTM D3017-88) were made prior to and after each tension infiltrometer measurement (figure 6.2). The results were then used to obtain van Genuchten parameters (saturated moisture content, residual moisture content, and moisture characteristic curve fitting parameters: α and n) and saturated hydraulic conductivity values using the DISC software package (Simunek et al, 2000).

DISC is a computer software package used for analyzing tension disc infiltrometer data by parameter estimation. The software package consists of the simplified HYDRUS2 computer program (DISCTENS), and the interactive graphics-based user interface (DISC). The DISCTENS program numerically solves the Richards' equation for saturated-unsaturated water flow. Flow is assumed to occur in a three-dimensional region exhibiting radial symmetry about the vertical axis. The DISCTENS code includes a Marquardt-Levenberg type parameter optimization algorithm for inverse estimation of soil hydraulic data from measured transient cumulative infiltration data. The governing flow and transport equations are solved numerically using Galerkin-type linear finite element schemes. The transport region was discretized automatically by the code into triangular elements based on the pregenerated files that were scaled to the actual geometry as given by the tension disc radius.

Figure 6.2. Density/Moisture Measurements

DISC required initial estimates of maximum and minimum values for the parameters to be solved for. DISC allowed for solution of each parameter to be optimized or its value could be fixed. The tension infiltrometer testing procedure yielded results based on soil sorption or wetting. Primarily due to air entrapment, hysteresis will produce a lower saturated moisture content for a given soil using this method. Consequently, the saturated moisture content for the DISC solution process was fixed at 90% of the value obtained in the laboratory determined through desorption (Rogowski 1971). All other variables were optimized in the solution process.

Moisture characteristic curves from the tension infiltrometer field measurements produced through the DISC software solutions are shown in Appendix B. The soil hydraulic parameters obtained from the DISC solution of the tension infiltrometer measurements are presented in Table 6.1. Measurements were made on each cover for each fine soil layer except for the compacted barrier soil layer of the Subtitle C Cover.

6.4 UNSAT-H and HELP Simulations

These soil data were used as input parameters for UNSAT-H and HELP simulations. The UNSAT-H input parameters included the van Genuchten unsaturated soil parameters and saturated hydraulic conductivity along with initial suction values. These initial suction values corresponded to the initial moisture contents based on the moisture characteristic curves presented in Appendix B. These initial moisture contents were those measured during construction quality control activities. Wilting point and field capacity moisture contents used as input parameters for HELP simulations are also included in Table 6.1. These values were those associated with suction values of 330 cm (field capacity) and 15,000 cm (wilting point) (Appendix B). All other input parameters used in this series of simulations were the same as those used for simulations in chapter 5 including the modeled gravel layers below the Subtitle D and ET Covers to simulate their drainage lysimeters. For direct comparison of the soil hydraulic properties presented in Table 6.1 used for simulations in this chapter to represent the final soil conditions versus those used for the final soil condition simulations, refer to Tables 5.1 through 5.6.

Cover, Soil Layer	van Genuchten Parameters				K_{sat} (cm/sec)	Initial Water Content (vol/vol)	Initial Suction (cm)	Wilting Point (vol/vol)	Field Capacity (vol/vol)
	θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n					
Subtitle D Cover, Topsoil	0.3895	0.04	0.1144	1.4791	9.08E-4	0.14[1]	140	0.04	0.10
Subtitle D Cover, Barrier	0.323	0.065	0.03158	1.3481	1.2E-5	0.14[1]	1200	0.08	0.18
Subtitle C Cover, Topsoil	0.3895	0.0552	0.10597	1.4345	1.15E-3	0.14[1]	1190	0.06	0.13
GCL Cover, Topsoil	0.3895	0.0545	0.1056	1.4467	1.17E-3	0.14[1]	1000	0.06	0.13
Capillary Barrier, Topsoil	0.3895	0.05519	0.106	1.4345	1.15E-3	0.10[2]	1000	0.06	0.13
Capillary Barrier, Compacted Soil	0.3506	0.055	0.04909	1.6823	5.15E-4	0.10[2]	300	0.06	0.10
Anisotropic Barrier, Topsoil	0.3895	0.06469	0.04971	1.4357	1.06E-4	0.06[2]	10,000	0.07	0.16
Anisotropic Barrier, Compacted Soil	0.351	0.04669	0.05037	1.5437	4.47E-4	0.06[2]	10,000	0.05	0.12
ET Cover, Topsoil	0.3895	0.045	0.1049	1.4537	1.20E-3	0.12[2]	300	0.05	0.12
ET Cover, Compacted Soil	0.3228	0.065	0.03206	1.4484	4.7E-5	0.12[2]	1200	0.07	0.16

[1] measured during construction quality control activities during the summer of 1995
[2] measured during construction quality control activities during the summer of 1996

Table 6.1. Input Parameters from Tension Infiltrometer Measurements (Final Soil Conditions)

6.5 Results

The simulation results using the infiltrometer data as input parameters where applicable were presented in Table 6.2.

Landfill Cover	UNSAT-H: Initial Soil Conditions				UNSAT-H: Final Soil Conditions			
	Runoff	Percolation	Soil Moisture Change	ET	Runoff	Percolation	Soil Moisture Change	ET
Subtitle D Cover	11.06	0.15	-0.06	284.01	9.68	35.35	8.67	241.04
Capillary Barrier	0.51	37.73	1.20	269.92	0.53	79.84	-10.84	240.05
Anisotropic Barrier	3.00	23.16	22.52	260.96	87.09	0.07	15.68	209.84
ET Cover	4.47	0.19	15.65	274.42	5.29	1.25	19.32	268.74

Table 6.2. Average Annual Simulation Results with UNSAT-H (all units = mm/year)

Landfill Cover	HELP: Initial Soil Conditions					HELP: Final Soil Conditions				
	Runoff	Percolation	Lateral Drainage	Soil Moisture Change	ET	Runoff	Percolation	Lateral Drainage	Soil Moisture Change	ET
Subtitle D Cover	0.07	17.80	0.00	0.88	258.60	0.07	33.50	0.00	33.11	243.26
GCL Cover	0.07	0.02	0.00	20.13	274.30	0.07	0.02	0.00	50.79	259.06
Subtitle C Cover	0.07	0.04	0.00	20.96	268.76	0.07	0.04	0.00	39.78	270.05
Capillary Barrier	0.07	42.89	0.00	-2.94	241.57	0.07	26.94	0.00	30.32	252.61
Anisotropic Barrier	0.07	8.76	0.00	-1.58	294.93	0.10	13.38	0.00	35.92	260.55
ET Cover	0.07	7.20	0.00	-0.32	287.04	0.07	0.00	0.00	73.19	236.69

Table 6.3. Average Annual Simulation Results with HELP (all units = mm/year)

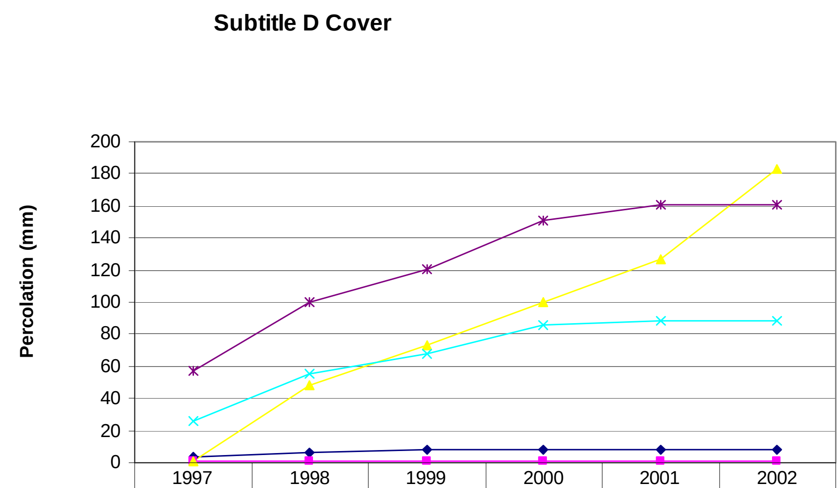
Landfill Cover	Field Data					
	Runoff	Percolation	Lateral Drainage	Soil Moisture Change	ET	Runoff
Subtitle D Cover	5.08	1.94	0.00	-14.80	310.70	5.08
GCL Cover	4.60	0.54	0.04	-17.71	315.44	4.60
Subtitle C Cover	3.28	0.04	0.03	-20.93	320.49	3.28
Capillary Barrier	3.88	0.22	0.00	2.29	296.53	3.88
Anisotropic Barrier	3.96	0.05	0.00	-21.39	320.29	3.96
ET Cover	3.36	0.06	0.00	-4.68	304.18	3.36

Table 6.4. Average Annual Field Results (all units = mm/year)

6.5.1 Subtitle D Cover

Cumulative percolation values are presented in figure 6.3 for the Subtitle D Cover. These values include the results of the HELP and UNSAT-H computer simulations using the soil parameters obtained with the tension infiltrometer (final soil conditions) as well as the simulation results using the initial soil conditions presented in chapter 5 and field-measured percolation results (Chapter 3) for comparison.

The HELP simulations that utilized the initial and final soil conditions each grossly over estimated the percolation through the cover profile. As was pointed out earlier, HELP has serious limitations in describing unsaturated water movement within a soil profile. The UNSAT-H simulation that utilized the final soil conditions also grossly over estimated percolation. In fact, this simulation produced even more percolation than those with the HELP program. On the other hand, the UNSAT-H simulation that utilized the soil's initial condition predicted very little flux through the cover profile. The dramatic difference between the two UNSAT-H simulations largely appeared to be due to the increased saturated hydraulic conductivity used with the final input parameters. The saturated hydraulic conductivity increased from 1.2E-6 cm/sec to 1.2E-5 cm/sec. This increase, although large, was less than other studies have reported (Waugh et al 1999) for changes in hydraulic conductivity over time. The significance of the saturated hydraulic conductivity for these simulations is that it is a scalar multiplier in UNSAT-H used to calculate the unsaturated hydraulic conductivity. The water storage capacity of the soil profile changed little from the initial condition to its final condition (5.1 cm to 5.4 cm, respectively). The cover's water storage capacity is the product of the soil profile's water holding capacity (field capacity less the wilting point; as described in chapter 4) and the soil depth.

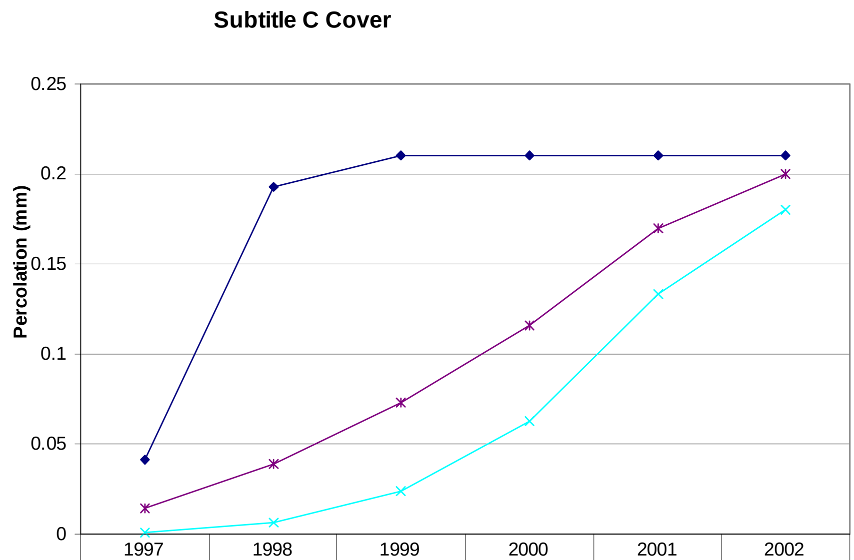


	1997	1998	1999	2000	2001	2002
Field	3.56E+00	6.04E+00	7.60E+00	7.60E+00	7.60E+00	8.34E+00
UNSAT-H Initial Soil Conditions	6.10E-01	7.10E-01	7.50E-01	7.70E-01	7.80E-01	7.80E-01
UNSAT-H Infiltrometer Soil Data	6.20E-01	4.82E+01	7.33E+01	9.97E+01	1.27E+02	1.83E+02
HELP Initial Soil Conditions	2.58E+01	5.55E+01	6.76E+01	8.61E+01	8.84E+01	8.84E+01
HELP Infiltrometer Soil Data	5.70E+01	1.00E+02	1.20E+02	1.51E+02	1.60E+02	1.60E+02

Figure 6.3. Comparison of the Cumulative Field Measured Percolation and. Simulation Predicted Percolation for the Subtitle D Cover

6.5.2 Subtitle C Cover

The HELP simulations on the Subtitle C Cover that utilized both the initial and final soil conditions along with the field-measured percolation values were presented in figure 6.4. These results were the closest predictions to the actual field measured values for both simulations. The flow was controlled through this cover by the defects in the geomembrane. Parameters other than the number and size of geomembrane defects had little impact on the cover's flux rate as indicated by the relative trend match between the two HELP simulations with different soil properties but the same geomembrane input parameters.

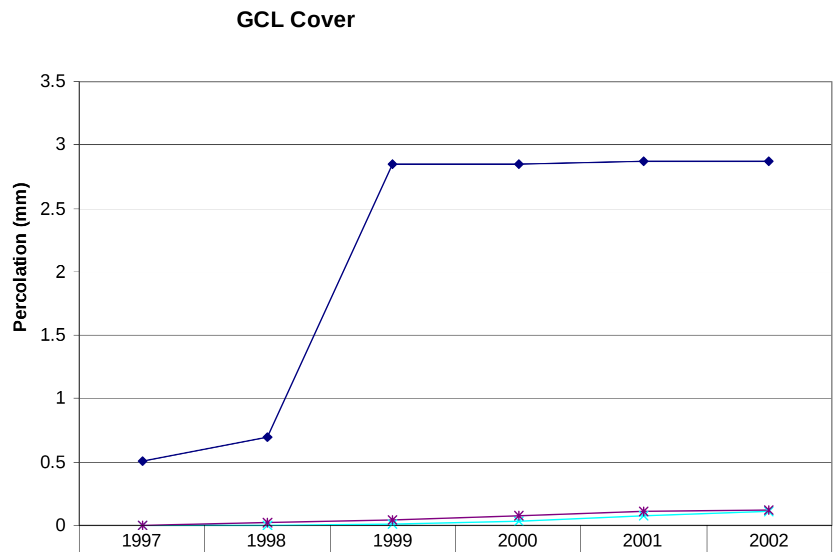


	1997	1998	1999	2000	2001	2002
Field	4.13E-02	1.93E-01	2.10E-01	2.10E-01	2.10E-01	2.10E-01
HELP Initial Soil Conditions	1.00E-03	6.00E-03	2.40E-02	6.30E-02	1.33E-01	1.80E-01
HELP Infiltrometer Soil Data	1.40E-02	3.91E-02	7.30E-02	1.16E-01	1.70E-01	2.00E-01

Figure 6.4. Comparison of the Cumulative Field Measured Percolation and. Simulation Predicted Percolation for the Subtitle C Cover

6.5.3 GCL Cover

The HELP simulations on the GCL Cover that utilized both the initial and final soil conditions along with the field-measured values are presented in figure 6.5. Similar to the Subtitle C Cover simulations, the flow through this profile was primarily controlled by the defects in the geomembrane. As discussed in chapter 3, degradation in the GCL was believed to be the reason for the discrepancy between the field measurements and the simulations for this cover. HELP does not provide for degradation in geosynthetics or any layer for that matter.

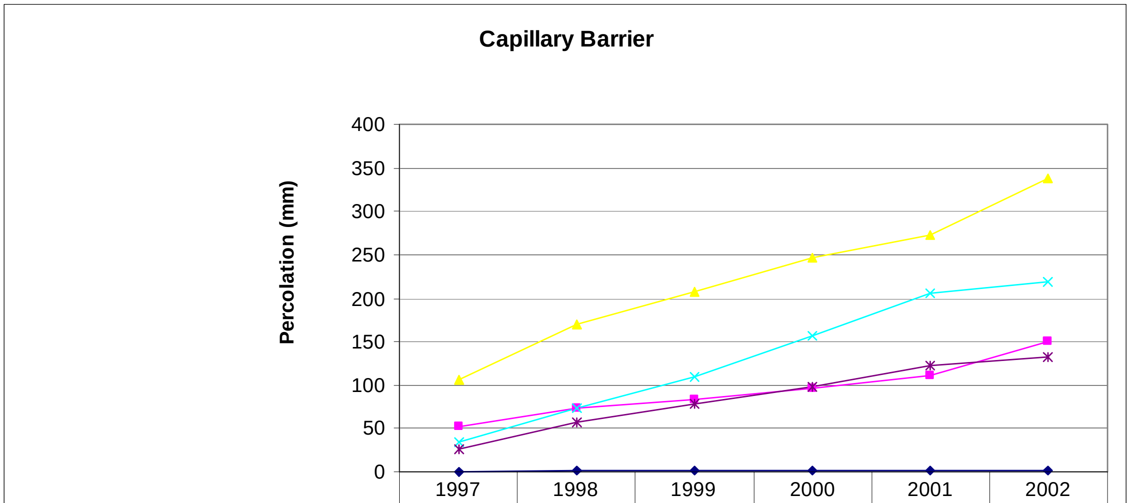


	1997	1998	1999	2000	2001	2002
Field	5.06E-01	6.95E-01	2.85E+00	2.85E+00	2.87E+00	2.87E+00
HELP Initial Soil Conditions	1.00E-03	1.00E-03	1.10E-02	3.50E-02	7.70E-02	1.05E-01
HELP Infiltrometer Soil Data	5.00E-03	2.35E-02	4.75E-02	7.70E-02	1.13E-01	1.24E-01

Figure 6.5. Comparison of the Cumulative Field Measured Percolation and. Simulation Predicted Percolation for the GCL Cover

6.5.4 Capillary Barrier

The simulations for the Capillary Barrier produced mixed results (figure 6.6). The HELP simulation that utilized the final soil conditions showed less percolation than the simulation that utilized the initial soil conditions. The UNSAT-H simulations produced the opposite effect: the simulation that utilized the final soil conditions produced about twice as much percolation as the simulation that utilized the initial soil conditions. There was very little change in the soil properties from the initial to final conditions. The saturated hydraulic conductivity for the compacted soil layer decreased from 5.14E-4 cm/sec to 4.00E-4 cm/sec. All of the simulations using both UNSAT-H and HELP on this cover grossly over estimated the percolation through the profile.



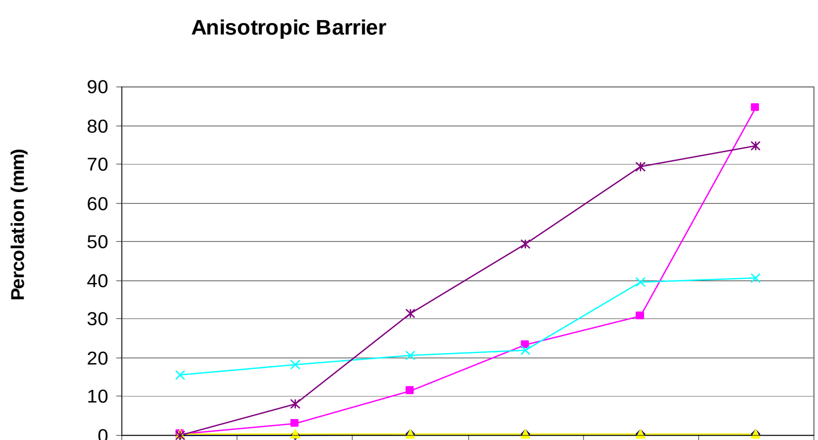
	1997	1998	1999	2000	2001	2002
Field	5.44E-01	9.53E-01	9.53E-01	9.53E-01	9.53E-01	9.53E-01
UNSAT-H Initial Soil Conditions	5.15E+01	7.34E+01	8.40E+01	9.64E+01	1.11E+02	1.50E+02
UNSAT-H Infiltrometer Soil Data	1.06E+02	1.70E+02	2.07E+02	2.46E+02	2.72E+02	3.38E+02
HELP Initial Soil Conditions	3.45E+01	7.42E+01	1.09E+02	1.56E+02	2.06E+02	2.19E+02
HELP Infiltrometer Soil Data	2.59E+01	5.64E+01	7.76E+01	9.82E+01	1.22E+02	1.33E+02

Figure 6.6. Comparison of the Cumulative Field Measured Percolation and. Simulation Predicted Percolation for the Capillary Barrier

6.5.5 Anisotropic Barrier

There was little difference between the initial and final soil conditions used as input for the simulation runs for the Anisotropic Barrier did not differ significantly amount with the exception of the initial moisture contents. The initial saturated hydraulic conductivity of the compacted soil layer was 4.00E-4 cm/sec while the final saturated hydraulic conductivity was 4.47E-4 cm/sec. The storage capacity decreased only slightly from the initial to final condition. The initial moisture content and associated suction head used however, was considerably different. The initial moisture content was 22% (measured on May 1, 1997 using TDR) for the compacted soil layer. The initial moisture content used for the final soil condition simulations that utilized the soil parameters obtained with the tension infiltrometer was only 6% (measured during quality control of the cover installation during the summer of 1996).

The HELP program again significantly over predicted percolation through the cover profile (figure 6.7). The UNSAT-H simulation that utilized the initial soil conditions produced more percolation than either of the HELP simulations. The UNSAT-H simulation that utilized the final soil conditions, predicted almost the exact same amount of percolation as measured in the field. The different initial moisture content used was the primary reason because it allowed for more initial water storage capacity. The initial moisture content of 22% was higher than the soil's field capacity (Table 6.1); therefore the soil had no excess initial water storage capacity. Whereas, the initial moisture content of 6% (final soil conditions) allowed for 4.65 cm of initial excess water storage capacity.



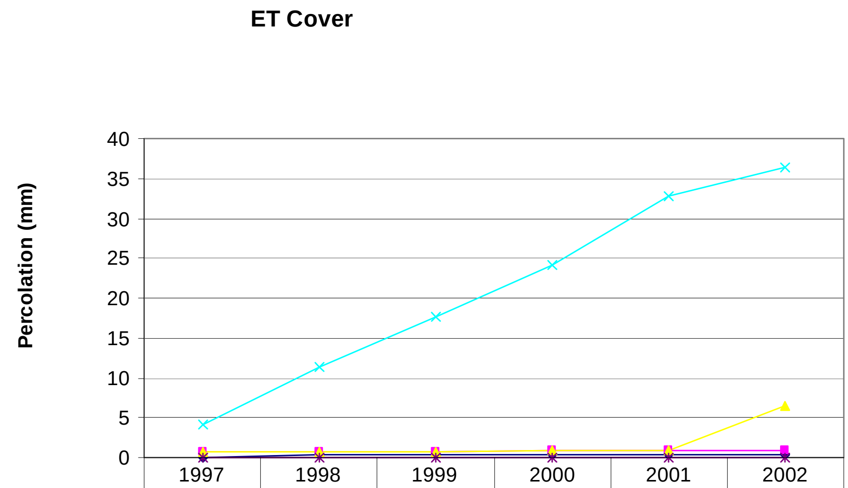
	1997	1998	1999	2000	2001	2002
Field	5.13E-02	1.20E-01	2.60E-01	2.60E-01	2.60E-01	2.61E-01
UNSAT-H Initial Soil Conditions	2.20E-01	3.16E+00	1.15E+01	2.35E+01	3.07E+01	8.48E+01
UNSAT-H Infiltrometer Soil Data	2.20E-01	2.40E-01	2.50E-01	2.50E-01	2.50E-01	2.50E-01
HELP Initial Soil Conditions	1.57E+01	1.84E+01	2.08E+01	2.20E+01	3.97E+01	4.05E+01
HELP Infiltrometer Soil Data	3.80E-02	8.28E+00	3.15E+01	4.93E+01	6.95E+01	7.48E+01

Figure 6.7. Comparison of the Cumulative Field Measured Percolation and. Simulation Predicted Percolation for the Anisotropic Barrier

6.5.6 ET Cover

The HELP simulation that utilized the final soil conditions actually under predicted the percolation compared to the field data. The HELP simulation that utilized the initial soil conditions significantly over estimated the percolation through the cover profile. The soil properties used did not differ significantly. The saturated hydraulic conductivities used were close (initial soil condition was 4.3E-5 cm/sec while the final soil condition was 4.7E-5 cm/sec). The storage capacities did not change that much (initial soil condition was 9.15 cm while the final soil condition was 8.63 cm) nor did the initial moisture content (15% was measured on May 1, 2002, while 12% was measured during construction QA). These differences in soil input parameters between the initial and final soil conditions utilized in the HELP simulations resulted in many orders of magnitude difference in estimation of the percolation through the cover.

The UNSAT-H simulation that utilized the final soil conditions, however, showed a significant increase in the percolation produced compared to the simulation that utilized the initial soil conditions. The slight increase in saturated hydraulic conductivity and small decrease in total storage capacity of the cover profile (9.15 cm for the initial soil and 8.63 cm for the final soil conditions) was enough of a change to produce the additional percolation through the cover.



	1997	1998	1999	2000	2001	2002
Field	7.55E-02	2.94E-01	2.99E-01	2.99E-01	2.99E-01	2.99E-01
UNSAT-H Initial Soil Conditions	6.60E-01	7.60E-01	8.00E-01	8.20E-01	8.30E-01	8.30E-01
UNSAT-H Infiltrometer Soil Data	6.60E-01	7.70E-01	8.10E-01	8.30E-01	8.50E-01	6.48E+00
HELP Initial Soil Conditions	4.19E+00	1.13E+01	1.77E+01	2.42E+01	3.28E+01	3.65E+01
HELP Infiltrometer Soil Data	3.01E-06	3.01E-06	1.76E-04	3.29E-04	4.33E-04	1.33E-03

Figure 6.8. Comparison of the Cumulative Field Measured Percolation and. Simulation Predicted Percolation for the ET Cover

6.6 Summary

A tension infiltrometer was used to collect soil hydraulic properties from the six test covers. These data were utilized in a set of simulations with HELP and UNSAT-H to produce water balance predictions for each test cover. These simulations were then compared to the simulations outlined in chapter 5 that utilized the test covers' initial soil conditions and to the field-measured data.

This study produced mixed results. The percent variance of percolation from each simulation (initial and final soil conditions) from the corresponding measured percolation is presented in Table 6.5. The adjusted soil properties made a relatively small difference on water balance predictions for cover profiles that contain a geomembrane (Subtitle C Cover and GCL Cover) using HELP. The defects in the geomembrane govern flow through these covers.

Landfill Cover	UNSAT-H				HELP			
	Initial Soil Conditions		Final Soil Conditions		Initial Soil Conditions		Final Soil Conditions	
	Variance (mm)	Percent Variance	Variance (mm)	Percent Variance	Variance (mm)	Percent Variance	Variance (mm)	Percent Variance
Subtitle D Cover	-8.26	-99	9.92	>100	80.08	>100	152.00	>>100
Subtitle C Cover	NA	NA	NA	NA	-0.03	-15	-0.01	-5
GCL Cover	NA	NA	NA	NA	-2.77	-96	-2.75	-96
Capillary Barrier	109.63	>>100	271.28	>>100	205.17	>>100	121.41	>>100
Anisotropic Barrier	84.49	>>100	-0.01	-4	40.28	>>100	75.59	>>100
ET Cover	-0.22	-72	0.35	>100	36.19	>>100	-0.30	-100

Table 6.5. Cumulative Variance of Percolation of the Simulations from the Field

The soil input parameter differences resulted in more significant variances with water balance predictions for cover profiles without geomembranes. UNSAT-H simulations on the Subtitle D Cover showed an increase from very little flux to a large predicted flux primarily due to just over an order of magnitude increase in saturated hydraulic conductivity produced from the sealed double ring infiltrometer field-measured initial soil condition compared to the tension infiltrometer field-measured final soil condition. The HELP simulations showed a two-fold increase in predicted flux for this cover, as well.

The UNSAT-H simulations on the Capillary Barrier showed a two-fold increase in predicted percolation from the initial to final soil conditions while the HELP simulation showed a decrease by about half. All simulations performed on the Capillary Barrier grossly over estimated percolation.

The UNSAT-H initial soil condition simulation on the Anisotropic Barrier over predicted percolation, while the percolation estimated from the final soil condition simulation was close to that measured in the field. The final soil condition established with a tension infiltrometer in the field measured in the summer of 2002 produced soil properties very similar to that used in the initial soil condition measured in the laboratory. However, the initial suction used for the compacted soil layer varied considerably. The initial soil condition used for the compacted soil layer on the initial soil condition simulation was the suction value that corresponded with a moisture content of 22%. This moisture content was measured on May 1, 1997 (the first day of field monitoring) in the field with TDR for the compacted soil layer. The moisture content used for the final soil condition simulation was 6%, which was the value, measured in the field during construction quality control activities during the summer of 1996. The UNSAT-H simulation (final soil condition) produced a percolation of 0.25 mm, compared with 0.26 mm measured; while the simulation described in chapter 5 (initial soil condition) predicted 84.8 mm of percolation through the Anisotropic Barrier. Both HELP simulations significantly over predicted percolation in this cover.

The UNSAT-H simulations on the ET Cover profile produced almost the opposite effect as the Anisotropic Barrier. The initial soil conditions on the ET Cover had a slightly higher storage capacity than the final soil condition (9.15 cm to 8.63 cm) and a slightly lower saturated hydraulic conductivity than the final soil conditions (4.7E-5 cm/sec to 4.34E-5 cm/sec). The initial soil condition's initial moisture content used was 15% while the final soil condition's initial moisture content used was 12%. These properties were not significantly different. One would expect that the percolation predictions would be similarly close. That was not the case. The initial soil conditions UNSAT-H simulation produced 0.08 mm, just under the field-measured amount of 0.30 mm. While the final soil condition UNSAT-H simulation produced 0.65 mm. This difference was largely due to small differences in the soil properties and initial suction values used. Using the same profile the HELP simulation produced the opposite affect as the UNSAT-H simulations did. The revised soil properties dropped the percolation from 36.5 mm for the initial soil condition simulation to 1.33E-3 mm for the final soil condition, an amount that was below the field-measured value.

6.7 Discussion

The large variability in percolation predictions in the programs based on the relatively small soil property changes leads one to question the applicability of these models. A single order of magnitude increase in saturated hydraulic conductivity produced an enormous increase in percolation between UNSAT-H simulations on the Subtitle D Cover. The simulation using the initial soil conditions produced no percolation while the simulation with the final soil conditions obtained in the field with a tension infiltrometer produced 194 mm, the single largest amount of percolation of all simulations performed. As previously discussed, it is reasonable and to some extent expected that a soil's hydraulic conductivity will vary both spatially and temporally. Measured values easily may vary by an order of magnitude or more for a given soil over distances of a few centimeters. In addition, measured hydraulic conductivity values for a soil may vary dramatically with respect to the measurement method used. Laboratory determined values rarely agree with field measurements, the differences often being on the order of two orders of magnitude or more (http://www.irim.com/ssm/ssm00064.htm).

Variability exists not only with measuring the same soil hydraulic property with the same method, but it exists between methods. A comparison was made of the Guelph permeameter, the velocity permeameter, a pumping test procedure, and the auger hole method for measuring saturated hydraulic conductivity (Dorsey et al, 1990). The methods were compared on a Ravenna silt loam and a Hoytville silty clay loam. The evaluations were conducted during high water table conditions established by sub irrigation. All the methods showed a wide variability in saturated hydraulic conductivity within each soil. The sensitivity of these programs to this value given the variability of obtaining accurate results lends to the unreliability of modeling results for accurate prediction of percolation. Furthermore, knowing the sensitivity of models to input parameters can lead to easy manipulation of output. The Anisotropic Barrier is a good example: altering the initial suction value in this study resulted in a seemingly very accurate prediction of flux through the cover profile when compared to the previous simulation presented in chapter 5 that grossly over predicted the cover's flux.

Chapter 7. Summary and Conclusions

7.1 Background

Perhaps the single largest environmental remediation effort is closing the more than 250,000 landfills (Dwyer 1998d) scattered across the United States. It is certainly the most expensive. Estimates for an RCRA-approved cover can reach $5 million per hectare in arid regions (Initiatives, 1999).

Prescriptive landfill cover designs have inherent flaws (Suter et al, 1993; Mulder and Haven, 1995; Dwyer 2000b) that have led to groundwater contamination in virtually all parts of the nation (EPA 1988). The momentum behind using prescriptive designs and lack of alternative cover performance data has been the largest hurdle to using closure designs best suited for a given site. Much effort has been expended educating regulators and marketing the results found in this research effort. Field data collected suggests that alternative covers such as capillary barriers and ET Covers are best suited for dry environments (Table 7.1), are easier to install (Dwyer 2000a) and much less expensive (Dwyer 1998) than prescriptive covers.

7.2 Field Data Summary

The ET Cover, Anisotropic Barrier and Subtitle C Covers were the best performing designs having the lowest measured flux rates. The ET Cover and Anisotropic Barriers cost less than half that of the Subtitle C Cover to install. (Dwyer 1998b) The low flux rate measured through the Subtitle C Cover was shown to primarily be a function of the low effective hydraulic conductivity of the geomembrane. The geomembranes placed in the Subtitle C and GCL Covers have unknown serviceable lives with no field data to reflect the effect on a cover's flux rate after degradation of the geomembrane. Koerner and Daniel (1997) claim that these geomembranes can continue to function as designed for several hundred years. The lack of available data on a serviceable life for the geomembranes is perhaps a limiting factor in their use in covers on landfills with long-lived waste such as radioactive waste.

Table 7.1 presents the cumulative percolation measured on the test covers. This data suggests that Subtitle D Covers are inadequate, exceeding the suggested maximum 1-mm/year flux requirement (Dwyer et al, in press, a). The Subtitle D Cover has an unprotected barrier layer that is subject to desiccation cracking (Montgomery and Parsons, 1990, Suter et al, 1993, Benson et al, 1994), biointrusion (roots, animals, ants, and earthworms) (Waugh et al. 1999), and damage due to freeze/thaw cycles (Benson et al 1995). All of these inherent flaws were shown to exist and contribute to increased saturated hydraulic conductivity for the layer. They also led to preferential flow through the cover that led to the relatively high flux rates measured.

The field data also suggests that GCL covers are suspect due to potential degradation from desiccation and ion exchange (James et al. 1997, Melchoir 1997, Lin and Benson 2000). The GCL can actually show severe degradation within the first few years of deployment from desiccation cracking, ion exchange problems, and root intrusion on unprotected GCLs (Hakonson 2001). The GCL cover was the only cover that showed an increase in flux rate from 1997 through 1999. 1999 was the last year of significant precipitation before a drought began in late 1999 that lead to minimal flux rates through the covers beyond that time.

Landfill Cover	**Average Annual Flux (mm/year)**
Subtitle D	1.39
GCL Cover	0.48
Subtitle C	0.04
Capillary Barrier	0.16
Anisotropic Barrier	0.04
ET Cover	0.05

Table 7.1. Average Annual Flux Measured

Flow through the covers was shown to always be unsaturated with significant contribution from preferential flow. The peak moisture contents in any of the bottom soil layers never reached saturation. Prescriptive design methodologies assume saturated flow through covers. Calculations on the Subtitle D Cover compared the calculated hydraulic conductivity using the van Genuchten parameters from the soil profile with the initial soil conditions (3.26E-10 cm/sec) with that calculated using the Darcy-Buckingham equation with the peak measured flux rate from March 1998 (9.3E-8 cm/sec). The difference between these two values suggests the possibility of preferential flow through the cover profile. Preferential flow appeared to increase with time as shown with similar calculations on the Subtitle D Cover: the hydraulic conductivity using the van Genuchten parameters from the soil profile with the initial soil conditions (4.54E-13 cm/sec) compared with that calculated using the Darcy-Buckingham equation with the peak measured flux rate from February 1999 (3.1E-8 cm/sec) produced a difference in these values of almost five orders of magnitude, up from the single order of magnitude seen from the March 1998 event.

Regulators to date have been very accepting of field data for the use of alternative cover designs. This is particularly true for this data set that has successfully passed a number of regulatory reviews as well as technical reviews from such entities as the National Academy of Sciences and DOE organized expert panels (Dwyer 1998c). The field data presented has been and continues to be used by regulators to both suggest the use of alternative covers and approve those that have been submitted throughout the arid and semi-arid regions of the country.

7.3 Computer Simulations Summary

A major problem with current design methodologies regardless of the type of landfill cover is the sole reliance on computer modeling in most cases to determine a cover profile. The accuracy of programs to simulate a cover's water balance is suspect (Roesler and Benson 2002), largely due to the complexity of the problem. The upper two meters or so of soil, where there are substantial fluctuations in the soil moisture, is referred to the "active zone." It is extremely difficult to predict the water balance in the active zone, in large part because important phenomena, such as freeze/thaw cycles, wet/dry cycles, root intrusion, earthworm intrusion, insect and burrowing animal's intrusion, are not explicitly included in the simulations, nor are their effects readily incorporated into the simulations.

Chapter 4 examined a typical design methodology using two popular programs (HELP and UNSAT-H) for the six different cover types. The design approach used soil properties obtained at the test site prior to the construction of the test covers. The weather data used was conservative in that an above average rainfall year was modeled for five consecutive years. This is a typical design approach. Additional simulations (Chapter 5) were performed using input parameters based on actual weather data collected at the site corresponding to the monitoring period. The soil properties used were those measured in the laboratory and field that corresponded with the initial or as-built conditions of the covers. The vegetation input parameters (LAI and percent bare area) were averaged values of those measured at the site during the monitoring period. Recognizing that the covers are part of a dynamic ecosystem and as the ecological status of the cover changed, so did performance factors such as water infiltration, water retention, ET, soil erosion, gas diffusion, and biointrusion. Consequently, a third set of simulations (Chapter 6) was performed based on the soil properties, as they existed at the end of the monitoring period (final soil conditions). A tension infiltrometer was used to measure the hydraulic properties of the upper fine soil layers in the test covers to determine the final soil conditions.

All of the aforementioned computer simulations were performed without manipulation of the modeled data to better predict the field-measured values. The simulations were performed simply to assess the program's capability of predicting the water balance of different landfill cover designs.

The HELP model does not take into account important physical processes that control unsaturated water movement such as matric potential in soil barrier layers. UNSAT-H better simulates this unsaturated water movement but neither model has the explicit capability to accommodate preferential flow through a profile that was shown to be a major contributor to the covers' flux rate. Neither model accurately predicts surface runoff. HELP consistently under predicted it using the SCS runoff method. This method does not take into account a rainstorm's intensity or duration. UNSAT-H indirectly calculates runoff as the precipitation rate that exceeds the cover profile's infiltration rate. Scanlon et al (in print) found that no program tested accurately represent runoff measured from landfill covers.

Table 7.2 represents the input parameters used for the HELP simulations and each HELP simulations' cumulative percolation results with the field measured cumulative percolation amounts. Table 7.3 represents the input parameters used for the UNSAT-H simulations and each UNSAT-H simulations' cumulative percolation results with the field measured cumulative percolation amounts.

Landfill	Layer	Porosity			Field Capacity (vol/vol)			Wilting Point (vol/vol)			Ksat (cm/sec)			Initial MC (vol/vol)		LAI			Cumulative Percolation (mm)			
		4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	Field
Subtitle D Cover	Topsoil	0.44	0.45	0.45	0.11	0.16	0.1	0.05	0.09	0.04	1.70E-03	1.00E-03	9.08E-04	0.19	0.14	1.2	1.5	1.5	280.46	88.42	160.34	8.34
	Barrier Soil	0.42	0.37	0.37	0.31	0.19	0.18	0.18	0.1	0.08	1.90E-05	1.23E-06	1.20E-05	0.37	0.14							
Subtitle C Cover	Topsoil	0.44	0.45	0.45	0.11	0.16	0.13	0.05	0.09	0.06	1.70E-03	1.00E-03	1.15E-03	0.19	0.14	1.2	1.5	1.5	1.24	0.18	0.20	0.21
	Sand	0.42	0.37	0.37	0.05	0.03	0.03	0.02	0.02	0.02	1.00E-02	1.82E-02	1.82E-02	0.12	0.12							
	Barrier Soil	0.43	0.37	0.37	0.42	0.19	0.19	0.37	0.1	0.1	1.00E-07	9.70E-07	9.70E-07	0.37	0.37							
GCL Cover	Topsoil	0.44	0.45	0.45	0.11	0.16	0.13	0.05	0.09	0.06	1.70E-03	1.00E-03	1.17E-03	0.20	0.14	1.2	1.5	1.5	0.05	0.11	0.12	2.87
	Sand	0.42	0.37	0.37	0.05	0.03	0.03	0.02	0.02	0.02	1.00E-02	1.82E-02	1.82E-02	0.15	0.15							
Capillary Barrier	Topsoil	0.44	0.45	0.45	0.11	0.16	0.13	0.05	0.09	0.06	1.70E-03	1.00E-03	1.15E-03	0.19	0.10	1.2	0.5	0.5	44.07	219.41	132.76	0.95
	Compacted Soil	0.42	0.41	0.41	0.31	0.18	0.1	0.18	0.09	0.06	1.90E-05	4.00E-04	5.15E-04	0.41	0.10							
	Sand	0.42	0.37	0.37	0.05	0.03	0.03	0.02	0.02	0.02	1.00E-02	1.62E-02	1.62E-02	0.09	0.09							
	Gravel	0.4	0.37	0.37	0.03	0.03	0.03	0.01	0.03	0.03	3.00E-01	4.42E+00	4.42E+00	0.03	0.03							
Anisotropic Barrier	Topsoil	0.44	0.45	0.45	0.11	0.16	0.16	0.05	0.09	0.07	1.70E-03	1.00E-03	1.06E-04	0.22	0.06	1.2	1.4	1.4	271.87	40.54	74.85	0.26
	Compacted Soil	0.42	0.41	0.41	0.31	0.18	0.12	0.18	0.09	0.05	1.90E-05	4.00E-04	4.47E-04	0.22	0.06							
	Sand	0.42	0.37	0.37	0.05	0.03	0.03	0.02	0.02	0.02	1.00E-02	1.62E-02	1.82E-02	0.09	0.09							
	Gravel	0.4	0.37	0.37	0.03	0.03	0.03	0.01	0.03	0.03	3.00E-01	4.42E+00	4.42E+00	0.03	0.03							
ET Cover	Topsoil	0.44	0.45	0.45	0.11	0.16	0.12	0.05	0.09	0.05	1.70E-03	1.00E-03	1.20E-03	0.19	0.12	1.2	1.8	1.8	279.38	36.48	1.33E-03	0.30
	Compacted Soil	0.42	0.37	0.37	0.31	0.19	0.16	0.18	0.1	0.07	1.90E-05	4.34E-05	4.70E-05	0.15	0.12							

(1) Design input parameters for HELP and HELP simulations as described in Chapter 4.
(2) Initial soil conditions input parameters for HELP and HELP simulations as described in Chapter 5.
(3) Final soils conditions input parameters for HELP and HELP simulations as described in Chapter 6.
(4) No specific initial moisture content used for forward simulations described in chapter 4. Default values for input parameters for HELP combined with prior modeled years used.

Table 7.2. HELP Input Parameters and Results with Field Results

Landfill	Layer	THETAS (vol/vol)			THETAR (vol/vol)			Ksat (cm/sec)			Initial Suction (cm)			LAI			Percent Bare Area			Cumulative Percolation (mm)			
		4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	4(1)	5(2)	6(3)	Field
Subtitle D Cover	Topsoil	0.4	0.43	0.39	0.06	0.06	0.04	1.70E-03	1.00E-03	9.08E-04	1000	700	140	1.2	1.5	1.5	85	89	89	377.89	0.77	18.26	8.34
	Barrier Soil	0.29	0.36	0.32	0.11	0.06	0.07	1.90E-05	1.23E-06	1.20E-05	1000	1000	1200										
Capillary Barrier	Topsoil	0.4	0.43	0.39	0.06	0.06	0.06	1.70E-03	1.00E-03	1.15E-03	1000	1000	1000	1.2	0.5	0.5	85	95	95	0.07	150.08	337.69	0.95
	Compacted Soil	0.29	0.4	0.35	0.11	0.06	0.06	1.90E-05	4.00E-04	5.15E-04	1000	10000	300										
	Sand	0.35	0.34	0.34	0.05	0.03	0.03	1.00E-02	1.62E-02	1.62E-02	50	16	16										
	Gravel	0.33	0.37	0.37	0.03	0.02	0.02	3.00E-01	4.42E+00	4.42E+00	25	11	11										
Anisotropic Barrier	Topsoil	0.35	0.43	0.39	0.05	0.06	0.06	1.70E-03	1.00E-03	1.06E-04	1000	1000	10000	1.2	1.4	1.4	85	90	90	0.00	84.75	0.25	0.26
	Compacted Soil	0.36	0.4	0.35	0.08	0.06	0.05	1.90E-05	4.00E-04	4.47E-04	1000	1000	10000										
	Sand	0.35	0.34	0.34	0.05	0.03	0.03	1.00E-02	1.62E-02	1.82E-02	50	16	16										
	Gravel	0.33	0.37	0.37	0.03	0.02	0.02	3.00E-01	4.42E+00	4.42E+00	25	11	11										
ET Cover	Topsoil	0.4	0.43	0.39	0.06	0.06	0.05	1.70E-03	1.00E-03	1.20E-03	1000	2643	300	1.2	1.8	1.8	85	82	82	121.22	0.84	0.65	0.30
	Compacted Soil	0.29	0.36	0.32	0.11	0.06	0.07	1.90E-05	4.34E-05	4.70E-05	1000	2643	1200										

(1) Design input parameters for UNSAT-H and UNSAT-H simulations as described in Chapter 4.
(2) Initial soil conditions input parameters for UNSAT-H and UNSAT-H simulations as described in Chapter 5.
(3) Final soils conditions input parameters for UNSAT-H and UNSAT-H simulations as described in Chapter 6.

Table 7.3. UNSAT-H Input Parameters and Results with Field Results

HELP grossly over estimated percolation through the Subtitle D Cover and both capillary barrier designs. HELP also grossly over estimated the percolation through the ET Cover (percent variance >>100%) except for the final soil conditions simulation. That simulation actually under predicted the percolation (percent variance of -99.6%). The significantly lower initial moisture content in the soil layers in the 'final soil condition' simulation compared to that of the 'initial soil condition' simulation allowed for more initial storage capacity was the primary reason for the lower flux rate prediction.

HELP tended to underestimate percolation through cover profiles that contained a geomembrane within them. The percolation predictions for the GCL Cover were significantly lower than the field measured values (percent variance of -96.3%). Degradation in the GCL as described in chapter 3 was believed to be the primary reason for this variance. Although the predicted percolation values and field-measured values were very close suggesting the HELP program is excellent for evaluation of a Subtitle C Cover, there was some doubt as to its actual accuracy. Field percolation through the Subtitle C Cover came in a few events, while the HELP program predicted a slow continual drainage through the cover as presented in Chapters 4, 5, and 6. In addition, the flow through the cover was shown to be a function of the calculated effective hydraulic conductivity of the geomembrane that in turn is a function of the number and size of defects assigned to the geomembrane. Soil properties had little effect on flux rate estimates in these covers. In reality, the number and size of defects is generally not determined. Consequently, this input data describing the defects in a geomembrane is merely an estimate and may or may not represent reality where holes in geomembranes can be much larger than 1-cm^2 and go undetected.

Changed soil input parameters made substantial differences in flux estimates with UNSAT-H simulations. A single order of magnitude difference in saturated hydraulic conductivity for the barrier layer in the Subtitle D Cover was the primary difference in UNSAT-H estimating very little flux (0.08 mm, percent variance –99%) through the cover versus overestimating it (18.26 mm, percent variance >100%). As previously discussed, a soil's hydraulic conductivity is a highly variable property. Measured values easily may vary by an order of magnitude or more for a given soil. Values measured on soil samples taken within centimeters of one another may vary by an order of magnitude or more. Measured hydraulic conductivity values for a soil may vary dramatically with respect to the measurement method used (Dorsey et al, 1990). In addition, laboratory determined values rarely agree with field measurements, the differences often being on the order of two orders of magnitude or more (http://www.irim.com/ssm/ssm00064.htm).

Altered van Genuchten parameters and thus water storage capacity differences resulted in a slight under prediction (percent variance of -72%) of the flux through the ET Cover versus over predicting it (percent variance >100%). The differences in the van Genuchten parameter values used between the initial and final soil condition simulations on each cover were generally within the differences of those values encountered in the RETC and DISC programs used to calculate the parameters. That is, varying initial parameter estimates; relaxing or tightening the parameter constraints (maximum or minimum values allowed); or allowing the program to optimize the parameter opposed to fixing it will all yield varied results that can easily vary the calculated parameters by variances seen in Table 7.3.

The UNSAT-H simulations on the Anisotropic Barrier showed that using different initial soil suction values made the difference in grossly overestimating the flux (percent variance >>100%) to almost exactly predicting it (percent variance of -4%). The initial soil moisture content or soil suction is generally not known when designing a landfill cover. It can be estimated from the design specifications. However, this value is one that is easy to manipulate to produce a more desired flux rate calculated by either UNSAT-H or HELP.

7.4 Computer Simulation Sensitivity Analysis

A set of computer simulations was performed on the ET Cover using the Initial Soil Conditions (chapter 5) as the baseline. That is, a set of sensitivity analyses were performed holding the parameters used on the Initial Soil Conditions set of simulations constant except for the parameter to be evaluated in each sensitivity analysis. Using HELP and UNSAT-H, the flux through the ET Cover was evaluated after altering the following input parameters: (1) saturated hydraulic conductivity, (2) LAI, and (3) initial moisture content or suction values. The saturated hydraulic conductivity was altered between the lowest values measured on the given soil no matter the installed conditions (1.23E-6 cm/sec) to the highest value measured (1.0E-3 cm/sec). The LAI was varied between the lowest possible value (0) to the highest practical number possible for the Albuquerque, NM site (2.0). The initial moisture conditions of the soil were varied between the values representing the permanent wilting point (matric potential of 15,000 cm, water content of 0.06) and the field capacity (matric potential of 330 cm, water content of 0.32). Table 7.4 represents the resulting fluxes from these simulations.

UNSAT-H							
Year	Initial Soil Condition (chap. 5)	Sat. Hyd. Cond., max	Sat. Hyd. Cond., min	Initial Suction, max	Initial Suction, min	LAI, min	LAI, max
1997	0.66	0.66	0.65	0.64	0.66	0.66	0.66
1998	0.10	0.10	0.10	0.09	0.11	18.77	0.10
1999	0.04	0.04	0.04	0.02	0.04	44.28	0.04
2000	0.02	0.02	0.02	0.01	0.02	59.01	0.02
2001	0.01	0.02	0.01	0.00	0.02	41.13	0.01
2002	0.00	0.01	0.00	0.00	0.01	62.41	0.00
Total	0.83	0.85	0.82	0.76	0.86	226.26	0.83
HELP							
Year	Initial Soil Condition (chap. 5)	Sat. Hyd. Cond., max	Sat. Hyd. Cond., min	Water Content, max	Water Content, min	LAI, min	LAI, max
1997	4.19	0.30	111.72	15.36	4.73	0.00	4.94
1998	7.10	0.01	109.36	9.47	4.95	0.00	7.48
1999	6.37	0.00	82.91	8.17	7.82	8.69	5.94
2000	6.51	0.03	110.89	6.57	6.54	18.57	8.24
2001	8.59	0.01	104.76	5.14	5.19	11.86	7.79
2002	3.73	0.00	23.80	3.84	1.52	3.64	3.98
Total	36.49	0.35	543.45	48.55	30.74	42.75	38.38

Table 7.4. Sensitivity Analysis: Flux Values for the ET Cover (mm)

The results show that the UNSAT-H program is very sensitive to changes in the LAI, particularly as the transpiration portion of ET is eliminated. The UNSAT-H produced flux values were relatively insensitive to the saturated hydraulic conductivity and initial suction values. The HELP program was most sensitive to variations in the saturated hydraulic conductivity values in the soil, while being relatively insensitive to variations in the LAI and initial moisture content.

7.5 Conclusions

Using the criteria established by the EPA of a maximum acceptable flux rate of 1 mm/year (Dwyer et al, in press, a), the Subtitle D Cover (Table 7.1) is not acceptable to be deployed within an arid or semi-arid climate. The Subtitle D Cover has a number of inherent problems that were summarized in chapters 2 through 6. Although the GCL Cover's annual average was less than 1 mm/year, it experienced greater than 1 mm in 1999 (2.56 mm/year, Table 3.4). The GCL Cover may degrade when deployed in dry climates with certain soil types (e.g. high in calcium carbonate). Using the more stringent flux requirements of 0.1 mm/year, the Capillary Barrier is also not acceptable for deployment under theses climate conditions. This cover due to design flaws had an inadequate storage capacity in its uppermost fine layer that resulted in its inability to maintain native vegetation and thus transpire water or minimize surface erosion. The ET Cover, Anisotropic Barrier and Subtitle C Cover (Table 7.1) all performed very well and are acceptable under the most stringent EPA requirements.

In general, the programs evaluated (UNSAT-H and HELP) are not adequate to use as the sole design tool for a landfill cover. They are unacceptable within the accuracy required by regulators and designers because of the large difference in predicted fluxes for the cover designs from relatively small differences in input parameters combined with the fact that the determination of these input parameters can easily vary by orders of magnitude. In addition, the ease with which models can be manipulated to produce desired results by altering input parameters within a seemingly acceptable envelope further leads one to question the reliance on the results of these simulations to design a landfill cover.

The problem with the use of these programs is the way in which they are currently used; namely, to predict flux through a cover. In general, the percolation through the cover is less than 1% of the total water balance. Runoff is generally larger than the drainage values and as discussed in previous chapters is not accurately calculated with either program. However, most of the inaccuracies result in the calculation of ET. ET is generally close to 100% of the total precipitation and dominates the water balance in dry environments such as Albuquerque where this research was performed. On the one hand, the ET is modeled relatively well with these programs. However, a small relative difference between the predicted and measured ET will result in a large discrepancy between the predicted and measured percolation.

The models used within the programs for calculating ET are approximate and empirical in nature. In calculating ET in both programs, transpiration was consistently larger than evaporation. Perhaps because of most engineers' lack of understanding of transpiration, little effort is made to measure input parameters in contrast to the usual effort to obtain soil hydraulic properties. Despite the significance of transpiration, most of the input values related to transpiration are approximated or default values are used which may or may not be representative of reality. Consequently, even small errors in the calculation of ET which are expected based on the use of approximate input values will lead to very large relative errors in the calculation of drainage through a landfill cover.

7.6 Future Research Needs

More accurate calculation of ET is required to allow for the use of these computer programs as accurate design tools based on the current flux acceptance requirements. This would require the assemblage of accurate vegetation parameters for sites of interest. Additionally, understanding the development and extent of macro pores that allow for preferential flow needs to be better understood to ultimately allow for a design factor of safety to be included with the output results form the computer programs used for the determination of cover profiles.

APPENDICES

Appendix A

Moisture Characteristic Curves for Soils based on Laboratory Measurements at As-Built Densities

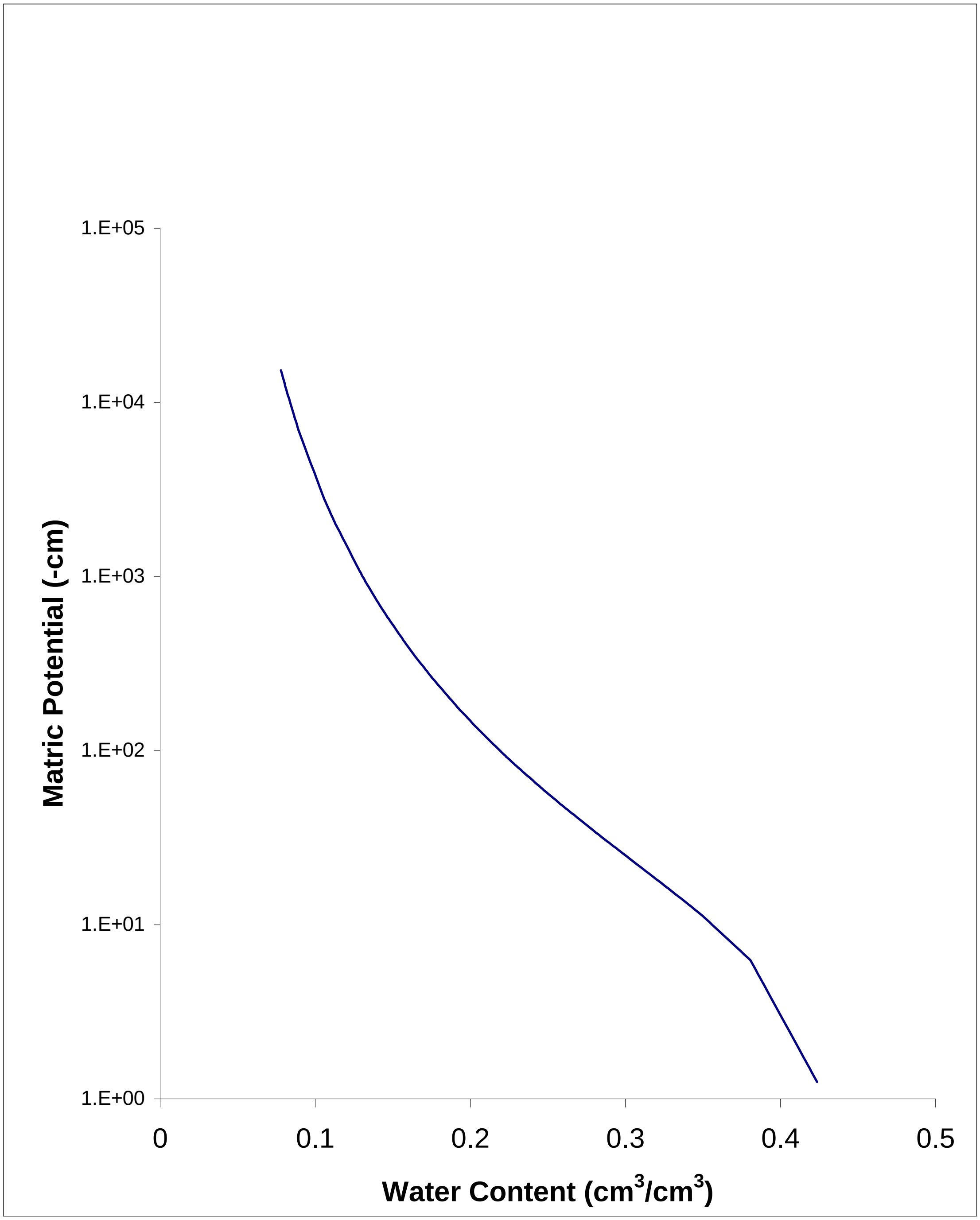


Figure A-1. Moisture Characteristic Curve for Soil with Low Compaction (1.5 g/cm^3)

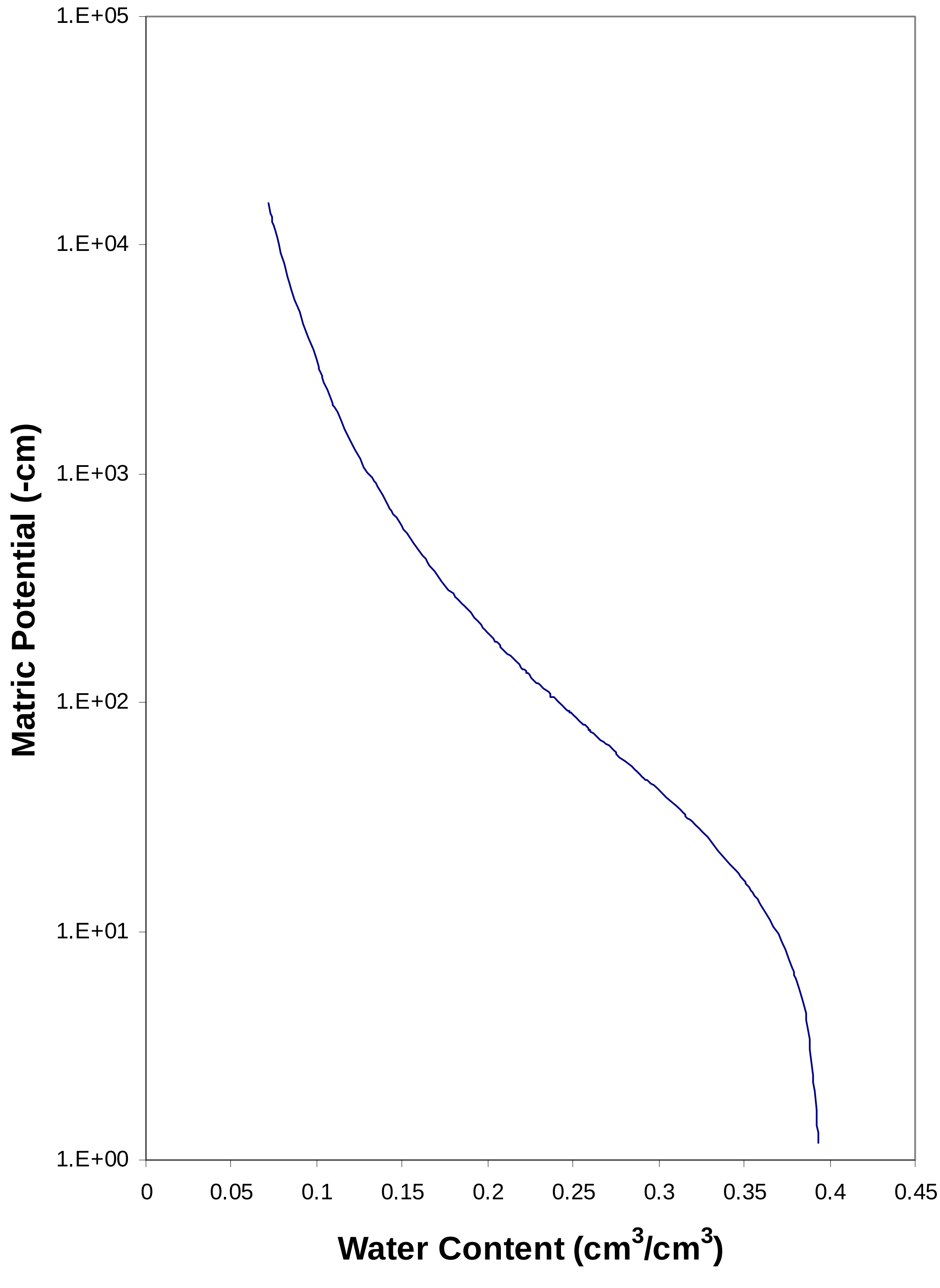


Figure A-2. Moisture Characteristic Curve for Soil with Low Compaction (1.5 g/cm^3)

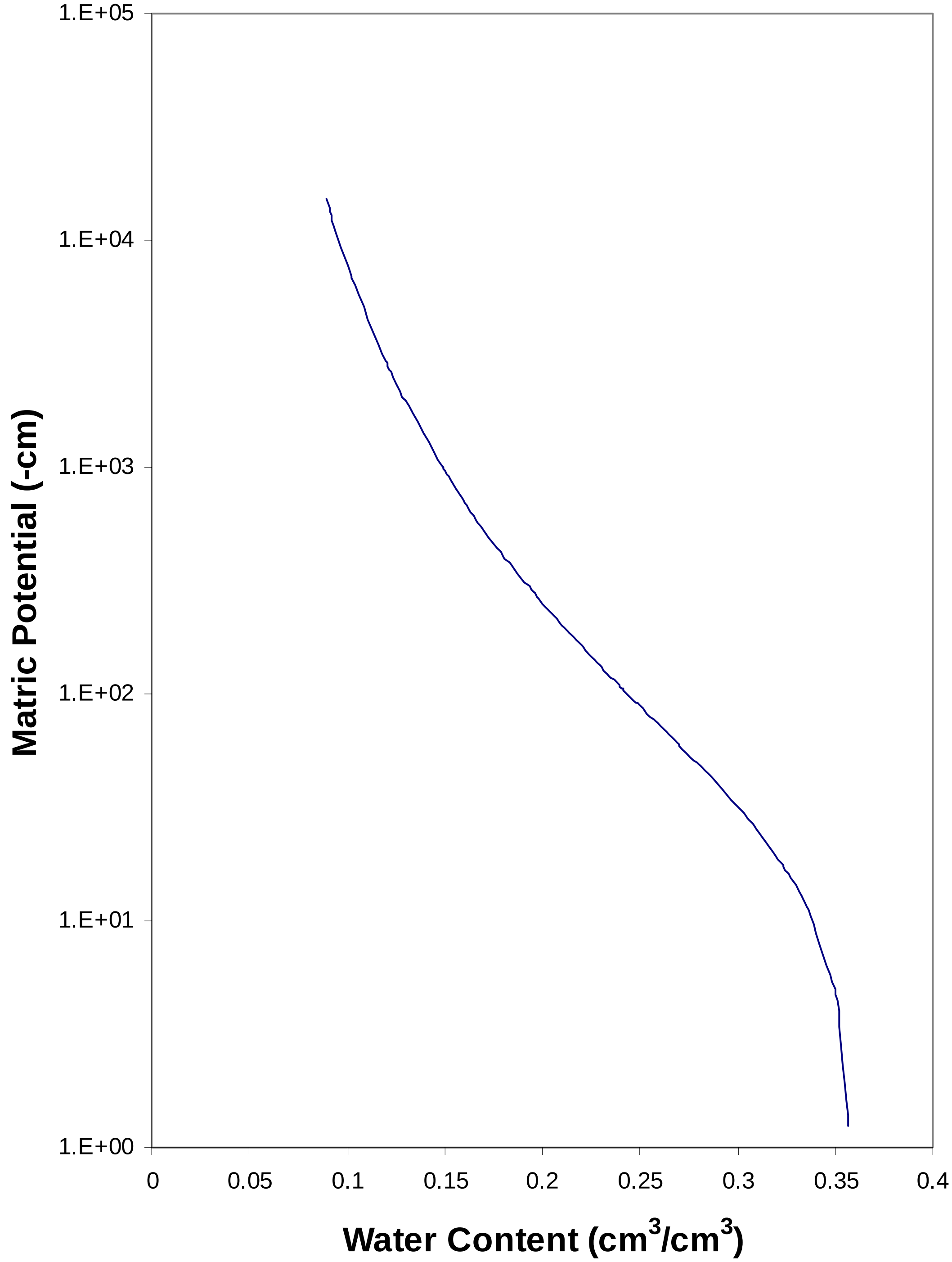


Figure A-3. Moisture Characteristic Curve for Soil with Heavy Compaction (1.7 g/cm^3)

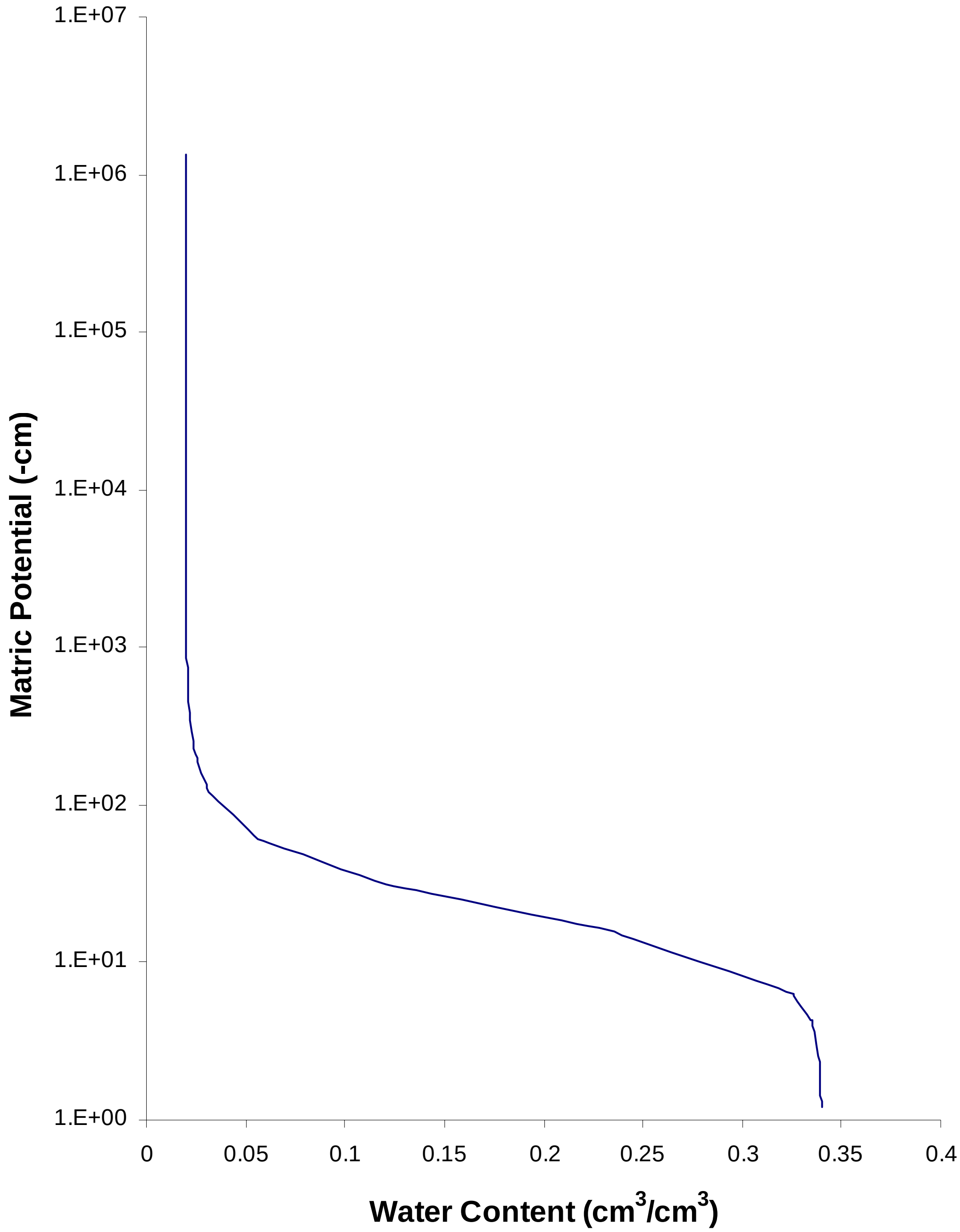


Figure A-4. Moisture Characteristic Curve for Sand

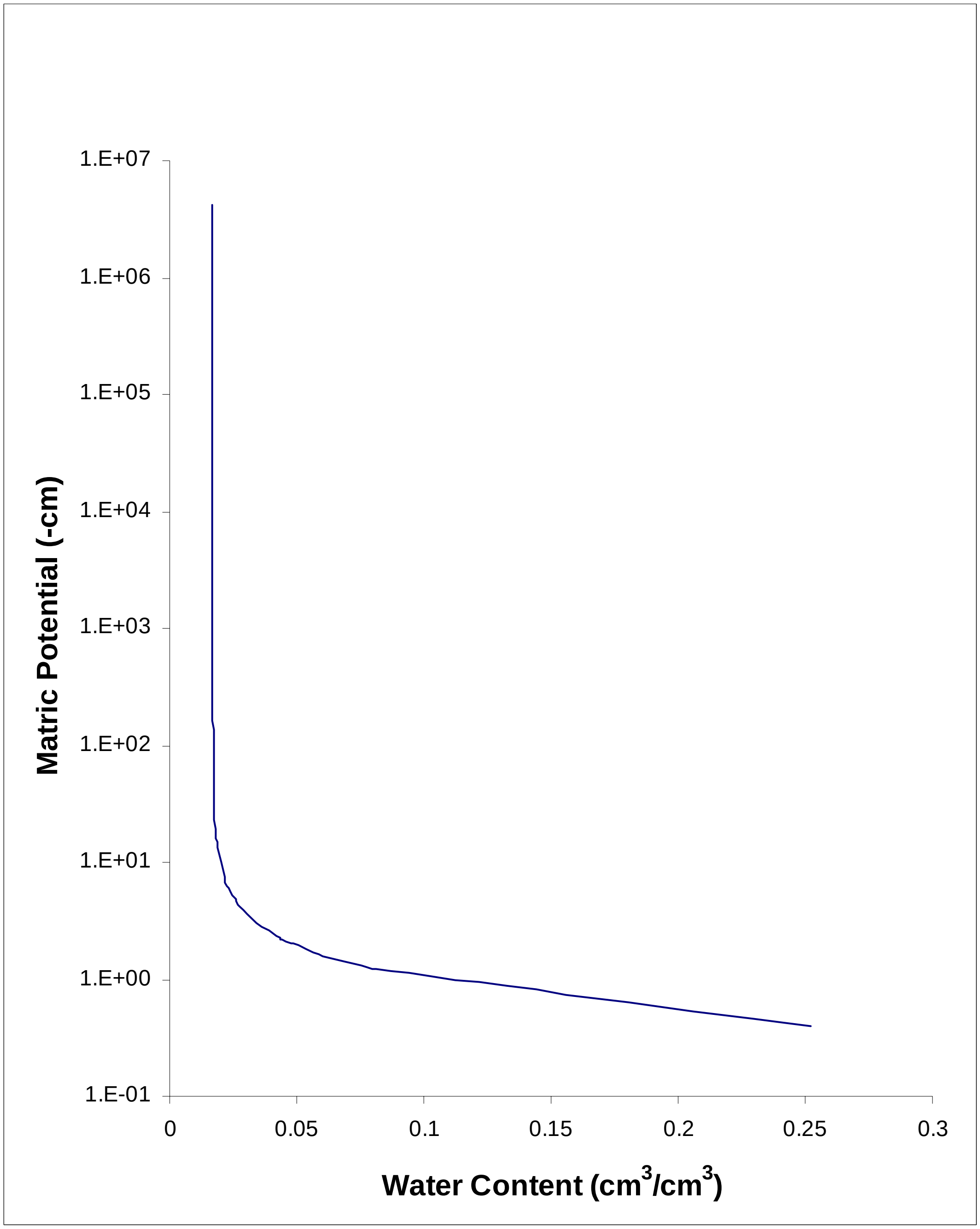


Figure A-5. Moisture Characteristic Curve for Pea Gravel

Appendix B

Moisture Characteristic Curves for Soils based on Field Measurements with Tension Infiltrometer

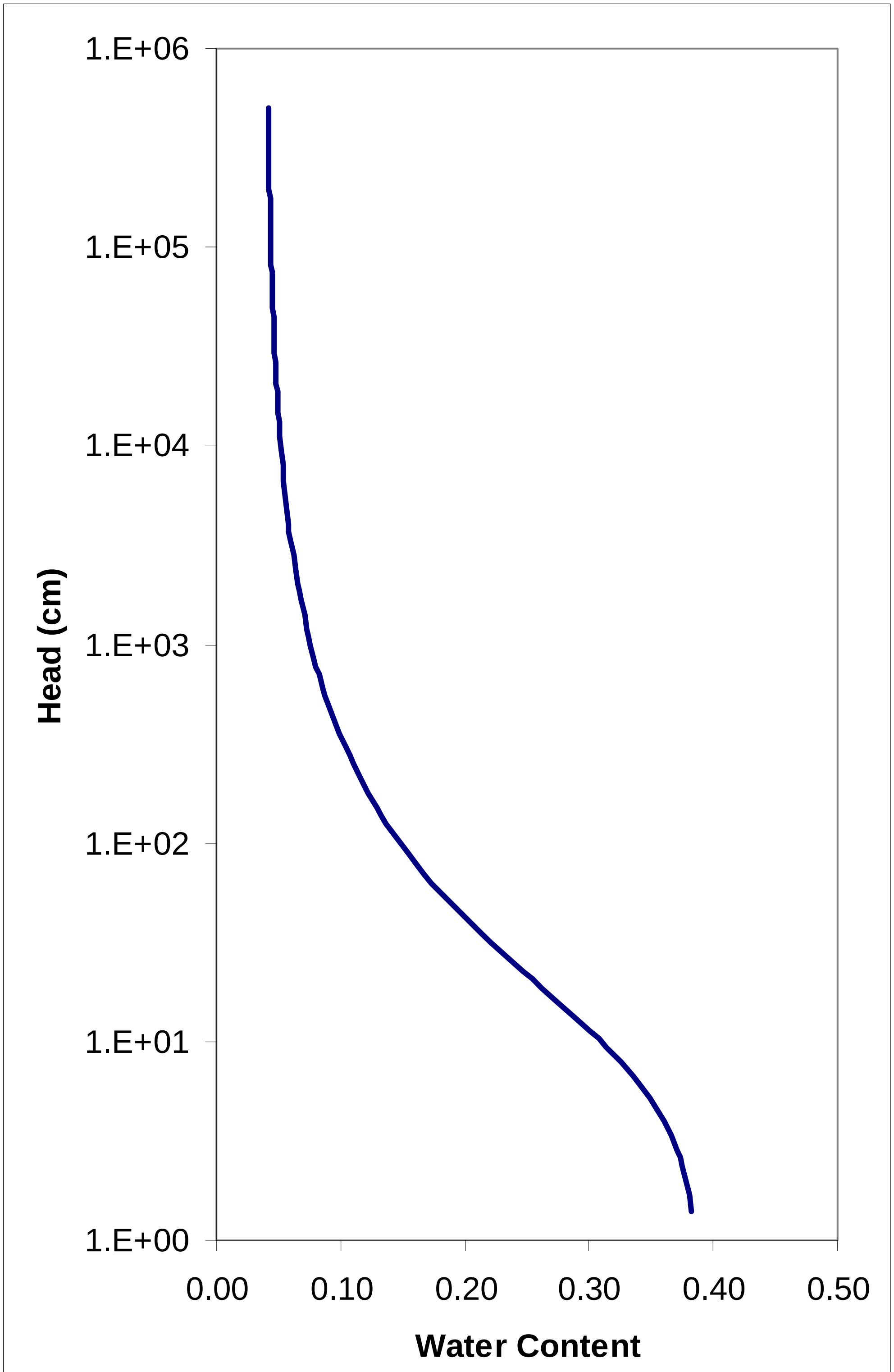


Figure B.1. Subtitle D Cover, Topsoil

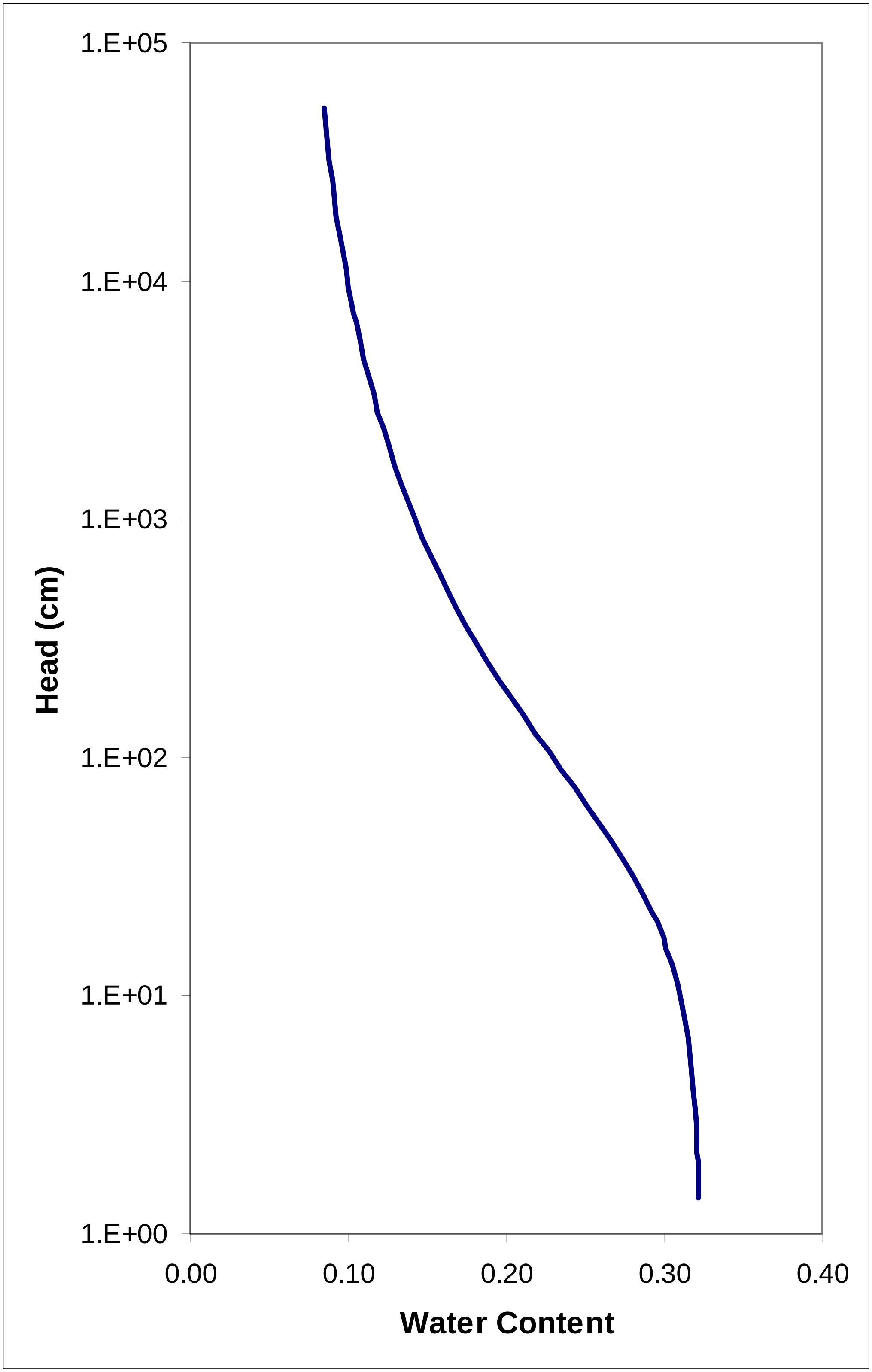


Figure B.2. Subtitle D Cover, Barrier Layer

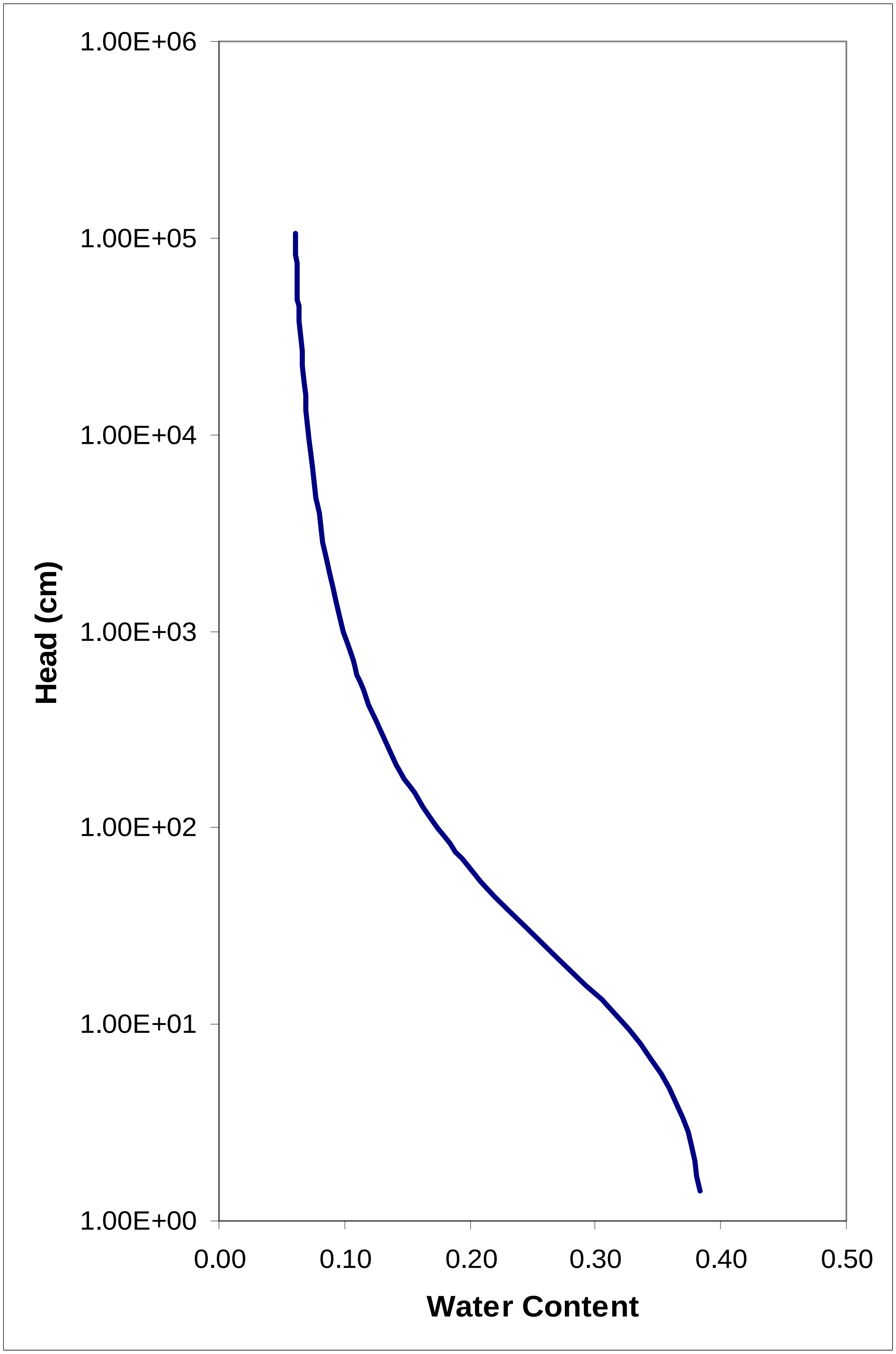


Figure B.3. Subtitle C Cover, Topsoil

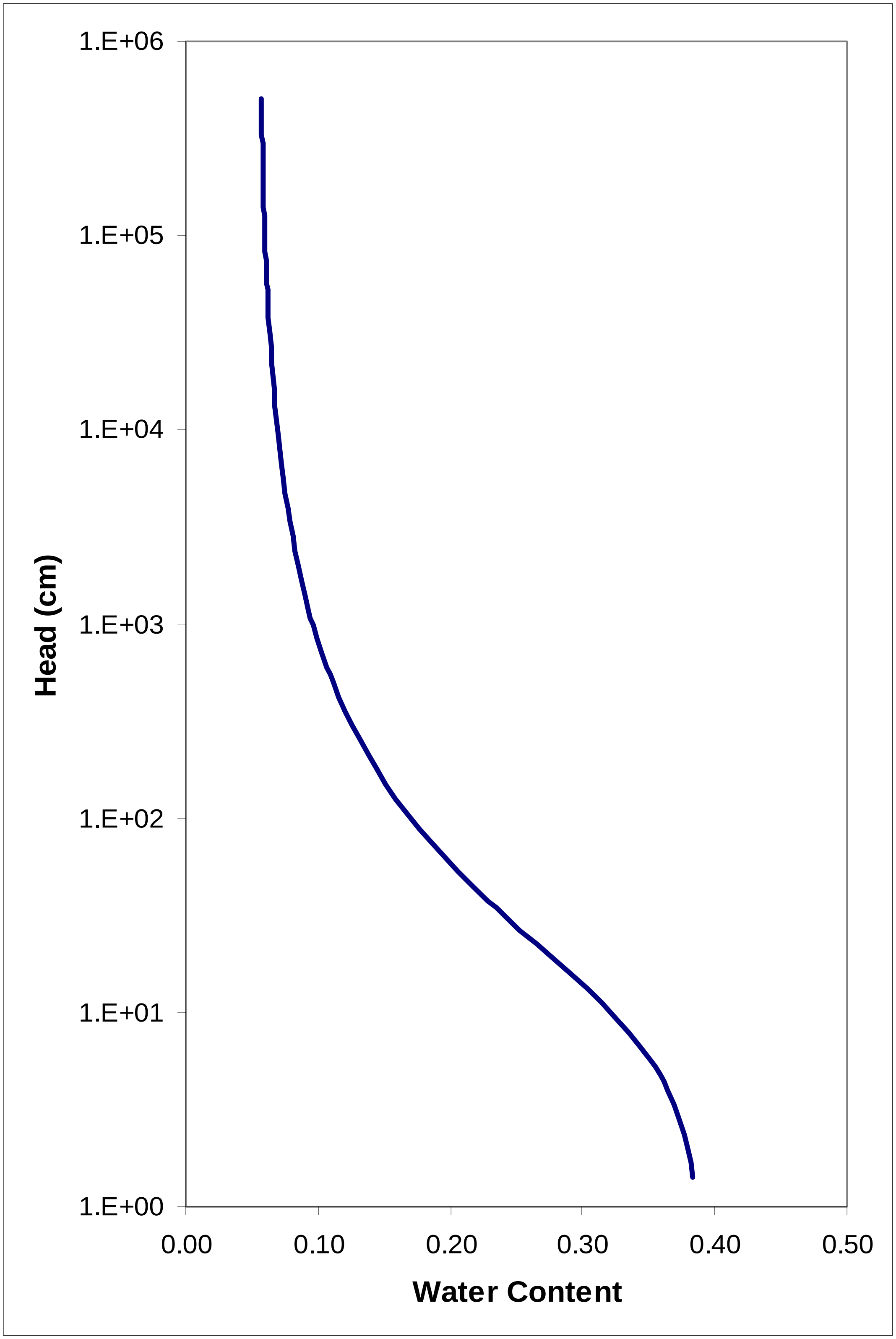


Figure B.4. GCL Cover, Topsoil

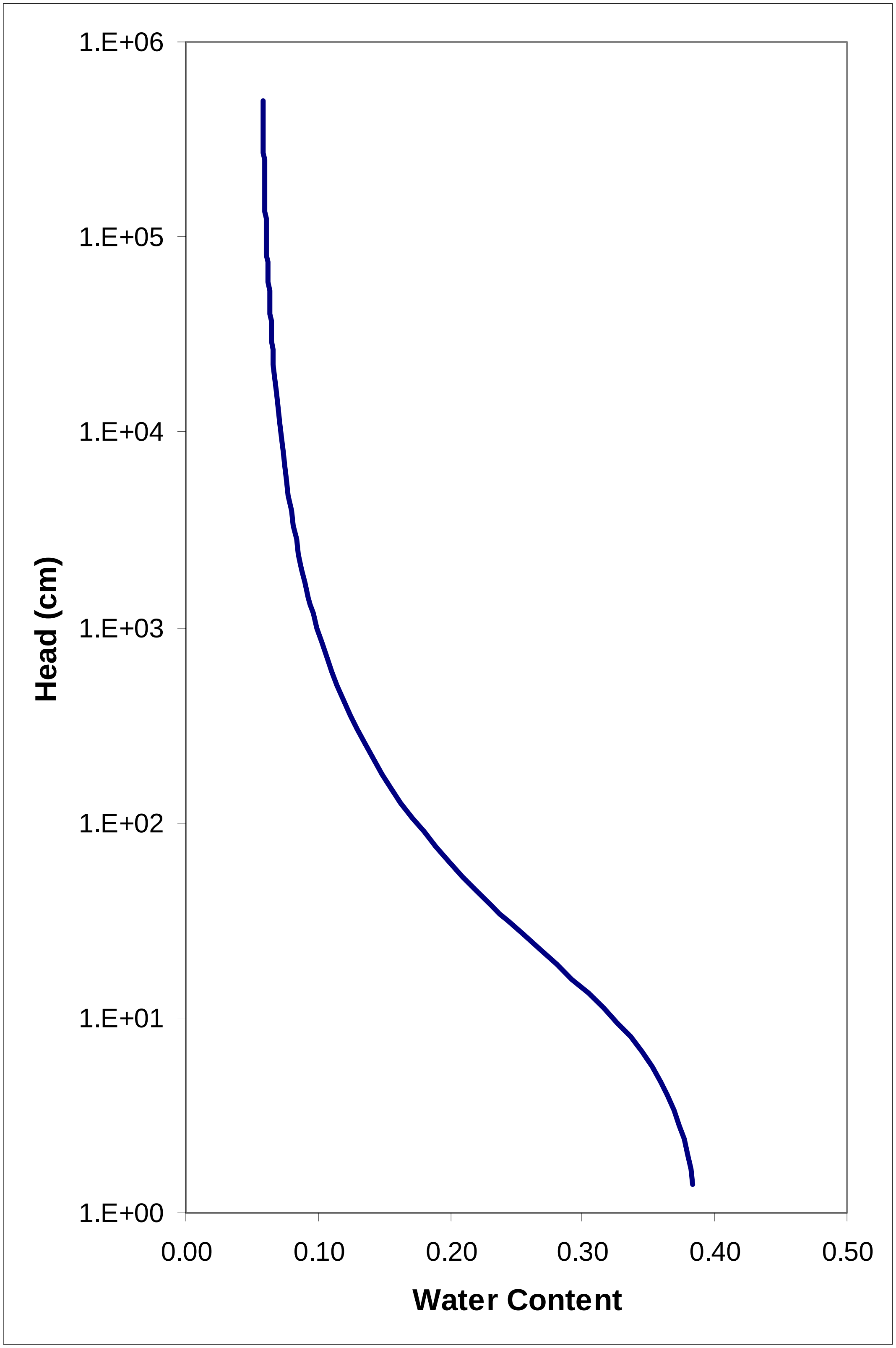


Figure B.5. Capillary Barrier, Topsoil

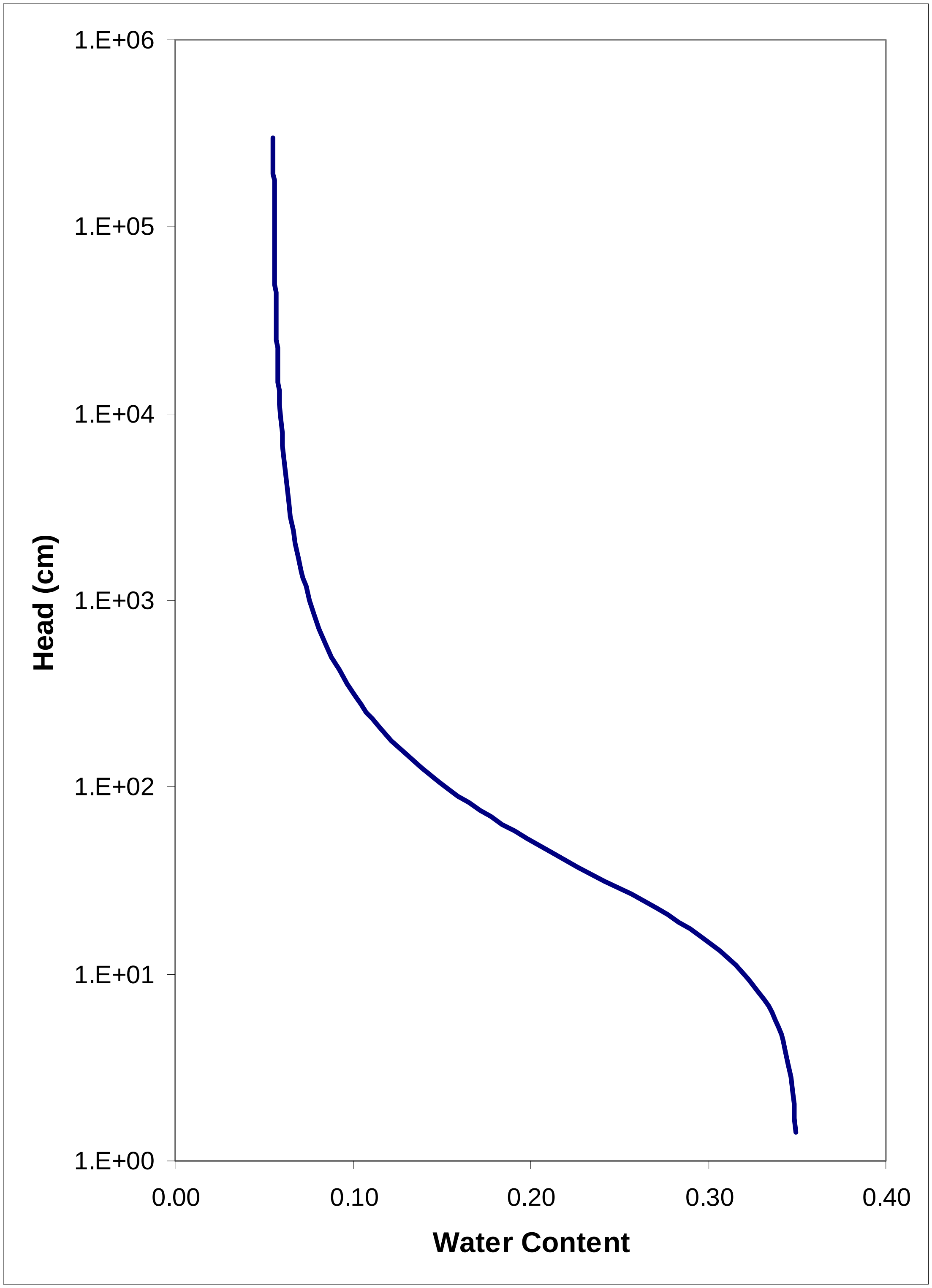


Figure B.6. Capillary Barrier, Compacted Soil Layer

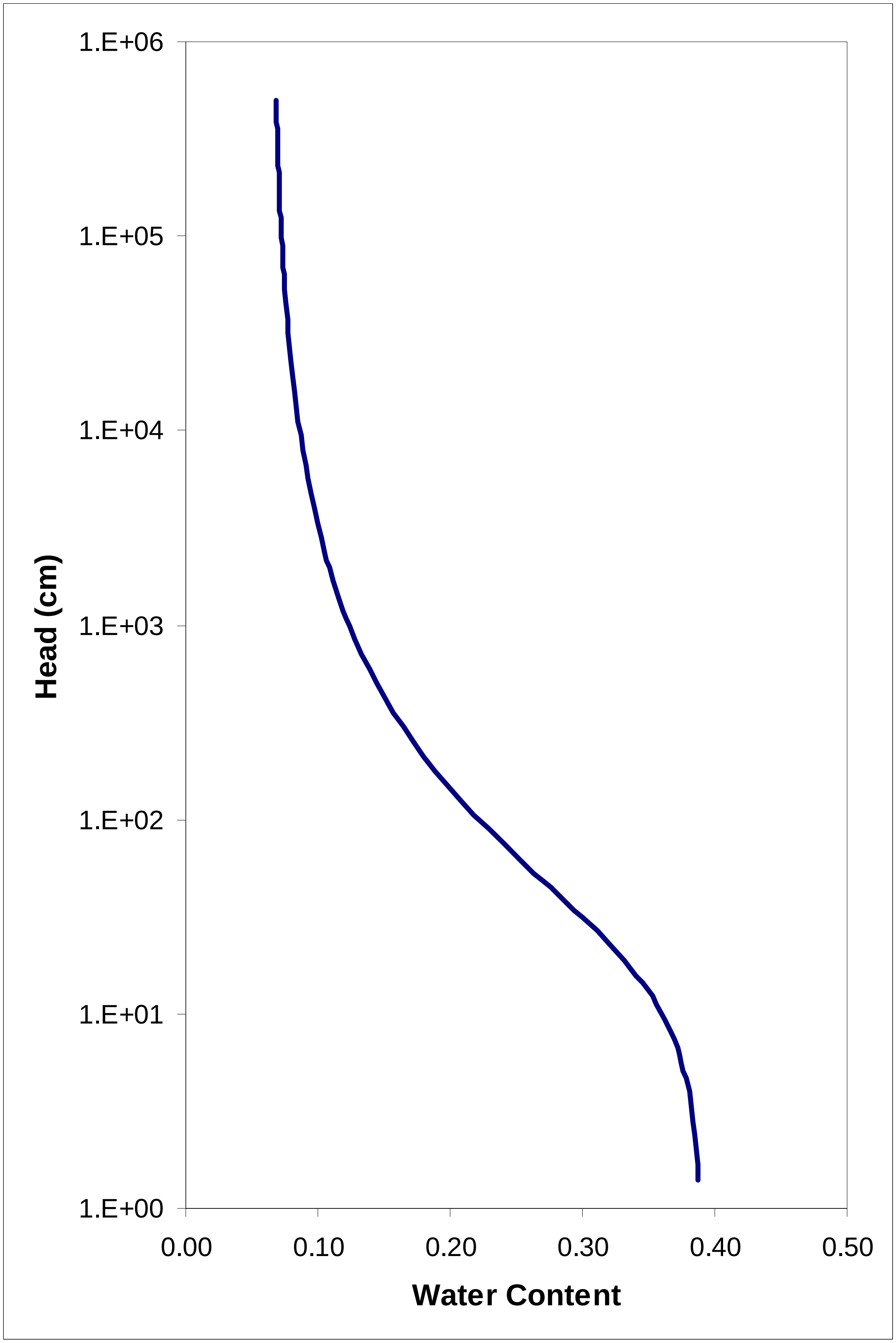


Figure B.7. Anisotropic Barrier, Topsoil

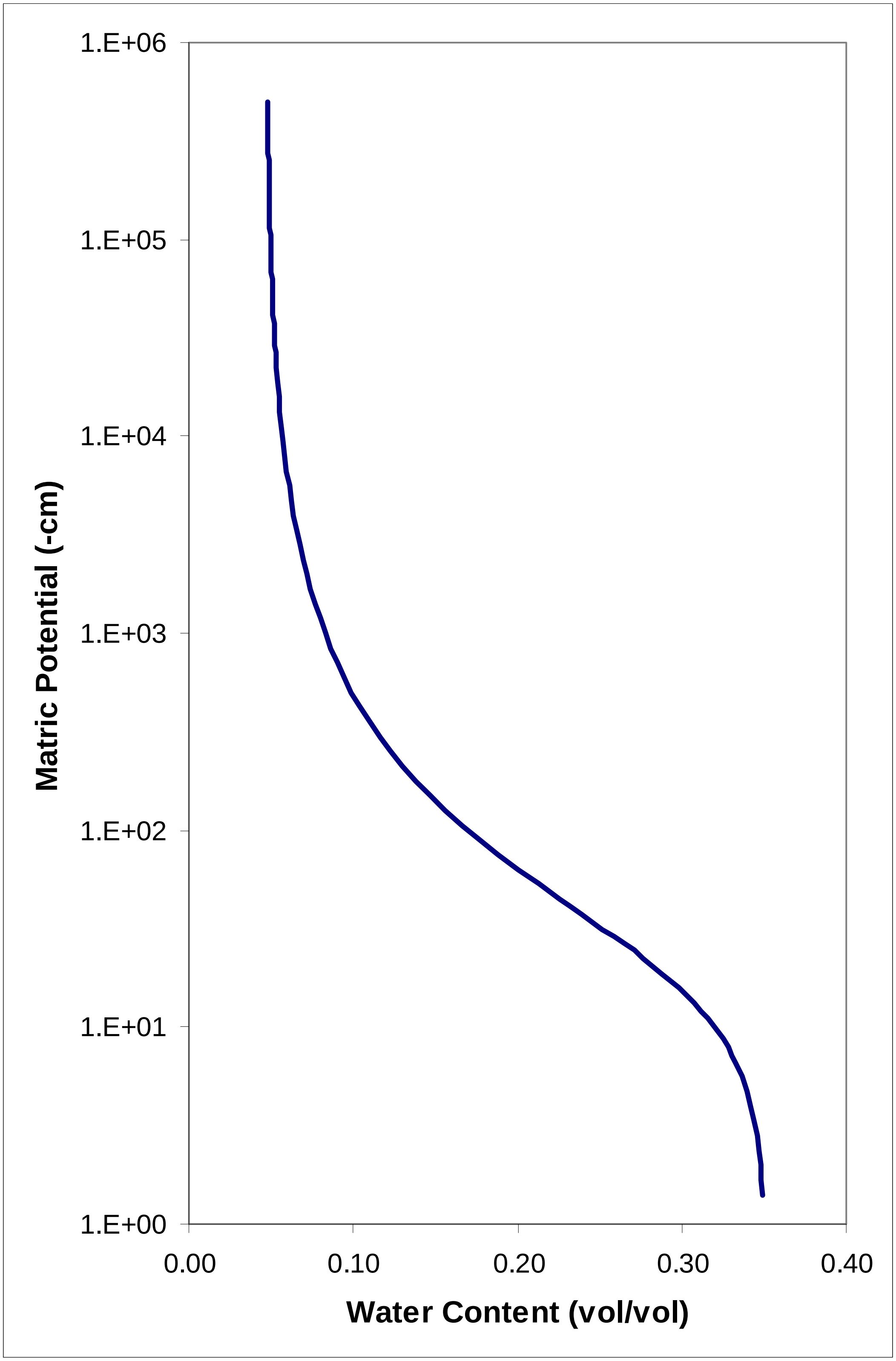


Figure B.8. Anisotropic Barrier, Compacted Soil Layer

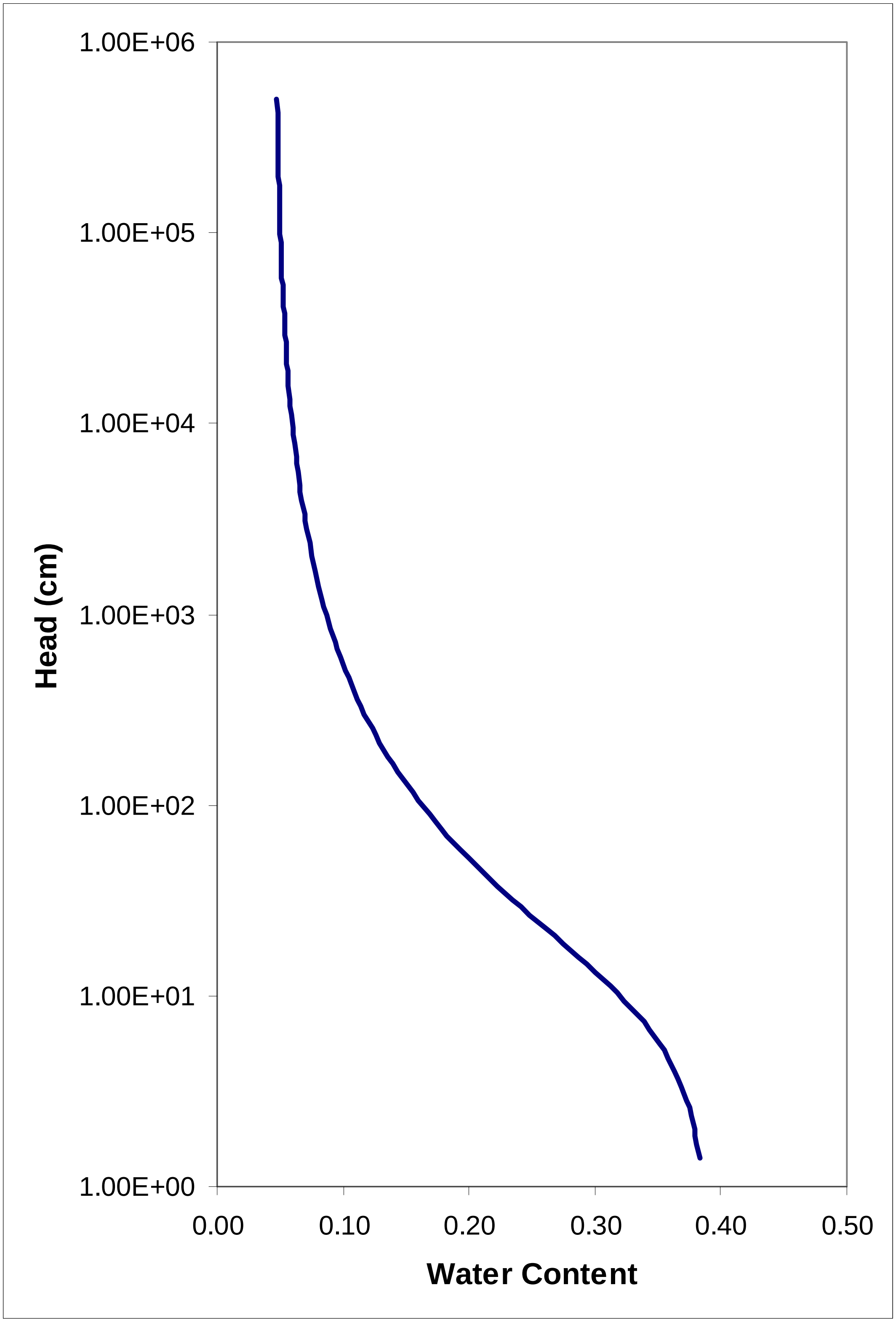


Figure B.9. ET Cover, Topsoil

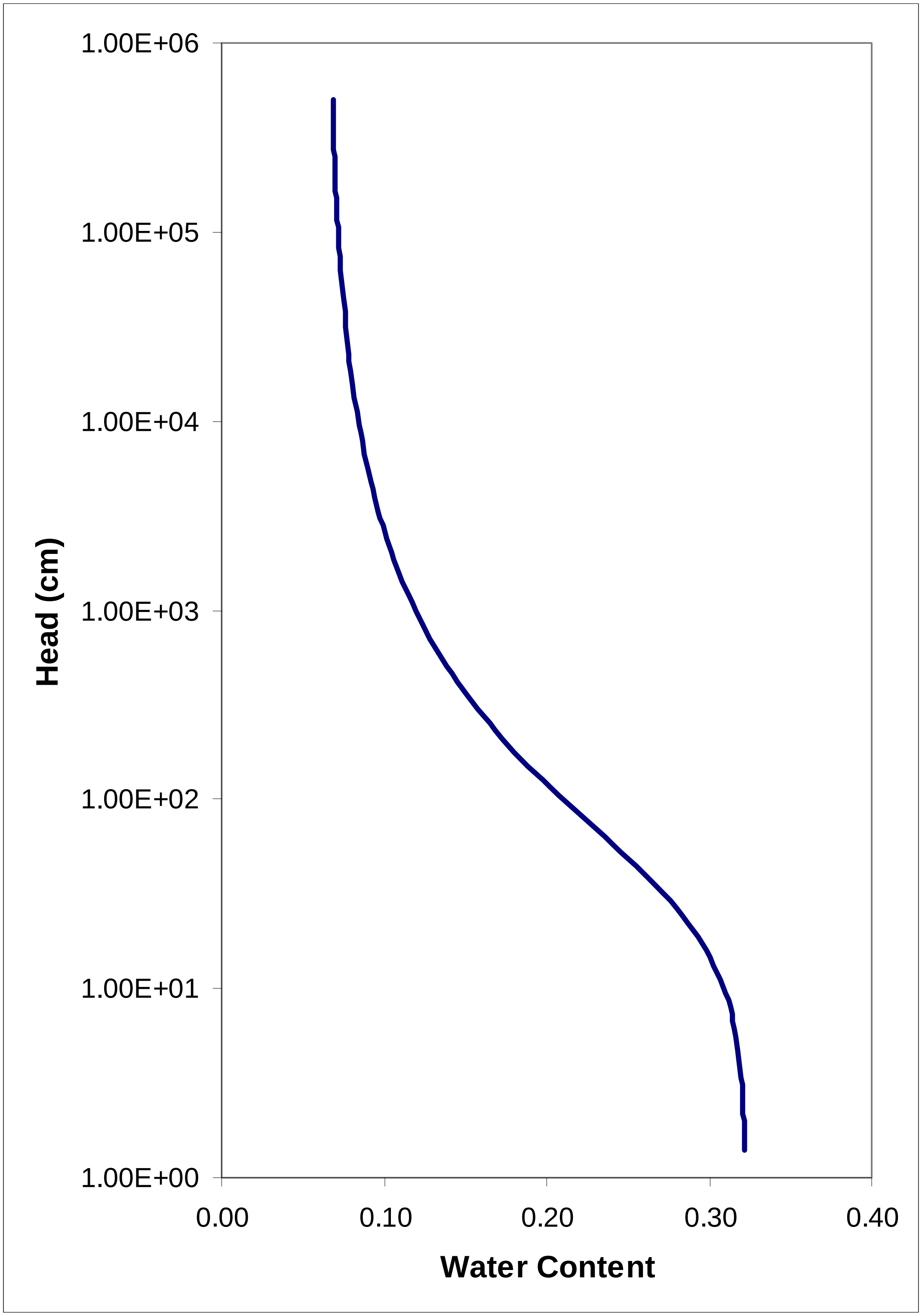


Figure B.10. ET Cover, Compacted Soil Layer

Appendix C

TDR Locations within the Test Site

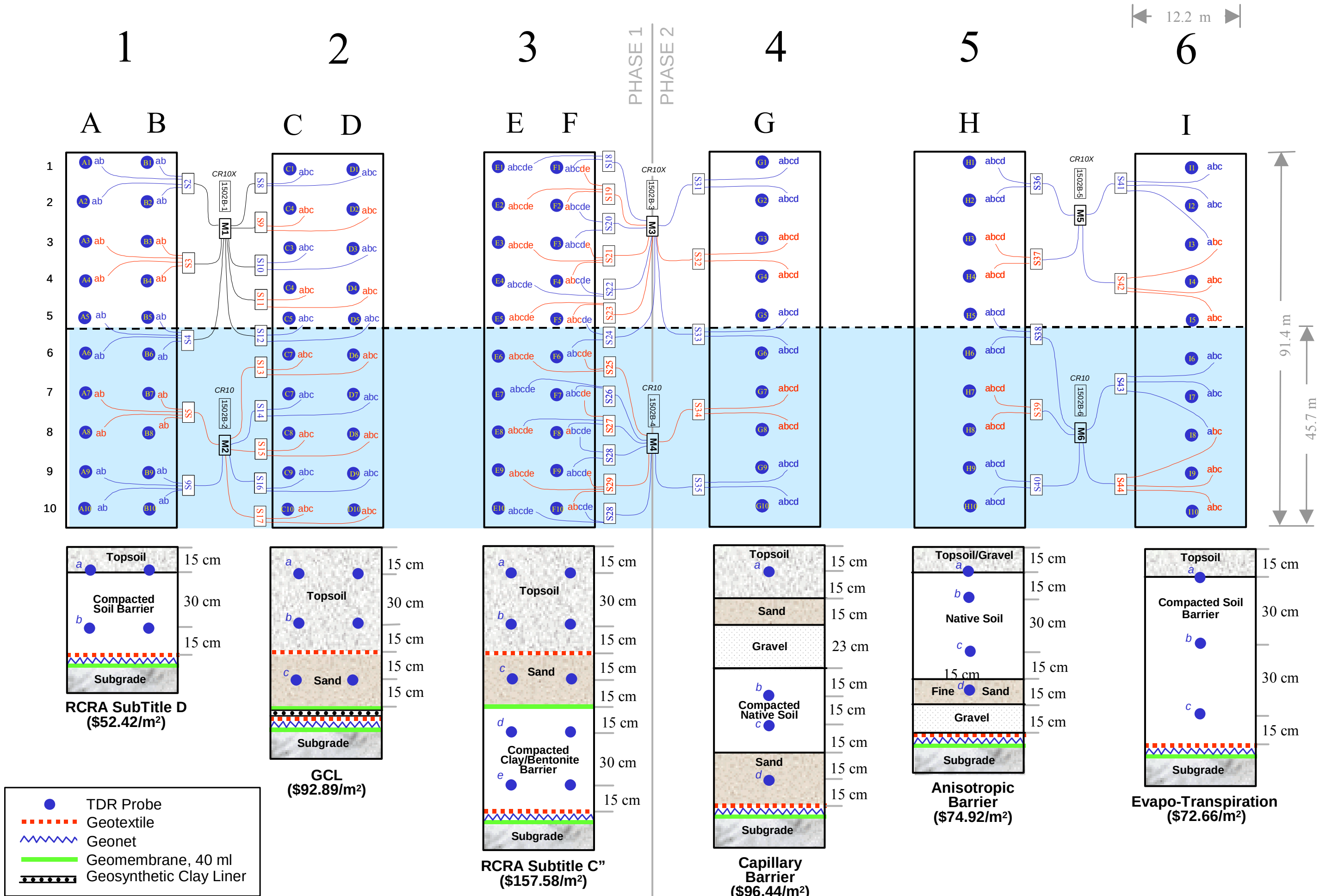


Figure C.1. TDR Probe Locations

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