The Dissertation Committee for Beth Ann Gross certifies that this is the approved version of the following dissertation:

Water Balance Evaluations for Monitored Evapotranspirative Cover Systems at Three Sites in the Semi-Arid and Arid Southwest U.S.

Committee:

____
Randall J. Charbeneau, Co-Supervisor

____
Stephen G. Wright, Co-Supervisor

____
Robert B. Gilbert

____
Edward Kavazanjian, Jr.

____
Bridget R. Scanlon

Water Balance Evaluations for Monitored Evapotranspirative Cover Systems at Three Sites in the Semi-Arid and Arid Southwest U.S.

by

Beth Ann Gross, B.S.C.E.; M.E.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

December 2005

Acknowledgements

I would like to express my appreciation to my committee co-supervisors, Drs. Randall J. Charbeneau and Stephen G. Wright, and committee members, Drs. Robert B. Gilbert, Edward Kavazanjian, Jr., and Bridget R. Scanlon. All have provided me with thoughtful input as I developed this dissertation and improved this document with their valuable comments.

The work described herein could not have been accomplished without access to the data for the three monitored sites described herein. I would like to thank Dr. Stephen F. Dwyer of Sandia National Laboratories, Dr. Tarik Hadj-Hamou of GeoSyntec Consultants, and Dr. Scanlon of Bureau of Economic Geology for providing me with these data.

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Publication No._____________

Beth Ann Gross, Ph.D.

The University of Texas at Austin, 2005

Supervisors: Randall J. Charbeneau and Stephen G. Wright

The focus of this dissertation is the water balance of monitored evapotranspirative cover systems constructed at sites in Yucaipa, California, Albuquerque, New Mexico, and Sierra Blanca, Texas. The contributions of the research are:

- a comprehensive assessment of the status of performance evaluations of evapotranspirative cover systems;
- an evaluation of the short-term (2 to 5-year) performance of the three cover systems using data from field monitoring programs and numerical modeling, without calibration;
- an evaluation of the suitability of using short-term performance assessments to predict intermediate-term (10 to 30-year) performance; and
- a comparison of the long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems at the Albuquerque site, one designed with loosely placed soil to promote plant growth and the other designed with compacted soil having a low saturated hydraulic conductivity.

For the short-term performance evaluation, the water balances of the cover systems were modeled using the HELP (version 3.07), LEACHM (version 4), and UNSAT-H (version 3.01) computer programs. The simulation results were compared to the results of the field monitoring programs. The comparison of simulated and measured drainage for the considered sites was not ideal because drainage was not monitored at the Yucaipa site and zero drainage was measured at the Albuquerque and Sierra Blanca sites.

The suitability of using the short-term performance assessments to predict the intermediate-term performance of the cover systems was evaluated by simulating the water balances of the cover systems with historical weather data and comparing the results of these simulations to the results of the short-term performance assessments.

The possible long-term performance of two hypothetical cover systems was evaluated using interval analysis that considers long-term soil density, vegetation, and precipitation. Simulation results suggest that, in semi-arid and arid climates that receive much of their precipitation in the summer, a cover system with looser soil and deeper roots may allow less drainage than a cover system with denser soil and shallower roots, but may be less reliable in the long term if precipitation patterns or vegetation changes.

Recommendations for assessing performance of evapotranspirative cover systems and for increasing reliability of evapotranspirative cover systems are presented.

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Chapter 1: Introduction

1.1 STATEMENT OF THE PROBLEM

Final cover systems (hereafter referred to as "cover systems") are used at waste management units (landfills, waste piles, and surface impoundments) and remediation sites. The purpose of these systems is to contain waste and waste by-products (leachate and landfill gas), control water and air infiltration into the waste, and prevent the occurrence of odors, disease vectors, and other nuisances. Cover systems are also used to meet erosion, aesthetic, and site end-use criteria. These systems are often intended to achieve their functional requirements for periods of many decades to hundreds or even thousands of years with minimal maintenance.

Cover systems frequently incorporate a compacted clay layer as a barrier or a barrier component (beneath an overlying geomembrane in a composite barrier) and rely on the low saturated hydraulic conductivity of the compacted clay barrier to minimize drainage through the cover system. Information developed over the last decade indicates that, when used without an overlying geomembrane and a sufficiently thick (at least 0.6 m) layer of cover soil, a compacted clay barrier in a cover system often does not maintain its low permeability for more than a few years (Montgomery and Parsons, 1989, 1990; Corser and Cranston, 1991; Corser et al., 1992; Basnett and Bruner, 1993; Melchior et al., 1994; Khire, 1995; Maine Bureau of Remediation and Waste Management, 1997; Melchior, 1997a,b; Waugh and Smith, 1997; Albrecht and Benson, 2001; Bonaparte et al., 2002; Gross et al., 2002; Roesler et al., 2002; Dwyer, 2003; Albright et al., 2004; Bonaparte et al., 2004; Benson et al., 2005). Based on laboratory tests of the effects of desiccation on compacted clays (Albrecht and Benson, 2001) and on periodic hydraulic conductivity measurements of compacted clay barriers in cover system field installations (Maine Bureau of Remediation and Waste Management, 1997; Waugh and Smith, 1997; Dwyer, 2003), a clay barrier compacted wet of its optimum water content to a saturated hydraulic conductivity on the order of 1×10^{-9} m/s can exhibit an increased hydraulic conductivity on the order of 1×10^{-7} m/s after several cycles of wetting and drying. The intrusion of plant roots into the clay can also contribute to an increase in hydraulic conductivity. A clay barrier compacted at optimum water content to a higher saturated hydraulic conductivity, on the order of 1×10^{-7} m/s, can also experience an increase in hydraulic conductivity when subjected to wetting and drying cycles and the penetration of plant roots. However, the relative increase in hydraulic conductivity is much smaller (less than an order of magnitude) than for a lower permeability clay barrier.

A compacted clay barrier is more likely to degrade over time if it is used at a semi-arid or arid site, is located above the depth of frost penetration, or is penetrated by plant roots as compared to a compacted clay barrier used at a humid site and located deeper in the soil profile, below the depth of frost penetration and the root zone. While there are several different systems used to classify the annual moisture availability of a site, this study uses the humidity index, defined as mean annual precipitation divided by mean annual potential evapotranspiration, i.e., the amount of water transpired in a given time by a short green crop completely shading the ground, of uniform height, and without water limitations. As classified by the U.N. Environmental Program (UNEP) (1997), arid zones have a humidity index ranging from 0.05 to less than 0.20, and semi-arid zones have a humidity index ranging from 0.20 to less than 0.50. A compacted clay barrier located above the depth of frost penetration in any climate may experience increased hydraulic conductivity due to desiccation cracking, freeze-thaw cracking, and frost heaving (Othman et al., 1994).

Due to the issues with the long-term hydraulic performance of compacted clay barriers and the cost of constructing these barriers, especially in areas where clayey soils are not readily available, evapotranspirative barriers are being increasingly used in lieu of compacted clay barriers to minimize infiltration through landfill covers in arid and semi-arid climates. An evapotranspirative barrier consists of a thick layer of relatively fine-grained soil, such as silty sand or sandy clay, that is capable of supporting vegetation due to its edaphic properties and its ability to store water and provide root oxygenation. The high water storage capacity of the fine-grained soils allows the evapotranspirative barrier to store a significant amount of water against the force of gravity by surface tension and capillary action until the water can later be removed by evapotranspiration. This mechanism has led to evapotranspirative barriers sometimes being called "store-and-release" barriers. The relatively low hydraulic conductivity of the fine-grained soils, even at high degrees of saturation, limits advancement of the wetting front into the evapotranspirative barrier during seasonal wet periods (rainfall or snow melt). Because they are constructed drier and generally with less compactive effort than compacted clay barriers, evapotranspirative barriers are less prone to desiccation cracking than compacted clay barriers when both are constructed with soils having the same texture (a soil classification used by soil scientists and based on the proportions of sand, silt, and clay).

While the hydraulic performance of conventional cover systems with geomembrane/compacted clay composite barriers is generally assumed to be adequate based on calculated rates of leakage through these cover systems and on their inferred performance extrapolated from liner system leakage data (Gross et al., 1997), the hydraulic performance of cover systems with evapotranspirative barriers (hereafter referred to as "evapotranspirative cover systems") is not easily measured and must be demonstrated through modeling and/or indirect monitoring. However, it is not clear how these performance demonstrations should be made. In most cases, the modeling demonstrations are conducted using soil properties measured during construction and the monitoring demonstrations are implemented over a relatively short time period (several years) after construction. With this approach, the performance assessment of an evapotranspirative cover system is strongly dependent on the initial hydraulic conditions of the cover system, and the modeled or monitored performance may have little relevance to long-term cover system performance.

The focus of this dissertation is the water balance of monitored evapotranspirative cover systems constructed at sites in Yucaipa, California, Albuquerque, New Mexico and Sierra Blanca, Texas. The short-term (2 to 5-year) performance of these cover systems was evaluated using data from field monitoring programs and the results of numerical modeling conducted for this study and presented herein. The suitability of the short-term performance assessments to predict the intermediate-term (10 to 30-year) performance of these cover systems was then evaluated by comparing the short-term water balances to water balances simulated with 30 years of historical weather data from nearby weather stations. Lastly, the long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems in Albuquerque, one designed with loosely placed soil to promote plant growth and the other designed with compacted soil having a low saturated hydraulic conductivity, was evaluated using numerical modeling with interval analysis and considering the effects of soil compaction, leaf area index, vegetation root depth, and amount of precipitation.

1.2 OBJECTIVES

The objectives of the study presented herein were to:

- review the state-of-practice for evapotranspirative cover system design, construction, and performance evaluation and identify issues impacting the assessment of evapotranspirative cover system performance;
- screen nine computer models for water balance that have been used to evaluate the performance of evapotranspirative cover systems and select several representative models to simulate the water balance of three monitored evapotranspirative cover systems located in the warm semi-arid and arid southwest U.S.: a small municipal solid waste landfill site in Yucaipa, California with the least extensive data collection; a research site in Albuquerque, New Mexico with more extensive instrumentation; and a highly-instrumented small research site in Sierra Blanca, Texas;
- assess the short-term (2 to 5-year) performance of the three evapotranspirative cover systems using data from field monitoring programs for the cover systems and the results of numerical modeling conducted with the selected computer models [Hydrologic Evaluation of Landfill Performance (HELP), Leaching Estimation and Chemistry Model (LEACHM), and UNSAT-H];
- evaluate the suitability of using short-term performance assessments to predict intermediate-term (10 to 30-year) performance of the cover systems by comparing the short-term water balances to water balances simulated with 30 years of historical weather data from nearby weather stations;
- evaluate the long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems in Albuquerque, one designed with loosely placed soil to promote plant growth and the other designed with compacted soil

having a low saturated hydraulic conductivity, using numerical modeling with interval analysis and considering the effects of soil compaction, leaf area index, vegetation root depth, and amount of precipitation; and

- develop recommendations for assessing the performance of evapotranspirative cover systems and for increasing the reliability of evapotranspirative cover systems.

1.3 ORGANIZATION

The remainder of this dissertation is organized as follows:

- the state-of-practice for the design, construction, and performance evaluation of evapotranspirative cover systems is reviewed in Chapter 2;
- the water balance process is described, water balance computer models for evapotranspirative cover systems are compared, and three models are selected for use in this study in Chapter 3;
- the design, construction, and monitoring of the three evapotranspirative cover systems considered in this study are described in Chapter 4;
- several significant studies of evapotranspirative cover system performance conducted by others and that involved water balance modeling and monitoring are summarized in Chapter 5;
- the short-term performance of the three evapotranspirative cover systems is evaluated in Chapter 6 by comparing the results of water balance simulations conducted for this study with the results of the field monitoring programs;
- the suitability of using the short-term performance assessments to predict intermediate-term performance and the long-term reliability of two hypothetical evapotranspirative cover systems in Albuquerque are evaluated in Chapter 7 with water balance simulations;

- conclusions and recommendations are presented in Chapter 8; and
- descriptions of the water balance computer models selected for the simulations summarized in Chapters 6 and 7 are presented in Appendix A.

Chapter 2: Review of State-of-Practice for Design, Construction, and Performance Assessment of Evapotranspirative Cover Systems

2.1 Cover System Components

Cover systems for waste containment and remediation sites may consist of multiple layers of different types of soils and/or geosynthetics, each with one or more specific functions. Potential cover system components include the following (Figure 2.1):

- surface layer, to resist erosion by water and wind, be maintainable, and provide a growing medium for vegetation, if present;
- protection layer, to protect underlying layers from erosion, exposure to wet-dry cycles, freeze-thaw cycles, and biointrusion by plants and animals, to temporarily store water until the water can be returned to the atmosphere by evapotranspiration, to support plant growth by providing a rooting media and water reservoir, and to reduce migration of gases, e.g., oxygen, methane, or radon, into or out of the contained waste;
- drainage layer, to limit the buildup of hydraulic head on an underlying barrier and drain the overlying layers;
- hydraulic barrier, e.g., geomembrane and/or compacted clay, to impede drainage of water through the cover system, promote storage or lateral drainage of water in the overlying layers, and restrict the migration of gases through the cover system;
- gas collection layer, to collect gases beneath the barrier and convey them to a controlled collection point; and

- foundation layer, to provide grade control for cover system construction, a firm subgrade for compaction of overlying layers, and adequate bearing capacity for overlying layers.

Evapotranspirative cover systems commonly include at least a surface layer. They may also include a biobarrier, gas barrier, and other layers. The simplest evapotranspirative cover system is a monolithic evapotranspirative barrier comprised of a single soil type (Figure 2.2).

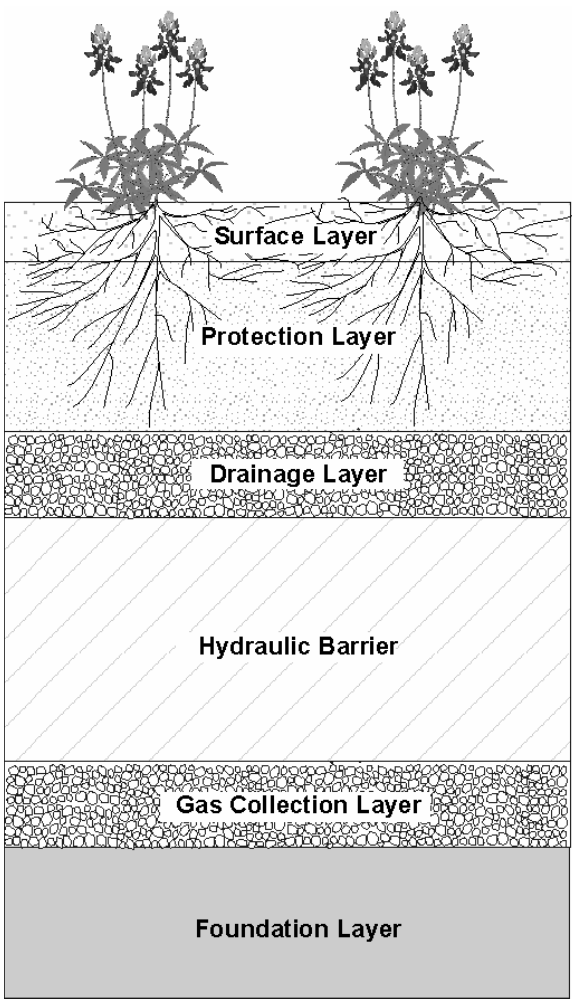

Figure 2.1: Typical Cover System Components.

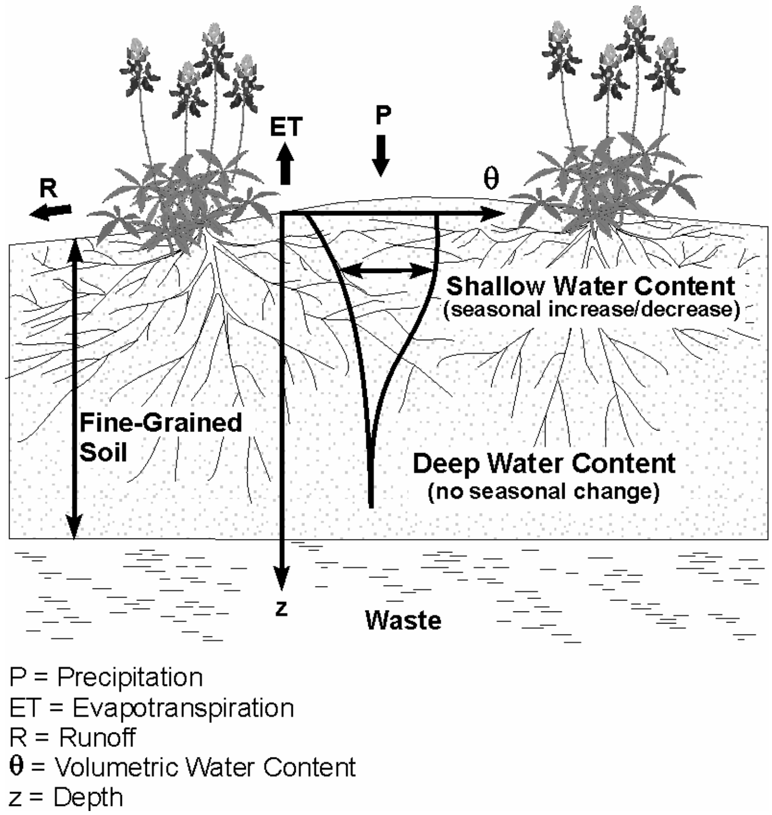

Figure 2.2: The Simplest Evapotranspirative Cover System: a Monolithic Evapotranspirative Barrier.

2.2 Design State-of-Practice

2.2.1 Design Drainage Rate

Because of the issues with compacted clay barrier performance in certain settings and the potential cost savings from employing an evapotranspirative barrier, evapotranspirative barriers, rather than compacted clay barriers, are being increasingly used in cover systems at semi-arid and arid sites. Evapotranspirative barriers are also used in cover systems for sites in humid climates, but to a lesser extent than for sites in drier climates and generally only when a relatively high level of drainage (percolation through the barrier) is acceptable, e.g., 50 mm/yr drainage in a humid climate versus 1 mm/yr drainage in a semi-arid climate. For example, the author designed a cover system with an evapotranspirative barrier for a fly ash basin located in Virginia, a humid site. The simulated average annual drainage through the cover system, which was constructed in 2002, was approximately 100 mm/yr.

For municipal solid waste and hazardous waste landfills, Federal regulations for cover systems (40 CFR §258.60 and §264.310, respectively) specify as a performance criterion minimization of water drainage into the waste (or, equivalently, minimization of liquids migration through the landfill by preventing the bathtub effect). The Federal regulations for municipal solid waste landfills include a provision for State approval of an alternative cover system, such as an evapotranspirative cover system, if hydraulic and erosion criteria are met. The hydraulic criterion is that an alternative cover system must include a barrier that provides reduction in drainage equivalent to that provided by the minimum standard barrier prescribed by the regulations. If the municipal solid waste landfill is unlined, the barrier in the alternative cover system must perform equivalent to a 0.45-m compacted soil layer having a maximum hydraulic conductivity of 1×10^{-7} m/s. If the landfill has a liner system, the barrier in the alternative cover system must perform equivalent to a composite barrier consisting of a geomembrane overlying the above compacted soil layer.

The Federal regulations for hazardous waste landfills also allow a performance-based cover system design. There are no prescription design criteria for hazardous waste landfills. However, the cover system for hazardous waste landfills recommended in U.S. Environmental Protection Agency (EPA) guidance (EPA, 1989) incorporates a composite barrier consisting of a geomembrane overlying a 0.9-m thick compacted soil layer having a maximum hydraulic conductivity of 1×10^{-9} m/s.

The EPA has not established maximum drainage rates for alternative cover systems to demonstrate performance equivalent to conventional cover systems. However, the design drainage rates reported for evapotranspirative cover systems in EPA's on-line database of alternative cover system projects (EPA, 2004) are generally less than 10 mm/yr, and over half of the design drainage rates are less than 3 mm/yr. The majority of cover systems in the database are located at semi-arid or arid sites. For some evapotranspirative cover systems, design drainage rates are considered a maximum value; for other cover systems, they are considered an average value. The database also shows that the design values were calculated with different computer models and design approaches, e.g., meteorological conditions.

Some researchers and design engineers are currently recommending that evapotranspirative cover systems be designed to accommodate precipitation for a relatively uncommon scenario, such as the highest annual rainfall on record modeled for five consecutive years (Khire et al., 2000). This recommendation is made without consideration of the cover system design life, the likelihood that such a weather pattern would occur, the fact that above-normal precipitation could, and has in field studies (Waugh et al., 1994; Scanlon et al., 2005), led to above-normal growth of vegetation (which dries the cover system out faster than normal), and the implications of failure. The effect of high precipitation on vegetation growth may typically not be considered because most computer models for water balance do not incorporate feedback between environmental conditions, such as solar radiation and temperature, and plant growth. Designing for an uncommon precipitation event may lead to evapotranspirative cover systems designs that are overconservative and may prohibit the use of evapotranspirative cover systems at sites where occasional moderate drainage, e.g., 10 mm in one year every

30 years, is acceptable based on risk considerations or for hydraulic performance equivalency.

While it is useful to understand the effect of a relatively uncommon design event, unless there is a concern that this event may lead to an acute contamination condition or some other undesirable condition, e.g., slope instability, a more rational design approach would generally be to first design an evapotranspirative cover system to achieve a specified average hydraulic performance (total flow) over its design life. The required performance for this cover system could be selected based on risk, preventing the "bathtub effect", and/or other factors. As a second step, the effect of an uncommon scenario could be considered (and should be, to verify that the cover system would not be anticipated to fail due to erosion, slope instability, etc.); but, it would be acceptable for the evapotranspirative cover system to have a short-term reduced level of hydraulic performance when stressed by this event. For the U.S. Department of Energy's (DOE's) Hanford Site, in Richland, Washington, for example, cover systems are being designed to isolate wastes for at least 1,000 years (Gee et al., 1997a). The design storms that are being considered are the 24-hr storm with a 1,000-year return period and the long-term average annual precipitation over the facility design life, which is inferred to be approximately three times the modern average annual precipitation based on studies of the paleoclimate.

2.2.2 Barrier Thickness

To minimize drainage, an evapotranspirative barrier should generally be sufficiently thick such that the soil water content does not change near the base of the barrier, i.e., changes in soil water storage should occur in the upper portion of the barrier (Figure 2.2). The minimum required barrier thickness is a function of the frequency and intensity of precipitation, the magnitude of potential evapotranspiration (PET) when most precipitation occurs, the unsaturated hydraulic properties of the soil, the type and vigor of vegetative cover, and other factors. The barrier should be thick enough to store excess precipitation during times of vegetation dormancy and/or low evaporation rates. Increasing the thickness of a barrier beyond some site-specific maximum, however, provides no significant incremental reduction in drainage (Zornberg et al., 2003) when water infiltrating the deeper reaches of the barrier is not removed by evapotranspiration. Evapotranspirative barrier thickness typically ranges from about 0.6 m to 2 m. In their draft final cover guidance for Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response and Liability Act (CERCLA) sites, EPA is recommending a minimum evapotranspirative barrier thickness of 0.9 m (Bonaparte et al., 2004).

2.2.3 Capillary Break

The water storage capacity of an evapotranspirative barrier can be enhanced by constructing a finer-grained, e.g., clayey silt, barrier over a coarser-grained, e.g., sand, soil layer (Figure 2.3). This special type of evapotranspirative barrier, which incorporates a capillary break at the interface of the two materials, is called a capillary barrier. As Johnson et al. (1982) and Cartwright et al. (1988) demonstrated through numerical modeling and laboratory and field experiments, the contrast in pore sizes at the boundary between the finer- and coarser-grained materials has the effect of increasing the water storage capacity of the finer-grained layer under unsaturated conditions when the matric potential (water pressure plus air pressure) along the boundary is somewhat less than the air-entry potential (the matric potential below which desaturation begins to occur, Figure 2.3) of the coarser-grained material.

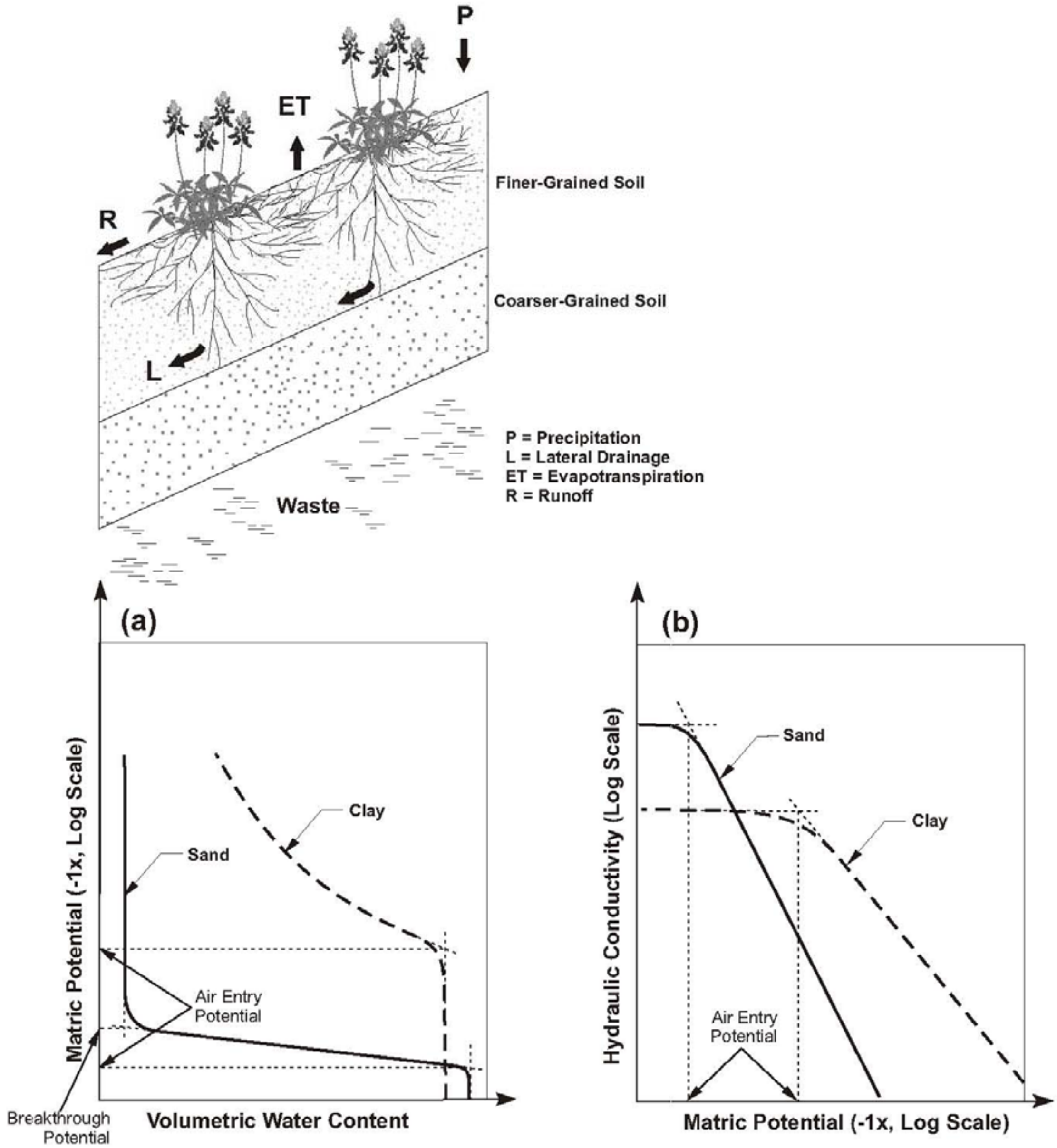

Figure 2.3: A Capillary Barrier Relies on Soil Textural Differences to Enhance the Water Storage Capacity of the Finer-Grained Soil at Low Matric Potentials: (a) Example Soil Water Characteristic Curves of Capillary Barrier Soils; and (b) Example Hydraulic Conductivity Functions of Capillary Barrier Soils.

Using the results of laboratory infiltration tests on column samples, Stormont and Anderson (1999) found that the potential at which the capillary break effect becomes ineffective (breakthrough potential) is controlled by the coarser-grainer material and is independent of the texture of the finer-grained material and infiltration rate. They also found the breakthrough potential to occur approximately at the inflection point in the matric potential versus water content curve (soil water characteristic curve, Figure 2.3) where the curve is steeply sloping and the water content is tending towards zero.

At low matric potential, the unsaturated hydraulic conductivity of the coarser-grained soil is much less than that of the finer-grained soil in a capillary barrier (Figure 2.3). As the soil becomes wetter and the matric potential increases, the saturated hydraulic conductivity of the coarser-grained soil begins to approach that of the finer-grained soil. When the breakthrough potential is reached, water starts to flow across the boundary between the two materials, but only at a slow rate because the unsaturated hydraulic conductivity of the coarser-grained soil is still low and generally less than that of the coarser-grained soil (Khire et al., 2000). If the matric potential again drops below the breakthrough potential, the capillary break between the two materials is reestablished (Stormont and Anderson, 1999).

The magnitude of storage capacity increase provided to the finer-grained soil by the coarser-grained soil depends on the absolute and relative pore sizes of the two soils and the thickness of the finer-grained soil layer. If the coarser-grained material is a coarse sand or coarser, the matric potential in the overlying finer-grained soil must typically approach near-saturated conditions before the breakthrough potential of the coarser-grained material is reached (Figure 2.3) and significant flow occurs from the finer-grained layer into the coarser-grained layer.

The coarse-grained capillary break constructed beneath a silt loam layer in a small tube lysimeter at the DOE Hanford Site, Richland, Washington increased the storage capacity of the silt loam layer by almost a factor of two (Gee et al., 1997a). [A lysimeter is a device used to collect water draining from soil under controlled conditions.] In their water balance simulations for instrumented evapotranspirative cover systems in Sierra Blanca, Texas and at Sandia National Laboratories in Albuquerque, New Mexico, Scanlon et al. (2005) estimated that inclusion of a capillary barrier increased the storage capacity of the overlying sandy clay loam and loamy sand soils by approximately a factor of 2.5.

If they are sloped, capillary barriers can divert infiltrating water via unsaturated lateral flow in the finer-grained soil adjacent to the interface between the finer- and coarser-grained soil layers (Johnson et al., 1982). The lateral diversion capacity of the finer-grained soil is dependent in large part on the hydraulic conductivity of the soil. Laboratory and field tests of capillary barriers with homogeneous finer-grained soil layers indicate that the effective diversion lengths are less than 10 m (Nyhan et al., 1990; Hakonson et al., 1994; Stormont, 1995; Stormont, 1996; Nyhan et al., 1997). These short diversion lengths are a consequence of the relatively low hydraulic conductivity of the finer-grained soils compared to the relatively high infiltration rates that occur when the soil is relatively wet, e.g., spring snowmelt. Thus, finer-grained soils that are often preferred as a rooting medium and for their water storage capacity may not be conductive enough to substantially divert water laterally above the capillary break.

To improve the lateral diversion capability of a capillary barrier, a "wicking layer", with characteristics intermediate to those of the coarser- and finer-grained layers, can be installed between the coarser- and finer-grained layers to intentionally convey infiltrating water by lateral flow (Stormont, 1995). The performance of an evapotranspirative cover system with a capillary barrier can also be enhanced if air can flow (passively or actively) through the coarser-grained layer and transport water vapor from the cover system, which would dry the overlying soil. This technology, sometimes referred to as the dry barrier concept, is currently being researched at Sandia National Laboratories, Albuquerque, New Mexico (Sandia National Laboratories, undated).

2.2.4 Natural Analogs

Natural analog studies for cover systems involve evaluating a natural, and sometimes archeological, material or setting that is analogous in some aspect to a proposed cover system material or setting to determine what properties are effective in a given environment or what processes may lead to possible modes of failure. These studies have been used in the design of evapotranspirative cover systems at DOE and other sites to predict long-term climate change, ecological change (vegetation succession, effects of vegetation disturbance, effects of climate change on vegetation, etc.), soil development (soil structure, calcification, effects of soil disturbance, etc.), and cover system water balance (Gee and Ward, 1997; Gee et al., 1997a; Waugh, 1997; Scanlon et al., 2005).

As an example, paleoclimate studies have been used to infer the long-term climate for design of an evapotranspirative cover system at the DOE Hanford Site (Gee et al., 1997a). From analysis of tree rings, packrat middens, and lake sediment pollen, the long-term average annual precipitation inferred for the site is three times the modern average annual precipitation.

Another example is the evaluation of the long-term water status or water balance of the natural system near a site to infer the potential long-term performance of a cover system at the site. An intensive subsurface investigation was performed at the Sierra Blanca, Texas test site to characterize unsaturated flow (Scanlon et al., 2005).

Measurement and modeling of matric potential and bomb chloride (fallout from atmospheric nuclear testing) concentrations at the site revealed that the site has been in a long-term drying period, with upward water movements over the last 10,000 to 15,000 years. Cover systems at the site were constructed with native soil and monitored for five years. During the monitoring period, the cover system soils were much wetter than the natural system due to water added to the soils during construction, precipitation that fell on the soils during construction, and irrigation water. In the very long-term, the water balance of the cover systems could approach that of the natural system. However, it will take many years for the disturbed soils to redevelop the same structure as the native soils. As Scanlon et al. (2005) noted, the native soils have been developing for a very long time and have thick caliche layers. They have also been subjected to 10,000 to 15,000 years of drying.

2.3 CONSTRUCTION STATE-OF-PRACTICE

Evapotranspirative barriers are typically constructed differently from compacted clay barriers because, unlike compacted clay barriers, one function of evapotranspirative barriers is to serve as a rooting medium. Instead of being compacted in thin 0.15-m thick lifts to achieve a relatively high bulk density (dry unit weight), e.g., 95% of the standard Proctor maximum dry density, and low saturated hydraulic conductivity, evapotranspirative barriers are often placed in thicker lifts with less compactive effort, e.g., 80 to 90% of the standard Proctor maximum dry density. Soil compaction reduces the volume and continuity of the larger soil pores, which are most conductive to the water and air needed for root growth. Compaction also hinders soil biological activity, which is needed to break down organic matter to release nutrients for subsequent uptake by plant roots. The limiting of rooting depth in compacted soils can further reduce the uptake of water and nutrients by plants by decreasing the available volume of soil for the roots to penetrate.

Roots are generally unable to enter pores narrower than their root caps. If they are to grow through a compacted soil, they must displace soil particles to widen the pores by exerting a pressure greater than the soil's mechanical strength (Clark and Barraclough, 1999). The effort of displacing the soil particles slows root growth, and thus, can affect the growth of the above-ground plant biomass. Roots also have a maximum axial growth pressure that they can exert on the soil before they buckle and are deflected laterally. For example, Clark and Barraclough (1999) and Clark et al. (2003) reported maximum axial root growth pressure of 0.24 to 0.58 MPa for the plants, primarily crops, they evaluated. To allow plant roots to reach their growth potential in a given soil, the U.S. Department of Agriculture (USDA) National Resources Conservation Service (NRCS) has developed guidance on ideal and root-limiting soil bulk densities (Table 2.1).

Table 2.1: General Relationship Between Soil Bulk Density and Root Growth (National Resources Conservation Service, 2000).

Soil Texture	Ideal Bulk Density (Mg/m^3)	Bulk Density that may Restrict Root Growth (Mg/m^3)	Bulk Density that Restricts Root Growth (Mg/m^3)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.30	1.60	>1.75
Silt loams, silty clay loams	<1.10	1.55	>1.65
Sandy clays, silty clays, some clay loams (35-45% clay)	<1.10	1.49	>1.58
Clays (> 45% clay)	<1.10	1.39	>1.47

1.0 Mg/m^3 = 9.81 kN/m^3

If an evapotranspirative barrier is over-compacted relative to the natural state of the native soils, the barrier soil, if subjected to the same environmental stressors as the native soil, will, over time, loosen and come into equilibrium with its environment. The persistence of soil compaction is influenced by the depth at which it occurs, the soil texture, the climate, and the potential for bioturbation (Hillel, 1998). Natural processes that act to loosen soil include wetting and drying cycles, freezing and thawing cycles, earthworm action, and root penetration. From field studies of the performance of compacted clay liners, it is apparent that the environmental stressors can significantly impact the structure of compacted surficial soils in a relatively short timeframe, i.e., several years (Montgomery and Parsons, 1989, 1990; Corser and Cranston, 1991; Corser et al., 1992; Basnett and Bruner, 1993; Melchior et al., 1994; Khire, 1995; Maine Bureau of Remediation and Waste Management, 1997; Melchior, 1997a,b; Albrecht and Benson, 2001; Bonaparte et al., 2002; Gross et al., 2002; Roesler et al., 2002; Dwyer, 2003; Albright et al., 2004; Bonaparte et al., 2004). However, it can take a much longer time for compacted surficial soils to return fully to their native state, with this time increasing with depth below the ground surface.

An example of a case where it took soil up to several decades to "recover" from compaction effects is found in the study by Kayyal and Wright (1991), who investigated the effect of wetting and drying on the strength of highly plastic compacted clays that had been used to construct embankments along Texas highways. The embankments had been prone to shallow slope failures of approximately 1.5 to 2.0 m deep that typically occurred 10 to 30 years after construction. Slope stability analyses previously conducted on the failed slopes had suggested lower soil shear strengths than those measured on samples of the clay when compacted and tested in the laboratory. Thus, it appeared that the strength of the compacted clay had decreased over time. Wetting and drying tests conducted by Kayyal and Wright (1991) on clay samples compacted and tested in the laboratory revealed that after approximately three cycles of wetting and drying, the clay samples would return to approximately the same gravimetric water content upon rewetting. After ten to fifteen cycles, no further breakdown in soil aggregates (from cracking) was observed. The initial bulk densities of the compacted samples were not explicitly given; however, from the available data it appears that they were about 1.35 to 1.52 Mg/m^3 (13.2 to 14.9 kN/m^3).

Kayyal and Wright (1991) also performed consolidated-undrained triaxial compression tests with pore pressure measurements on three specimen types: (i) compacted clay samples; (ii) compacted clay samples that had undergone 20 cycles of wetting and drying; and (iii) normally consolidated clay samples. The samples that had undergone cyclic wetting and drying had a similar shear strength envelope to that of the normally consolidated samples. These results, combined with the results of the wetting and drying tests and subsequent x-ray diffraction tests, demonstrated that the structure of the compacted clay had essentially returned to a normally consolidated state after 20 cycles of wetting and drying. Kayyal and Wright (1991) concluded that the embankment failures were partially attributable to the weakening of the compacted soil as it was subjected to wetting and drying cycling. Because the shallow slope failures occurred at depths of 1.5 to 2.0 m, the natural processes that affect soils apparently were effective to a depth of at least 2.0 m.

As another example of the long-term impact of soil compaction, Sharratt et al. (1998) evaluated the physical properties of a loam within and adjacent to a historic wagon trail in western Minnesota. Though the trail had last been used over 120 years earlier, there was still evidence of wagon wheel ruts and the soil within the ruts had a higher bulk density and lower hydraulic conductivity than the soil adjacent to the trail.

For semi-arid and arid evapotranspirative cover sites in the southwest U.S., such as those described herein, the effect of evapotranspirative barrier over-compaction may be quite persistent. Due to the climate in the southwest, there is little opportunity for the soils to be subjected to the magnitude of wet-dry and freeze-thaw effects that soils in the northern and eastern part of the country experience. In addition, in this harsher environment, there is generally less opportunity for soil disturbance by plants and animals than there is in parts of the country that are more humid.

Even if the evapotranspirative barrier is not over-compacted, its bulk density may change over time. Anderson et al. (1993) summarized water balance data for ten 3.0 m wide by 10.7 m long test trenches that were constructed in 1983 at the Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho and subsequently monitored. The 2.4-m deep trenches were filled with on-site silt loam compacted to a bulk density of approximately 1.4 Mg/m^3 (14 kN/m^3). Based on the bulk density values in Table 2.1, this density is somewhat greater than the ideal bulk density for silt loam [less than 1.10 to 1.30 Mg/m^3 (10.8 to 12.7 kN/m^3)], but less than the bulk density that may restrict root growth [less than 1.55 to 1.60 Mg/m^3 (15.2 to 15.7 kN/m^3)]. Eight test trenches were vegetated, and two trenches were left bare. By 1987, after four growing seasons, the bulk density of the test trenches had decreased to approximately 1.28 Mg/m^3 (12.6 kN/m^3). No information was given by Anderson et al. (1993) on the range in bulk densities between the different trenches or on the natural bulk density of the silt loam at the site.

In practice, there has been reluctance to place soils for evapotranspirative cover system at bulk densities that are beneficial for plant growth, probably because design engineers or regulators are used to constructing soils to serve as structural members or hydraulic barriers and because they are more comfortable relying on low saturated hydraulic conductivity rather than evapotranspiration for hydraulic control. In addition, relatively high soil bulk densities may be required to provide slope stability of evapotranspirative cover systems on steep slopes, such as on the 2 horizontal: 1 vertical slopes of the Yucaipa, California cover system evaluated herein. Consequently, soils used as vegetative layers in evapotranspirative cover systems have sometimes been constructed like a structural fill layer or like a compacted clay barrier, except drier.

Hauser et al. (2001) commented on the importance of limiting the bulk density of evapotranspirative cover systems soils and noted that the finer-grained soil layers in capillary barrier test plots constructed at Hill Air Force Base had a bulk density of 1.86 Mg/m^3 (18.2 kN/m^3), which, based on the criteria in Table 2.1, would be root restricting for any soil type. The specified soil densities for the three cover system test plots evaluated herein ranged from 95% to 110% of the standard Proctor maximum dry density (ASTM D 698) for one site to a minimum of 90% of the modified Proctor maximum dry density (ASTM D 1157) for the other two sites. All three were constructed with average bulk densities that are considered root restricting, i.e., average bulk densities of 1.8 to 1.97 Mg/m^3 (17.7 to 19.3 kN/m^3).

It is noted that the bulk densities of native site soils may themselves be relatively dense and root restricting. For example, at the Sierra Blanca, Texas test site evaluated herein, bulk densities of native soil samples ranged from 1.65 to 1.81 Mg/m^3 (16.2 to 17.6 kN/m^3) (Dames & Moore, 1996).

2.4 PERFORMANCE EVALUATION STATE-OF-PRACTICE

2.4.1 Precision of Water Balance Assessments

While the hydraulic performance of conventional cover systems with geomembrane/compacted clay composite barriers is generally assumed to be adequate based on calculated rates of leakage through these cover systems and on their inferred performance extrapolated from liner system leakage data (Gross et al., 1997), the hydraulic performance of evapotranspirative cover systems must be demonstrated through modeling and/or monitoring. However, it is not clear how these demonstrations of equivalency should be made. It is important to use a demonstration method that will provide an acceptable level of precision and accuracy.

Benson et al. (2001) evaluated the precision of five methods for evaluating drainage through monolithic evapotranspirative cover systems: (i) analyzing the water balance by estimating or measuring all components of the water balance (including evapotranspiration) except for drainage and then calculating drainage using a mass balance approach; (ii) monitoring soil water contents and potentials and inferring drainage based on trend analysis; (iii) monitoring soil water contents and potentials and calculating drainage using these data and Darcy's equation; (iv) performing tracer experiments; and (v) measuring drainage directly using a lysimeter. Excluding tracer experiments, the precision of which could not be quantified, Benson et al. (2001) ranked the above methods from least to most precise as monitoring and trend analysis, water balance analysis, monitoring and Darcy's equation approach, and lysimetry. They estimated that drainage rates determined using the water balance method have a precision (fineness of measurement) of approximately 50 mm/yr in arid and semi-arid climates and 100 mm/yr in humid climates.

The uncertainties in drainage presented by Benson et al. (2001) are high because they are absolute and represent the largest anticipated uncertainties for the considered cover system scenarios. A more probable precision when the water balance components are measured is calculated by considering the measurements of the water balance components to be independent and their errors governed by a normal distribution. Each measurement has a 50% chance of being underestimated and a 50% chance of being overestimated. The most probable error for water balance can then be calculated as the square root of the sum of the squares of each error. Considering the same scenario as Benson et al. (2001), i.e., a 1-m thick evapotranspirative cover system, the most probable errors propagated to drainage are approximately 36 mm/yr in arid and semi-arid climates and 70 mm/yr in humid climates, still relatively high values.

Calculating the uncertainty of drainage determined from water balance calculations is more complex because, in a simulated water balance, not all of the water balance components are independent. For example, if runoff is overestimated, less water infiltrates into the cover system and thus soil water storage, evapotranspiration, and consequently drainage, are likely to be underestimated. Thus, correlation between the variables tends to be negative (the errors tend to cancel each other out). For example, if evapotranspiration is assumed to have a precision of 30 mm/yr, this does not mean that the precision of the simulated drainage value is at least 30 mm/yr. Instead, the effect of this imprecision would be distributed among the different water balance components in accordance with hydrologic principles and would take into account the hydraulic properties of the cover system materials. It is accepted, however, that water balance calculations have a moderate level of imprecision and inaccuracy. The numerical methods used for water balance require input parameters that are not typically measured and for which only a limited database is available. Even when the parameters are measured, there can be significant differences between laboratory or field-measured values and representative field values due to bias associated with measurement technique, spatial variability, scale effects, and time effects. In addition, the analytical methods for a number of models have not been well validated.

In contrast to the water balance approach, Benson et al. (2001) calculated a precision of 0.00004 to 0.5 mm/yr for drainage rates measured using the drainage lysimeter developed for the Alternative Cover Assessment Program (ACAP), a cover system monitoring program developed by the EPA. The lower value of precision corresponds to one tip of a 8-mL tipping bucket over a one-year period, and the higher value corresponds to one count of a dosing siphon over a one-year period. Though not explicitly stated by Benson et al. (2001), the precision values are for measurement of drainage from the lysimeter.

It the lysimeter was considered part of the system for measuring drainage (in addition to the tipping bucket or dosing siphon), the precision of drainage rates measured using the ACAP lysimeter would likely be somewhat higher than the lower end of the precision values reported by Benson et al. (2001). Flows into the lysimeter will be somewhat higher than flows from the lysimeter. For example, the geomembrane floor of the lysimeter may not be completely flat and may contain small wrinkles or depressions that capture small amounts of water. In addition, small amounts of water draining from the cover system may be retained by capillarity in the geotextile component of the geocomposite drainage layer above the geomembrane.

It is noted that the lysimeter itself affects the accuracy of the drainage measurement. The drainage layer in the ACAP lysimeter creates a capillary break (seepage face boundary) beneath a cover system, and the lysimeter barrier induces an artificial no-flow boundary beneath the capillary break (Benson et al., 2001). The former effect may lead to underestimation of cover system drainage and overestimation of storage capacity if the natural boundary beneath the evapotranspirative cover system does not approximate a capillary barrier (Scanlon et al., 2005). The latter effect prevents the upward or downward movement of liquid or vapor across the lysimeter boundary and may overestimate cover system drainage.

2.4.2 Short-Term Performance Monitoring

Relatively "complete" field data have recently began to be collected for evapotranspirative cover systems, providing information on cover system performance that is more comprehensive. While the monitoring systems in the past focused on the major water balance components (e.g., runoff, drainage), current monitoring systems often include sensors to continuously monitor soil water content and potential. However, the monitoring system may impact the field water balance, e.g., the bottom boundary when a lysimeter is used, and the effect of in-situ sensors on the measured and actual field water balance has not been well quantified, e.g., the impact of looser soil around the sensors and sensor cables.

To better understand cover system performance and the relative performance of cover systems constructed with different soils and vegetation in different climates, the EPA has developed the ACAP (Wilson et al., 1999; Bolen et al., 2001; Roesler et al., 2002; Albright et al., 2004). Under this program, evapotranspirative cover systems at eleven sites in different regions of the U.S. (Figure 2.4) have been instrumented, and data on the field water balances are being collected. The goal is to collect and evaluate at least five years of data from each site. Besides the sites in the ACAP, evapotranspirative cover system test sites in the U.S. have been located at the DOE Hanford Site, Richland, Washington (Fayer et al., 1992; Link et al., 1993; Waugh et al., 1994; Sackschewsky et al., 1995; Fayer and Gee, 1997; Gee et al., 1997a,b; Gee et al., 2002), Los Alamos National Laboratory, Los Alamos, New Mexico (Nyhan et al., 1989a,b, 1990, 1993, 1997), Sandia National Laboratories, Albuquerque, New Mexico (Dwyer, 1997, 2003; Dwyer et al., 1998, 2000; Scanlon et al., 2005), Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho (Anderson et al., 1991; Anderson et al., 1993; Limbach et al., 1994; Anderson, 1997; Laundré, 1997; Porro and Keck, 1997; Gaglio et al., 2001; Porro, 2001; Scanlon et al., 2002), Hill Air Force Base, Layton, Utah (Hakonson et al., 1994; Paige et al., 1996), Sierra Blanca, Texas (Scanlon et al., 2001, 2002, 2005), Greater Wenatchee Landfill, Wenatchee, Washington (Khire, 1995; Khire et al., 1999), and other locations.

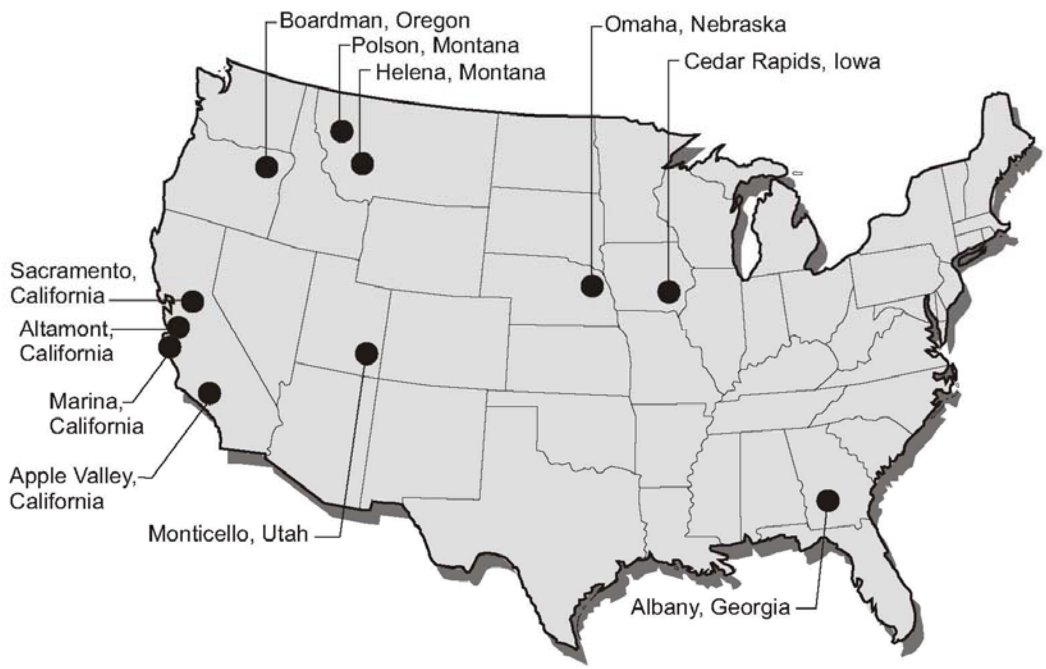

Figure 2.4: ACAP Test Sites (based on Albright et al., 2004).

2.4.3 Long-Term Performance

The performance of an evapotranspirative cover system observed during a relatively short-term monitoring period may bear little resemblance to the long-term average performance of the cover system. As suggested by Fayer and Gee (1997), when trying to predict the performance of a cover system over hundreds or even thousands of years, monitoring periods of 30 years or more may be needed to capture significant hydrologic events. Additionally, it will take some time for the cover system soils to reach initial "equilibrium conditions" with the natural environment and vegetation to become established. Over time, the natural environment will be transformed due to disturbances, climate change, etc. and the cover system soils and vegetation will change in response. As the ecological status of the cover system changes, so will performance factors such as water infiltration, evapotranspiration, soil water retention, and soil hydraulic conductivity. In an attempt to address some of the deficiencies of short-term monitoring, cover system test plots are sometimes stressed by irrigation, e.g., the cover systems at the Hanford Site (Gee and Ward, 1997) and the Sierra Blanca, Texas site (Scanlon et al., 2005), to simulate potential long-term climate conditions.

Suter et al. (1993) described the procession of vegetation succession and its effect on cover systems. The status of vegetation initially planted on a cover system will change over time due to plant establishment, competition, and herbivory, soil pedogenesis, and the action of physical agents such as frost. Because the process of succession is dynamic, it is not possible to accurately state what the cover system vegetation will be at some time after closure. At some sites, rapid changes in the status of evapotranspirative cover systems have been observed within a relatively short timeframe after construction as cover systems move from their as constructed conditions towards equilibrium with their natural environments. Monitored evapotranspirative cover systems have been observed to lose excess water retained during construction, develop preferential flow, and be colonized by different plant communities due to natural invasion by surrounding vegetation (Hakonson et al., 1994; Gee and Ward, 1997; Dwyer, 2003; Scanlon et al., 2005).

Hakonson et al. (1994) described the short-term plant dynamics for an evapotranspirative cover system at a test site in Utah. Three test plots were vegetated with native perennial grasses and a fourth plot was vegetated with native perennial grasses and two shrub species. The dominant shrub at the site was not one of the two that were planted on the test plot. Within 46 months after seeding and planting, forbs (herbaceous broadleaf plants that are not grasses or grasslike) and shrubs made up the majority of the vegetation on the grassed plots. Total plant cover ranged from 56 to 67%, with forbs and shrubs established on 31 to 58% of the ground surface and grasses growing on 9 to 25%. The plot that had been vegetated with grasses and shrubs had similar composition, with total plant cover of 63% and forb and shrub coverage of 41%.

At semi-arid and arid sites, after the initial establishment of plants, changes in species composition are often slow and annual pioneer species, such as Russian thistle (*Salsola kali*), also known as "tumbleweed," may be "permanent" residents of the site for some time. For the DOE Hanford Site, the succession from bare ground to a shrub-steppe (sagebrush, bunchgrass, etc.) plant community normally requires 30 to 40 years (Suter et al., 1993). Even if late successional plant species do become established, they may not be present in the long-term. At the Hanford Site, there is awareness that the native deep-rooted perennial vegetation may be displaced by non-native shallow-rooted annual species, such as cheatgrass (*Bromus tectorum* L.), in the future. Because of this, assessments of long-term performance of the cover system have considered that the cover system may be vegetated with shallow-rooted plants in the future (Gee and Ward, 1997).

Chapter 3: Water Balance Analysis and Screening and Selection of Computer Models

The purpose of this chapter is to describe the water balance analysis for evapotranspirative cover systems, compare available computer models to perform this analysis, and select several different computer models to simulate the water balance of evapotranspirative cover systems at three monitored test plots.

3.1 WATER BALANCE EQUATION

In a water balance analysis, water is routed into and out of a control volume using a series of calculations that require conservation of water mass. General pathways for water movement into and out of a cover system are illustrated in Figure 3.1. Though not shown in the figure, water can also move laterally within soil layers other than drainage layers. This two-dimensional effect, along with the effects of runoff on infiltration (more surface water flows near the toe of the slope than near the crest of the slope, so there is more opportunity for water to infiltrate into the soil near the slope toe), may impact the spatial distribution of soil water at evapotranspirative cover system sites by contributing to the drying of soils near the crest of the slope and wetting of the soils near the toe of the slope. Evidence of this effect has been observed for monitored cover systems, e.g., the cover systems at the Albuquerque, New Mexico site (Dwyer et al., 2000), and has been manifested as increasing soil water content and vegetation vigor with distance below the slope crest.

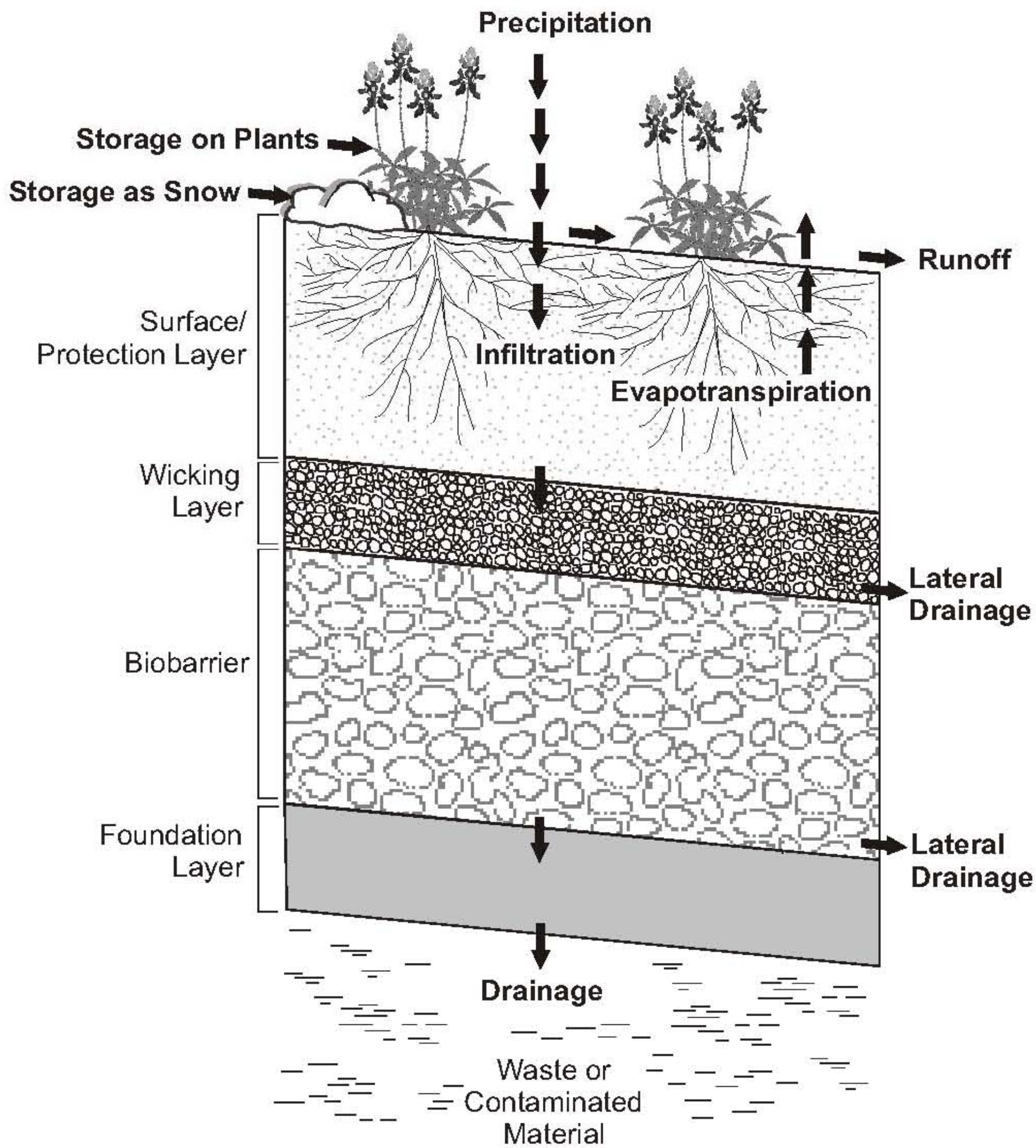

Figure 3.1: Water Balance Components for an Evapotranspirative Cover System.

The water balance for a cover system can be expressed in terms of water inflows and outflows and storage changes for a given cover system volume over some arbitrary time interval as:

$$D = P - R - \Delta W_{surface} - \Delta W_{plants} - \Delta W_{soil} - ET - L \quad \text{(Eq. 3.1)}$$

where D = vertical drainage (percolation) from the cover system, P = precipitation (rain, snow, irrigation), R = runoff, $\Delta W_{surface}$ = change in water storage on soil surface, ΔW_{plants} = change in water storage on plant leaves, stems, and litter (interception), ΔW_{soil} = change in water storage in soil, ET = evapotranspiration, and L = lateral drainage. Equation 3.1 was developed assuming that there are no contributions to the water balance from surface-water runon, ground-water inflow, or the water in landfill gas. Considering only the mass balance of the above-ground water and assuming that there is no evaporation during precipitation, Equation 3.1 can be rewritten as:

$$I = P - R - \Delta W_{surface} - \Delta W_{plants} \quad \text{(Eq. 3.2)}$$

where I = infiltration and all other variables are as defined previously. Considering only the mass balance of the subsurface water:

$$D = I - ET - \Delta W_{soil} - L \quad \text{(Eq. 3.3)}$$

Water is input to the cover system as precipitation in the form of rain, irrigation, or snow and lost from the cover system by runoff, evapotranspiration, and drainage. Water also is stored on the cover system as ponded water or snow, on plants (alive or dead), and in cover system soils by surface tension and capillary action. Storage of water in soil coupled with removal of water by evapotranspiration are the most important mechanisms for limiting vertical drainage of infiltration. Flow from drainage layers or wicking layers is typically a much smaller component of the water balance than is evapotranspiration, and drainage for adequately designed cover systems is even smaller still.

Except for the few models that consider interception or surface storage of liquid and frozen water, all of the water balance models described in this chapter use some form of Equations 3.2 and 3.3 to evaluate the water balance. In the mass balance of water at the soil surface (Equation 3.2), it is assumed that there is no evaporation during precipitation. Furthermore, the models that use numerical techniques to solve equations for water flow do not allow infiltration and evapotranspiration to occur in the same time step, unless they are one of the few computer models, e.g., SWIM and SoilCover, that treat evaporation and transpiration as sink terms. In semi-arid and arid climates, such as those described herein, evaporation can occur during rainfall, especially if precipitation is light and the air and soil are initially dry and warm.

When using meteorological forcing (climatic conditions) to model the upper boundary of the flow field, the boundary varies from prescribed-flux to prescribed-head based on the condition at the boundary. For example, if a soil is initially very wet, evaporation is modeled as a constant-flux boundary equal to the potential evaporation rate. As the soil dries, evaporation is limited by the unsaturated hydraulic conductivity of the soil and is modeled as a variable-flux boundary, depending on hydraulic gradient and unsaturated hydraulic conductivity. If the soil dries further, the matric potential at the boundary reaches a prescribed minimum value and the boundary condition changes from prescribed-flux to prescribed-head. These boundary conditions cannot be simulated simultaneously, though they are sometimes accounted for simultaneously during rainfall by applying a reduced precipitation rate at the upper boundary, as in the HYDRUS-1D computer model.

Though Equations 3.2 and 3.3 appear simple, the components of the water balance are dependent on many factors, are difficult to quantify, and are interdependent. It can be especially difficult to quantify drainage in arid and semi-arid environments, where almost all precipitation is consumed by evapotranspiration. Unlike in wetter climates where actual evapotranspiration may approach the magnitude of potential evapotranspiration, i.e., the process is energy-limited, in drier climates actual evapotranspiration is generally much smaller than potential evapotranspiration due to the lack of available water, i.e., the process is water-limited. Evapotranspiration is more difficult to estimate accurately when water is limited. Because the magnitude of drainage in drier climates is so much smaller than the magnitudes of precipitation and evapotranspiration, relatively small errors in these parameters can result in relatively large errors in estimated drainage. Similar to the example presented by Gee and Hillel (1988), considering a simplified case of Equation 3.1 with no runoff, lateral drainage, or change in storage on an annual basis (i.e., $R = L = \Delta W = 0$), if the error associated with precipitation, P, is approximately ± 5%, the error associated with evapotranspiration, ET, is approximately ± 20%, and P and ET differ by 10%, the most probable error in the calculated vertical drainage, D, is ± 190%. For example, with $P = P \pm 0.05P$ and $ET = 0.9P \pm 0.18P$, the calculated drainage is $0.1P \pm 0.19P$. As the relative difference between P and ET decreases, the relative error in D increases. If P and ET differ by 5% in the above example, the calculated drainage is $0.05P \pm 0.20P$ and the most probable error in D is ± 400%.

The terms in Equations 3.1 and 3.2 are briefly discussed below. Also mentioned are the general methods used in computer models for water balance to evaluate these terms.

3.2 COMPONENTS OF WATER BALANCE EQUATION

3.2.1 Precipitation

At the start of a precipitation event, water is stored on the surface in depressions or as snow, or is lost to evaporation or plant interception. After the available surface storage and interception capacity has been filled, any additional rainfall will generate runoff if the rate of precipitation is greater than the rate of infiltration plus evaporation or if the ground surface is frozen. The water balance during a precipitation event is affected by the discretization of the event. Some models require that daily precipitation be uniformly applied over a 24-hour period. When a short precipitation event, e.g., a 1-hour event, is spread out over 24 hours, runoff will be underestimated and infiltration will be overestimated. If the model does not allow evaporation to occur during precipitation and if the user does not account for evaporation by modifying the precipitation record, evaporation will also be underestimated.

Most of the computer models for water balance described in this chapter do not consider surface storage of liquid water, snow storage, frozen ground, or plant interception. The importance of these factors to the water balance depends on the characteristics of the site being modeled. Evapotranspirative cover systems are typically graded to drain, so there should not be significant surface storage of liquid water on their surface.

The focus of this dissertation is the performance of evapotranspirative cover systems at three semi-arid or arid sites in the southwest U.S., where snow storage or precipitation on frozen ground only occurs for a short time period, if at all, because the sites are located in warm climates or receive the majority of their precipitation in the warmer months. Therefore, snow storage and frozen ground should generally not have a significant impact on the water balance at these sites. [This is in contrast to the significance of snow storage and frozen ground on the field water balance at sites in the wetter northwest, such as the Hanford Site (Fayer et al., 1992: Fayer and Gee, 1997), or hypothetical sites in the southwest that are too wet to be considered semi-arid and that typically have snow accumulation in the winter, for example sites in Flagstaff, Arizona.]

3.2.2 Interception

The impact of interception on the water balance depends on the characteristics of the cover system vegetation and when precipitation occurs relative to the available interception capacity of the vegetation. Mature broad-leafed trees intercept more precipitation than grasses, and bunchgrasses intercept more precipitation than sod grasses. Areas with accumulated plant residue store more water than areas without plant residue, e.g., areas that have recently burned. Thurow et al. (1987) evaluated the interception capacity of the short-stature bunchgrass, curleymesquite (*Hilaria belangeri*), and the mid-stature bunchgrass, sideoats grama (*Bouteloua curtipendula*), at a semi-arid site in west Texas with average annual precipitation (1918-1984) of 609 mm. Excluding plant residue, they measured an interception storage capacity of 1.0 mm for the field dominated by curleymesquite (above-ground biomass density of 1,490 kg/ha) and 1.8 mm for the field dominated by sideoats grama (above-ground biomass density of 3,640 kg/ha). Annual interception estimated for these two grass species was approximately 10.8 and 18.1%, respectively, of annual rainfall.

For grasses, limited data suggest that interception by plant residue is even higher than interception by standing biomass (Brye et al., 2000). In a 2.5-yr field water balance study conducted at a tallgrass prairie in Wisconsin with three years of residue accumulation at the start of the study, plant residue intercepted 1.3 to 30.4 mm (10.4 mm average) of rainfall from a series of 1.3 to 32.7 mm (17.0 mm average) storms (Brye et al., 2000). The dominant plant species in the prairie were big bluestem (*Andropogon gerardii*), indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), purple coneflower (*Echninacea purpurea*), goldenrod (*Solidago* spp.), and blackeyed susan (*Rudbeckia hirta*). During the 2.5-year monitoring period, the prairie produced approximately 1,500 kg/ha of above-ground biomass and 1,000 kg/ha of plant residue per year.

If the majority of precipitation occurs in the winter when plant biomass and evaporation are relatively low and if there is little plant residue, interception may be negligible. However, if interception occurs when plant biomass is relatively high and if plant storage is emptied by evaporation between precipitation events, interception may be a significant component of the water balance at sites in arid and semi-arid climates.

3.2.3 Runoff

The computer models for water balance described in this chapter contain a number of assumptions that tend to make runoff estimates inaccurate. In general, there has not been good agreement between simulated and measured runoff. While some researchers have reported that certain models underestimated runoff for evapotranspirative cover systems at certain sites, e.g., Scanlon et al. (2002), other researchers have reported the opposite, e.g., Roesler et al. (2002). For the latter study, the difference between measured and simulated runoff was much greater than measured drainage. It is noted that some of the comparisons of modeling and monitoring results presented in the technical literature have been conducted using calibrated models. The trends in water balances reported when calibrated models are used may be different from those reported when uncalibrated models are used.

The lack of agreement between simulated and measured runoff is likely due, in large part, to not considering the effects of frozen ground or snowmelt (Khire et al., 1999), to the uncertainties in the hydraulic conductivity and antecedent moisture content of the soil at the surface of the cover systems, to the uncertainties in precipitation intensity, to not considering the effect of surface slope in the model, and to not considering interception of precipitation by plants. The effect of snowmelt is not included in most computer models for water balance. This may lead to the overestimate of runoff because snow water is applied in simulations as liquid water when it falls and not slowly released later as the snow melts. It can be accounted for, however, using the procedures suggested by Fayer et al. (1992) to modify precipitation and potential evapotranspiration data to simulate the effects of snow accumulation and melt and frozen ground. Frozen ground is also not included in many water balance models. When it occurs, it essentially cuts off infiltration. Thus, not considering frozen ground may result in the underestimation of runoff.

It addition to the difficulties with accurately accessing the soil water characteristic curve (SWCC) and hydraulic conductivity function of a cover system soil when it is initially placed, natural dynamic processes act to change these properties over time. These processes include the development of a structural crust at the soil surface, which forms in response to desiccation, freeze and thaw, or raindrop impact, and can greatly increase runoff and the development of a relatively permeable macrostructure due to wetting and drying cycles, plant roots, worms, and other stresses, which can decrease runoff. Most of the models currently available to evaluate the performance of evapotranspirative cover systems do not include these processes. Thus, input data must be manipulated to account for these effects. For example, in a study of the water balance of a capillary barrier, the effect of a surface crust was incorporated into a simulation as a static process by using a reduced saturated hydraulic conductivity for the upper 50 mm of the soil profile (Scanlon et al., 2005).

Most of the commonly used computer models for water balance are one-dimensional and do not consider the effect of surface slope on runoff. Because the quantity of runoff generally always increases with surface slope, it is expected that one-dimensional water balance models would tend to underestimate runoff from evapotranspirative cover systems, which are generally sloped. Instead, the models typically treat runoff as equal to the amount of precipitation in excess of that stored on the surface, lost to evaporation, or infiltrated into the soil.

Another factor that could affect the runoff estimate is the rate that precipitation is applied within the models. Some models, such as HELP, spread out daily rainfall uniformly over 24 hours, which decreases precipitation intensity, thereby increasing infiltration and decreasing runoff. Other models allow the user to use smaller time intervals to discretize precipitation, which better reflects the actual precipitation intensity, because the duration of most storms is less than 24 hours.

With all the model limitations that affect the simulated runoff, such as those mentioned above, it is surprising that there is an expectation by researchers that the models should be able to accurately simulate runoff. If a model, as it is typically applied, does accurately predict runoff for a cover system, it will generally be fortuitous. Scanlon et al. (2002) suggest that to accurately simulate runoff, water balance models may need to be calibrated by modifying the hydraulic conductivity of the soil at the surface of a cover system.

3.2.4 Infiltration

Infiltration is the process of water entry into the soil profile. At the start of an infiltration event, water moves into the soil under the influence of matric potential and gravity gradients and the instantaneous infiltration rate, or infiltrability, of the soil is at a maximum. As long as the rate of water delivery to the soil surface is smaller than the soil's infiltrability, water will penetrate the soil as fast as it arrives and there will be no runoff. Infiltration during this time is considered flux limited. As the wetted part of the soil profile lengthens, the matric potential gradients across the wetted area decrease and the influence of gravity becomes more dominant, i.e., unit gradient (gravity-driven) flow conditions exist. The infiltrability of the soil decreases asymptotically to a value approaching the field saturated hydraulic conductivity of the most impeding layer within the wetted portion of the profile. If the rate of water delivery to the soil surface becomes larger than the soil's infiltrability, runoff will occur. Infiltration during this time is considered head limited. When interception and runoff are overestimated, infiltration is underestimated and vice versa. Because infiltration represents the water input to the soil subsurface, as shown in Equation 3.3, and thus controls the subsurface water balance, it is very important that interception and runoff estimates be carefully made.

Most of the models described in this chapter use some form of the Richards' equation (Richards, 1931) to evaluate infiltration. This equation is obtained by combining the differential form of Darcy's equation for unsteady vertical flow with the one-dimensional differential form of the conservation of mass equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k_u(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S(z,t) \qquad \text{(Eq. 3.4)}$$

where θ = volumetric water content, t = time, z = vertical coordinate (positive downward), k_u = unsaturated hydraulic conductivity, h = matric potential (head), and S = sink term representing water uptake by transpiration. Many models that employ Richards' equation evaluate transpiration using the sink term shown in Equation 3.4. VS2DT, however, considers transpiration as part of an evapotranspiration boundary condition.

Richards' equation is highly nonlinear, especially in dry soils where hydraulic conductivity and matric potential can change an order of magnitude or more with small changes in water content. Except for special cases, solving this non-linear partial differential equation requires numerical approximations. The models that employ Richards' equation solve the equation using finite difference or finite element methods. Since these models were first developed in the late 1970's and forward, the computer coding and numerical techniques used with the finite difference and finite element methods have evolved to reduce mass balance error, numerical oscillations, and instabilities and computer processing speed has increased (Celia et al., 1990). It is now reasonable to use very small steps in time and space in simulations to obtain small mass balance errors.

Water balance models employ a number of different constitutive relationships developed to mathematically describe the SWCC ($\partial h/\partial \theta$ relationship) and hydraulic conductivity function ($\partial k_u/\partial h$ relationship) of soils. The water retention functions most commonly used to characterize SWCCs in water balance models are those parameterized by Brooks and Corey (1964) and van Genuchten (1980) or some modified form of these functions. The Brooks-Corey water retention function is defined by:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{h_b}{h}\right)^{\lambda} \qquad \text{(Eq. 3.5)}$$

where h_b = Brooks-Corey water retention function parameter (also called bubbling potential or air-entry potential), θ = volumetric water content, θ_r = residual water content, θ_s = saturated water content, λ = Brooks-Corey water retention function parameter (also called pore-size distribution index), and all other variables are as defined previously. The Brooks-Corey relationship produces L-shaped curves when matric potential is plotted at a logarithmic scale. It has been found to model the water retention function of coarse-grained soils with relatively narrow pore size distribution functions much better than the water retention function for finer-grained soils with relatively broad pore size distribution functions (van Genuchten and Nielsen, 1985). Because of its slope discontinuity near saturation, i.e., where the L-shaped curve intersects saturated water content at a matric potential greater than zero, and its infinite differential ($\delta\theta/\delta h$) near saturation, the Brooks-Corey function can be problematic in numerical models when soil water contents are near saturation. To correct for this and better model observed soil behavior, some of the water balance models described in this chapter use versions of the Brooks-Corey water retention function that have been modified to incorporate a smooth slope transition in place of the discontinuity. Some models also incorporate other forms of the Brooks-Corey function, such as the one proposed by Campbell (1974). The Campbell retention function is simply the Brooks-Corey water retention function with the residual water content set equal to zero and different fitting parameters.

The van Genuchten (1980) water retention function is defined by:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{-m} \qquad \text{(Eq. 3.6)}$$

where α, n, and m are parameters for the van Genuchten water retention function and all other variables are as defined previously. The parameter m is often assumed to equal (1 - 1/n). The van Genuchten relationship produces S-shaped curves when matric potential is plotted at a logarithmic scale. However, as described by Rossi and Nimmo (1994), the van Genuchten and the Brooks-Corey relationships often give poor results when they are extrapolated to low matric potentials e.g., potentials somewhat lower than -150 m (-1500 kPa) as water retention is controlled more by adsorption theory than capillary theory. Neither the van Genuchten nor the Brooks-Corey water retention functions allow the volumetric water content to be zero at some matric potential less than negative infinity, which as discussed by Rossi and Nimmo (1994), is unrealistic. From thermodynamic considerations and experimental data, zero water content should be reached at a matric potential slightly less than -100,000 m (-10^6 kPa) (Fredlund and Xing, 1994). To correct for this (and better model observed soil behavior) some of the water balance models described in this chapter use versions of the van Genuchten water retention function that have been modified to incorporate adsorption theory at low matric potentials.

The hydraulic conductivity functions most commonly used to characterize soils in water balance models are those that use the Brooks-Corey or van Genuchten water retention functions or some modified form of these functions with the theoretical pore-size distribution models of Mualem (1976) or Burdine (1953). A modified version of the Brooks-Corey-Burdine hydraulic conductivity function has been proposed by Campbell (1974) and is used in several of the models:

$$k_u = k_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{3+\frac{2}{\lambda}} \qquad \text{(Eq. 3.7)}$$

where k_u = unsaturated hydraulic conductivity, k_s = saturated hydraulic conductivity, and all other variables are as defined previously. The van Genuchten (1980) hydraulic conductivity function is defined by:

$$k_u = k_s \{1 - (\alpha h)^{n-1} \left[1 + (\alpha h)^n\right]^{-m}\}^2 \left[1 + (\alpha h)^n\right]^{-\ell m} \qquad \text{(Eq. 3.8)}$$

where ℓ = pore interaction term, and all other parameters are as defined previously. For the pore-size distribution models of Burdine (1953) and Mualem (1976), the pore interaction terms are 2 and 0.5, respectively. Some researchers, e.g., Schaap and Leij (1999), have found lower values of the pore interaction term, in the range of -1 to 0, to better fit field data (lower values of ℓ give lower unsaturated hydraulic conductivities at low matric potentials); however, there is no physical basis for using a pore interaction term less than zero. A pore interaction term of zero corresponds to no pore interaction.

Pore-size distribution models for calculating unsaturated hydraulic conductivity are based on capillary bundles and are expected to be less accurate as the soil dries and adsorption forces, rather than capillary forces, dominate. Because of this, Stephens (1992) has suggested that values of soil unsaturated conductivity at matric potentials less than -10 m (-100 kPa) be measured rather than calculated. Accurately measuring unsaturated hydraulic conductivity, however, is difficult. At the Hanford Site, drainages calculated using hydraulic conductivity functions determined five different ways were compared to measured deep drainage from a large lysimeter (Gee and Ward, 2002). The hydraulic conductivity functions were determined from three laboratory methods (soil texture correlation, column outflow, and ultracentrifuge) and two field methods (Guelph permeameter and instantaneous profile). Considering the approximate water content and matric potential of the soil in the lysimeter, the hydraulic conductivities determined by the five methods varied by more than three orders of magnitude.

3.2.5 Storage

Water that infiltrates into the soil profile may be stored in the soil matrix or removed from the profile by evapotranspiration, lateral drainage, or vertical drainage. Redistribution of infiltration through the soil profile, where it may be stored, is a complex process to simulate accurately because the soil matric potential and water content relationship is hysteretic, i.e., it is history dependent, as shown by the SWCCs in Figure 3.2. For a given matric potential, the soil will be at a higher water content (and thus a higher hydraulic conductivity) under drying conditions than under wetting conditions. The main drying curve is referred to as the desorption curve, the main wetting curve is shown as the sorption curve, and the intermediate curves that are followed as a partially wetted soil dries or a partially dry soil wets are referred to as scanning curves. Also shown in Figure 3.2 is the field saturation point of a soil that was initially saturated, dried, and then rewetted. The field saturation is less than full saturation due to entrapped air. The primary reason for hysteresis is the “ink-bottle” effect, where a flow channel of varying diameter empties at a relatively low matric potential, dependent on the smallest diameter of the flow channel, and fills at a relatively high matric potential, dependent on the largest diameter of the flow channel.

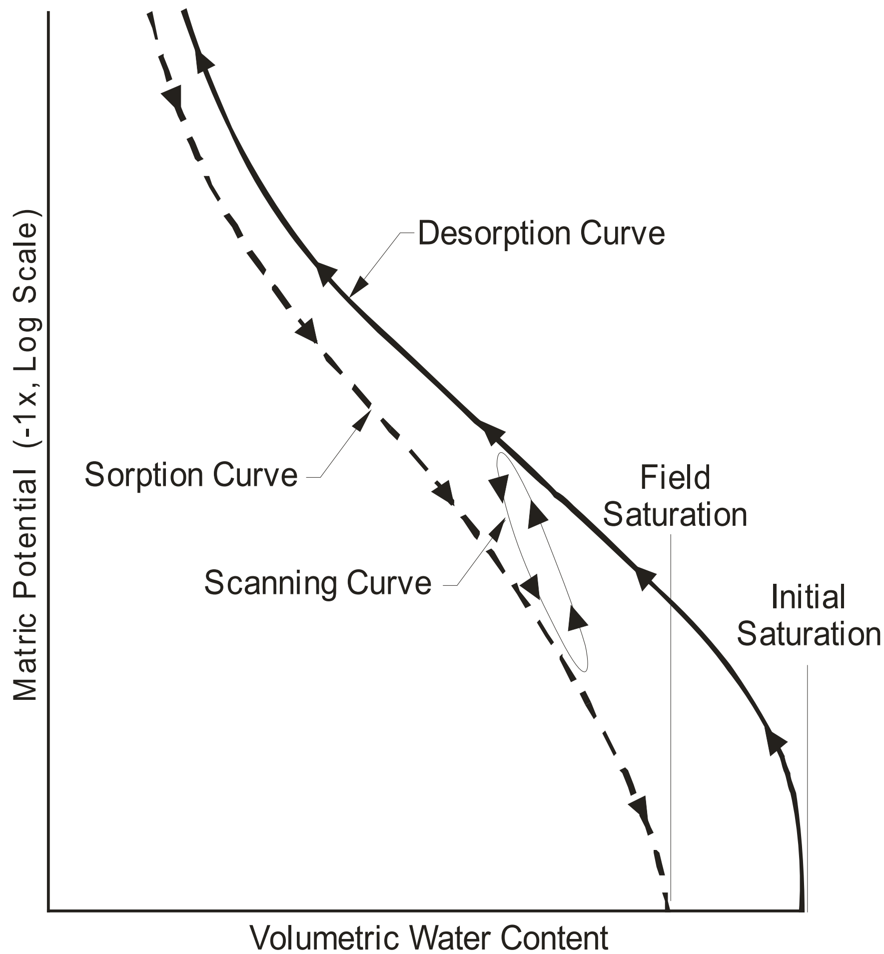

Figure 3.2: Effect of Hysteresis on Soil Water Characteristic Curves.

The effect of hysteresis on water redistribution in the soil profile is to inhibit redistribution and retain water in the wetted zone that would otherwise move deeper into the soil profile (Hillel, 1998). This effect can be especially beneficial to plants in semi-arid and arid climates by retaining water in the root zone. In addition to affecting the water retention function, hysteresis also affects the soil hydraulic conductivity function, the matric potential form of the function, e.g., Equation 3.7, more than the water content form, e.g., Equation 3.8. Hysteresis affects all of the water balance components that involve the movement of water through soil (infiltration, evapotranspiration, redistribution, and drainage). However, hysteresis is currently only included in a few water balance models (UNSAT-H, SWIM, HYDRUS-1D). It is difficult to include the effects of hysteresis in water balance simulations for constructed cover systems because, unless field matric potential and water content measurements are made and desorption, sorption, and scanning curves are defined, it is not known which retention curve the soil is tracking. After the water is redistributed in the soil, storage can be calculated by integrating the water content profile.

3.2.6 Evapotranspiration

Evapotranspiration consists of evaporation of water stored on the soil surface, intercepted by plants, and stored within the soil profile and transpiration by plants. Because it is generally difficult to separate evaporation and transpiration, these two interdependent processes are often lumped together. Evapotranspiration is driven by the difference in water vapor pressure at the evaporating surface and that of the atmosphere. As water evaporates from a surface under the energy provided by solar radiation and, to a lesser extent, ambient air temperature, the atmospheric vapor pressure increases and the rate of evapotranspiration decreases. Evapotranspiration will proceed only as long as there is a water vapor pressure gradient. This gradient can be maintained if the wetted air is replaced with drier air; thus, wind speed is also a factor in evapotranspiration.

3.2.6.1 Potential Evapotranspiration

The maximum evapotranspiration that can occur if the supply of water to the evaporating surface is not limited is referred to as the potential evapotranspiration and is a function of meteorological conditions alone. Most of the water balance models described in this chapter evaluate evapotranspiration using the potential evapotranspiration concept, which assumes that potential evapotranspiration for a bare soil surface is the same as the evaporation for a free water body or the evapotranspiration for a reference crop and that evaporation occurs under isothermal conditions, i.e., heat flow is not considered. Potential evapotranspiration is input directly into the model or calculated within the model using meteorological data.

Water balance models that have the option of calculating potential evapotranspiration typically use analytical methods based on Penman (Penman, 1948) and require different levels of meteorological input, e.g., from only daily solar radiation and average temperature to daily solar radiation, average temperature, wind speed, and relative humidity. Potential evapotranspiration is then partitioned into potential evaporation and potential transpiration based on some empirical function that considers vegetation and often is a function of leaf area index (LAI). Leaf area index is the one-sided leaf surface area per unit area of ground that may be representative of one plant or a group of plants.

As described by Allen et al. (1998), the methods used to predict potential evapotranspiration vary widely and sometimes erratically in their performance. For example, the modified Penman equation presented by Doorenbos and Pruitt (1977) has frequently been found to overestimate potential evapotranspiration. This equation is used in the UNSAT-H water balance model. Interestingly, in water balance simulations of lysimeters at the DOE Hanford Site that were conducted by Fayer et al. (1992), the model calibration to improve agreement between predicted and measured soil water storage included decreasing potential evapotranspiration by 30%. The Food and Agricultural Organization (FAO) of the United Nations currently recommends the FAO Penman-Monteith method for evaluating potential evapotranspiration (Allen et al., 1998).

The Penman equation was developed for evapotranspiration under isothermal conditions and energy-limiting conditions, where energy supplied by the atmosphere would be primarily utilized to evaporate water. In semi-arid and arid climates, where water is limiting, excess energy is transferred to the soil and atmosphere as sensible heat. The heating of the soil and atmosphere creates a thermal gradient for water flow in both liquid and vapor phases. Thermal gradients for water flow can also be developed from subsurface heating, e.g., from the decomposition of municipal solid waste in below-grade landfills.

As described by Hillel (1998) and demonstrated by the results of simulations conducted by Scanlon et al. (2002) for two sites with evapotranspirative cover system test plots, isothermal vapor flow is generally an insignificant component of drainage (except when the soils are very dry) in evapotranspirative cover systems due to the low vapor pressure gradients that are generated in unsaturated soils under isothermal conditions. Thermal vapor flow in arid settings, however, can be important. In their evaluation of heat and water fluxes in soils at a Chihuahuan Desert site in west Texas, Scanlon and Milly (1994) calculated a net downward thermal vapor flux of 0.9 mm/yr at a depth of 1 m below the ground surface. Andraski (1997) made a similar observation for monitored vegetated and unvegetated test plots at a Mojave Desert site in southwest Nevada. He calculated downward thermal vapor fluxes of 0.9 to 1.6 mm/yr at a depth of 1.2 to 1.6 m using monitoring data from September 1990 and September 1992. Isothermal fluxes were about two orders of magnitude lower, and liquid fluxes were several orders of magnitude lower still. It should be noted that the reported thermal vapor fluxes are net values. Thermal vapor flux was directed downward in the summer and upward in the winter. If these sites were underlain by pan lysimeters that captured condensating vapor in the summer, the beneficial effect of the upward flow of water in the winter would be lost.

Thermal flux of water may also affect drainage for municipal solid waste landfills. The relatively high temperatures in these moist landfills relative to ambient temperature can general thermal vapor fluxes out of the landfill. Thus, water that drains through the cover system may pass back through the cover system and to the atmosphere as vapor. The net effect on drainage, however, has not been quantified herein.

Only one of the water balance models described in this chapter (SHAW) has the capability of simulating thermal vapor flow for vegetated soil layers. It does so by coupling the water, energy, and heat balances in the soil-plant-atmosphere continuum.

3.2.6.2 Evaporation

Evaporation can be considered to occur in three phases: (i) an initial constant-rate, energy-limited stage, which occurs while the soil is still wet and conductive enough to supply water at a rate equal to the evaporative demand; (ii) a falling-rate, soil-limited stage, during which evaporation is limited by the rate at which the gradually drying soil can convey water; and (iii) a diffusion-limited stage, which occurs when the soil surface is so desiccated, without continuous water channels to the subsurface, that liquid flow of water effectively ceases and vapor flow, possibly near steady state, dominates (Hillel, 1998). Evaporation can take place when there is a continual supply of heat to evaporate water, the vapor pressure in the atmosphere is lower than that at the soil surface, and there is a supply of water to the soil surface. In arid climates, the total matric potential difference between soil moisture and atmospheric humidity can exceed 10,000 m (100,000 kPa) (Hillel, 1998). Though evaporation can occur under matric potential and temperature gradients, as previously discussed, most of the water balance models described herein only consider the effects of vapor density gradients under isothermal conditions.

3.2.6.3 Transpiration

Transpiration occurs when total water potential gradients develop between plant leaves and roots (Figure 3.3). As a point of reference, the total water potential for an unsaturated rigid soil is defined as the sum of the gravitational, solute, air, and matric potentials. In this dissertation, it is assumed that the soil solute potential is negligible and the air potential equals zero, i.e., the soil air pressure equals atmospheric pressure. Thus, the total water potential is equal to the sum of the gravitational and matric potentials.

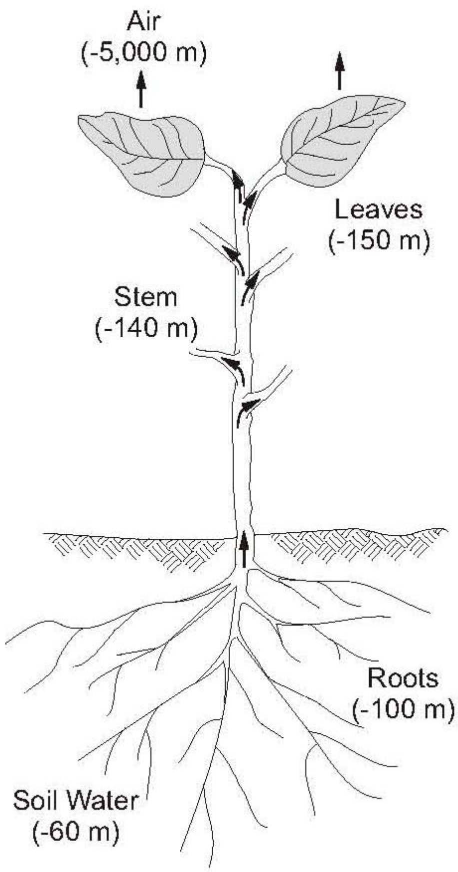

Figure 3.3: Example of Soil-Plant-Atmosphere Water Potential Variation in an Arid Climate (modified from Hillel, 1998).

The assumption that the soil solute potential is negligible is considered reasonable for a newly constructed cover system with blended non-calcareous soil from a borrow area. Over time, in a natural semi-arid or arid setting, a solute potential gradient may develop in an evapotranspirative cover system as infiltrating water carries ions down into the soil and then leaves them behind as it evaporates. However, even if a solute potential gradient develops, it may not be significant compared to the matric potential gradient. For three sites in the semi-arid and arid southwest U.S, solute potential gradients in the surficial soil profile were estimated from chloride concentration data and found to be an order of magnitude less than matric potential gradients (Scanlon et al., 2003). These sites had been experiencing upward flow and accumulation of salts in the shallow soil profile over the last 12,000 to 16,000 years.

The assumption that soil air pressure equals atmospheric pressure is also considered reasonable. There will actually be some small air potential gradients as the soil air responds to small changes in barometric pressure, e.g., 0.05 m (0.5 kPa) diurnal variation and 0.5 m (5 kPa) during a front, but these gradients are generally considered insignificant when modeling water flow.

The largest portion of the overall potential difference in the soil-plant-atmosphere system occurs between the plant leaves and the atmosphere. As a plant intakes carbon dioxide for photosynthesis through its stomata (pores on leaves that can be opened and closed), it loses water through its stomata in response to the water potential gradient. Water evaporating from the leaves creates a low potential at the leaf surface. In response, the plant roots extract water from the soil, in proportion to their rooting depth and density and the water potential gradient. Considering a soil at a uniform water potential, deeper roots are less efficient in the uptake of water than shallower roots due to a decrease in the potential gradient.

When evaporative demands are high or water is not readily available, most plants react to these stresses by closing stomata, thus reducing transpiration. The gradients that are created by evaporation at the leaf surface are only strong enough to extract water from the soil to a certain potential referred to as the wilting point. Once a plant reaches its wilting point, it is no longer transpiring and it will exhibit leaf drop and tissue death

(Saxton, 1982). The wilting point is often assumed, by convention, to occur at a matric potential of approximately -150 m (-1500 kPa). However, it is actually plant specific and lower matric potential values have been reported for certain vegetation growing in semi-arid and arid climates. For example, in the study by Odening et al. (1974) on the effect of decreasing water potential on the transpiration of three warm desert shrubs [Creosote bush (*Larrea divaricata*), Goldenhills (*Encelia farinosa*), and Desert willow (*Chilopsis linearis*)], the shrubs exhibited wilting points at water potentials between -750 and -350 m (-7400 and -3400 kPa).

When a surface is well vegetated with active plants, transpiration is usually the dominant mode of water loss from the soil profile. Even when vegetation is sparse, transpiration can still be significant.

Most of the water balance models discussed in this chapter use the potential transpiration concept and distribute the transpiration demand within the user-specified root zone depth based on the user-specified distribution of root length density within the root zone. When a cover system is being monitored, plant root depth and root length density are sometimes measured. For design, published data on root depth and root length density are often relied upon. However, most of the published data are for crops in tilled soils or natural plant communities in uncompacted soils and may not be representative of (may over-predict) the root depth in the compacted soils that have been frequently used to construct evapotranspirative cover systems.

A conceptual model of root distribution developed by Schenk and Jackson (2002) for plants in water-limited climates is that roots only grow as deep as needed to meet plant water and nutrient requirements. In arid climates, precipitation does not infiltrate very far into the soil profile before it is removed by evapotranspiration. Unless there is a deeper source of water that can be tapped by the plant roots, there is no benefit for deep roots in this climate. Instead, plant roots tend to spread laterally to opportunistically capture infiltrating water. When there is a deep source of water, certain plants in arid climates have developed exceptionally deep roots. In their analysis of the maximum rooting depths of plants in different biomes, Candall et al. (1996) found that the mean maximum root depth of desert plants reported in the literature was 9.5 m, with the highest value of 53 m reported for a mesquite (*Prosopis juliflora*) in the Sonoran Desert. The depth and lateral extent of roots is related to the above-ground biomass of the plant (Schenk and Jackson, 2002), with trees having deeper and wider root systems than grasses. From the regression parameters presented in Schenk and Jackson (2002), at arid sites that receive 150 to 250 mm of precipitation a year, on average, the calculated maximum root depth of annuals is 0.28 to 0.42 m and the calculated maximum root depth of perennial grasses is 0.69 to 0.84 m. At semi-arid sites that receive 250 to 500 mm of precipitation a year, the calculated maximum root depths of annuals and perennial grasses are 0.42 to 0.74 m and 0.84 to 1.1 m, respectively.

All of the water balance models discussed in this chapter consider the effects of water stress on transpiration by one of two methods. One group of models uses a water-stress response function to reduce potential transpiration as a function of matric potential. The other group of models calculates transpiration using a macroscopic root resistance approach that routes water though the soil to the roots via radial flow and then from the roots to the xylem. Both soil and root resistances are included along the water flow path. As the soil begins to dry, the root and soil resistances increase and transpiration decreases.

Plants are important to the performance of an evapotranspirative cover system, and it would be expected that they would be especially beneficial for cover systems in cold desert climates that are stressed by snowmelt. Anderson et al. (1991, 1993) described a field study of ten prototype cover systems that were constructed at the Idaho National Engineering and Environmental Laboratory in 1983. This site receives most of its precipitation, including snow, in late winter and early spring. Trenches were excavated about 2.4-m deep and then filled with silt loam to create a prototype cover system. Eight of the cover systems were vegetated with grasses or shrubs, and two were bare. Based on water content measurements, the vegetated trenches performed well over four growing seasons, even when they were irrigated to simulate a wet year. The two unvegetated trenches wetted up and began draining. There was little water lost by evaporation. From the water content versus time profiles of these unvegetated trenches, Anderson et al. (1991) concluded that evaporation might extract water to a depth of about 1 m. In contrast, the depth of water extraction from the vegetated trenches extended to at least 2.2 m. Other studies (Nyhan et al., 1990; Gee et al., 1994; Waugh et al., 1994; and Scanlon et al., 2005) have demonstrated the benefit of plants and of certain plant species over others, including using deeper-rooted plants over shallower-rooted plants and using a mixture of warm-season and cool-season plants to prolong transpiration during the growing season.

The Scanlon et al. (2005) work mentioned above is interesting because it contains data for an evapotranspirative cover system test plot in Sierra Blanca, Texas that was unvegetated for the first year, planted with native perennial grasses the second year, and subsequently colonized by salt cedar (*Tamarix gallica*) and other invasive species. The matric potential measured at two locations in the cover system with heat dissipation sensors is shown as a function of time in Figure 3.4. Also shown is the water potential in the adjacent natural setting measured using thermocouple psychrometers. The native soils at the site have been undergoing long-term drying over the past 10,000 to 15,000 years and have developed thick caliche layers.

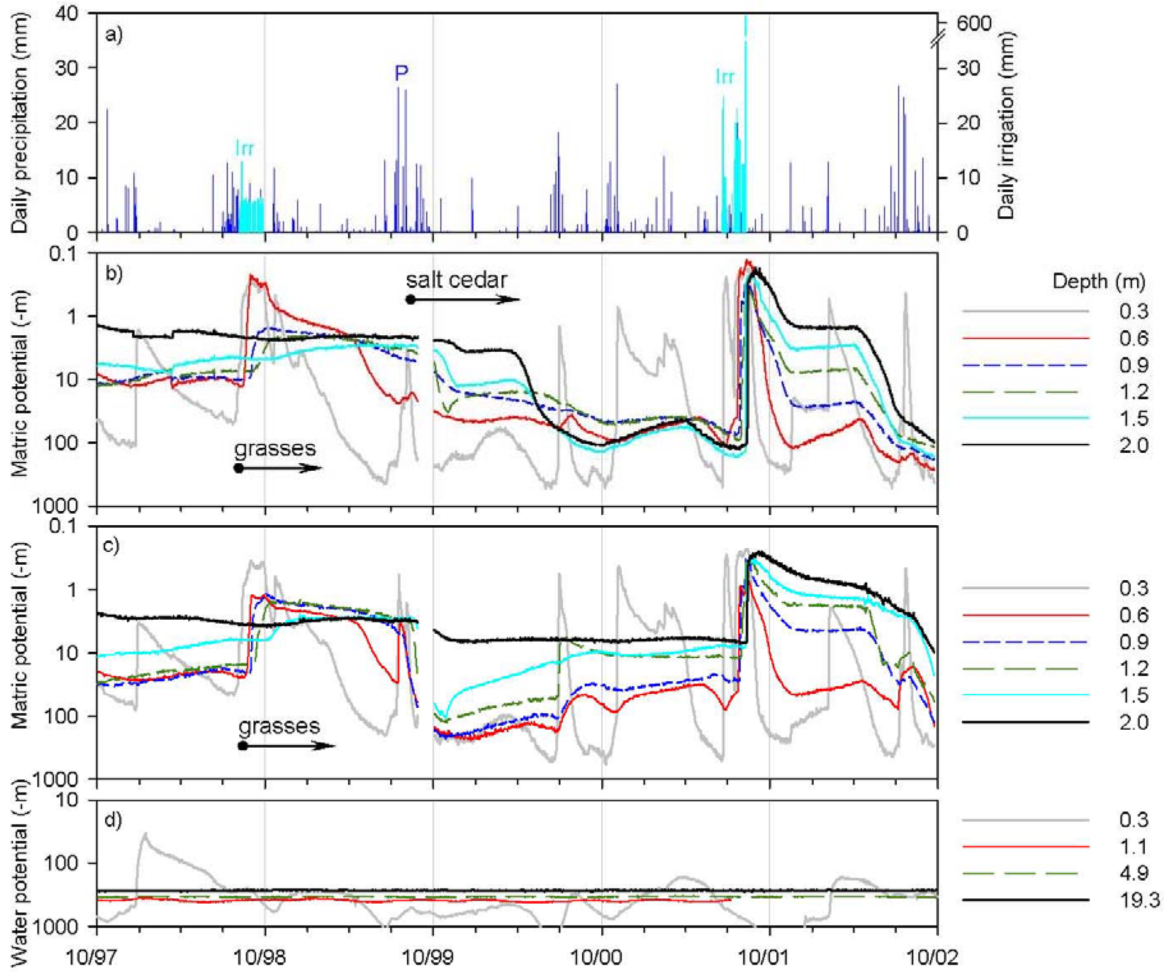

Figure 3.4: Effect of Vegetation on Field Water Balance at an Evapotranspirative Cover System Test Plot in Sierra Blanca, Texas: (a) Daily Precipitation (P) and (Irr) Irrigation; (b, c) Matric Potential at Two Locations in the Evapotranspirative Cover; and (d) Water Potential in the Adjacent Natural Setting (from Scanlon et al., 2005).

During the first year, when the cover system was unvegetated, the depth of evaporation ranged between 0.3 and 0.6 m. As grasses became established, water was removed from deeper in the soil profile. The salt cedar, which became established approximately two years after the cover system was constructed, appears to have dried the cover system even more.

3.3 Screening of Computer Models for Water Balance

There are a number of computer models available to simulate the water balance of evapotranspirative cover systems. Most of the models were originally developed to evaluate water flow in the vadose zone or for agricultural modeling. For this research study, the following water balance models were considered (with the models based on the storage routing approach, rather than Richards' equation, listed first):

- Erosion-Productivity Impact Calculator (EPIC) (also called Environmental Policy Integrated Climate model), version 0320 (version 5300 documentation, formerly on-line at http://brcsun0.tamu.edu/epic/ introduction/aboutmanual.html and based on Williams et al., 1990 and Sharpley and Williams, 1990; version 5300 documentation, Mitchell et al., 1996; version 0320 Fortran code dated June 5, 2000);
- Hydrologic Evaluation of Landfill Performance (HELP), version 3.07 (version 3 documentation, Schroeder et al., 1994a,b);
- HYDRUS-1D, version 7 [Simunek et al., 1998 (version 2.0 documentation)];
- Leaching Estimation and Chemistry Model (LEACHM), version 4.0 (version 3.0 documentation, Hutson and Wagenet, 1992; version 4.0 documentation, Hutson, 2003);
- Simultaneous Heat and Water (SHAW), version 2.3.5 (Flerchinger, 2000a,b); SoilCover 2000, version 5.2 (Geoanalysis 2000 Ltd., 2000);
- Soil Water Infiltration and Movement (SWIM), version 2.1 (Verburg et al., 1996);
- UNSAT-H, version 3.01 (version 3.0 documentation, Fayer, 2000); and

- Variably Saturated 2 Dimensional Transport (VS2DT), version 3.0 (October 26, 1986 version documentation, Lapella et al., 1987; April 1, 1990 version documentation, Healy, 1990; version 2.5 documentation and version 1.0 graphical user interface documentation, Hsieh et al., 2000).

All of these models consider the major water balance processes, except for interception and vapor flow, which are only considered by a few models and are only significant in certain cases. All of the models have been used previously to simulate the hydraulic performance of evapotranspirative cover systems. Except for SWIM and SoilCover, all of the models are in the public domain. (SoilCover was formerly in the public domain, but was incorporated into the proprietary Vadose/W model in 2003.) UNSAT-H appears to currently be the most commonly used model to design evapotranspirative cover systems in the U.S., though HELP, LEACHM, and HYDRUS have also had significant use and SHAW is seeing increasing use at sites that experience snow cover. The characteristics of these models are compared below (Table 3.1). Some of the attributes of the models have been previously described and contrasted by Wilson et al. (1999) and Scanlon et al. (2001, 2002).

At least some of these models are continually being updated and revised. The documentation, however, is generally revised much slower. Therefore, it is not always clear how the different models work. In addition, the models are sometimes modified for special projects, but these modifications are not included in the public domain versions. For example, in a study of flow and transport in the vadose zone conducted by Scanlon et al. (2003), HYDRUS-1D was modified to include isothermal and thermal vapor flow.

Table 3.1: Characteristics of Water Balance Computer Models.

Model Processes and Attributes	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SWIM	SoilCover	UNSAT-H	VS2DT
Precipitation									
User specified	•	•	•	•	•	•	•	•	•
Historical weather database	•	•							
Weather generator	•	•							
Weather time step									
Daily	•	•	•	•	•	•	•	•	•
Hourly			•	•	•	•	•	•	•
User Specified			•	•		•	•		•
Ponding on Soil Surface (with Meteorological Forcing)	•	•			•	•			
Water Storage on Plants	•				•				
Runoff									
Runoff is a function of surface slope, soil texture, and vegetation (USDA SCS, 1985; modified to consider surface slope)	•								
Runoff is a function of soil texture, land use, and management practices (USDA SCS, 1972; modified to consider surface slope)		•							
Runoff is a function of surface slope, soil texture, and vegetation (Williams, 1991)				•					
Runoff equals precipitation in excess of infiltration	•	•	•	•	•	•	•	•	•
Runoff equals precipitation in excess of infiltration and surface ponding					•	•			
No runoff, precipitation in excess of infiltration ponds on surface	•	•				•			•
Infiltration									
Storage routing	•	•		•					
Green and Ampt (1911)		•			•				
Richards (1931)			•	•		•	•	•	•
Redistribution									
Storage routing	•	•		•					
Richards (1931)			•	•	•	•	•	•	•
Vapor Flow									
Isothermal					•	•	•	•	
Thermal					•			•	

Table 3.1: Characteristics of Water Balance Computer Models (cont.).

Model Processes and Attributes	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SoilCover	SWIM	UNSAT-H	VS2DT
Evapotranspiration									
Potential evapotranspiration									
User specified									
Potential evapotranspiration				•		•	•	•	
Pan evaporation rate and pan factor				•					
Potential evaporation and potential transpiration			•						•
Calculated									
Penman (Penman, 1948)		•				•			
Modified Penman (Penman, 1963)	•								
Modified Penman (Monteith, 1965)		•							
Modified Penman (Doorenbos and Pruitt, 1977)								•	
Priestley and Taylor (1972)		•							
Hargreaves and Samani (1985)		•							
Baier and Robertson (1965)		•							
Linacre (1977)				•					
Not specified or calculated					•				
PET partitioning into potential evaporation and potential transpiration									
PET applied to surface evaporation, then subsurface evaporation, then transpiration	•	•							
Childs and Hanks (1975)				•					
Ritchie and Burnett (1971)								•	
Hinds (1975)								•	
Tratch (1995)						•			
User specified			•				•		•
Not specified or calculated					•				
Evaporation									
Ritchie (1972)	•	•							
Campbell (1985)					•	•	•	•	
Modified Penman (Wilson, 1990)						•			
Neuman et al. (1974)			•						
Flux is a function of matric potential gradient between soil and atmosphere and soil hydraulic conductivity				•					•

Table 3.1: Characteristics of Water Balance Computer Models (cont.).

Model Processes and Attributes	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SoilCover	SWIM	UNSAT-H	VS2DT
Transpiration									
Function of potential transpiration and plant stress factors									
Ritchie (1972)	●	●							
Tratch (1995)						●			
Feddes et al. (1978)			●					●	
Modified Feddes (van Genuchten, 1987)			●						
Flux is a function of LAI, vapor density, and stomata and canopy resistances					●				
Flux is a function of water potential and root and soil resistance									
Nimah and Hanks (1973)				●					
Campbell (1985)							●		
Molz (1981)									●
SWCC Parameters									
Non-applicable (uses saturated hydraulic conductivity)		●							
Tabular data						●			●
Pedotransfer functions				●					
Polynomials (Bond et al., 1984)								●	
Brooks-Corey (Brooks and Corey, 1964)	●		●				●	●	●
Modified Brooks-Corey (Fayer and Simmons, 1995)								●	
Modified Brooks-Corey (Hutson and Cass, 1987)							●		
Modified Brooks-Corey (Ross et al., 1991)							●		
Campbell (1974)			●		●		●	●	●
Modified Campbell (Hutson and Cass, 1987)				●					
Havercamp (Havercamp et al., 1977)								●	●
van Genuchten (1980)			●				●	●	●
Modified van Genuchten (Fayer and Simmons, 1995)								●	
Modified van Genuchten (Vogel and Císlerová, 1988)			●						
Fredlund and Xing (1994)						●			
Rossi-Nimmo sum model (Rossi and Nimmo, 1994)								●	
Rossi-Nimmo junction model (Rossi and Nimmo, 1994)								●	
One-parameter exponential function to describe macroporosity (matrix-macropore effect) (Ross and Smettem, 1993)							●		

Table 3.1: Characteristics of Water Balance Computer Models (cont.).

Model Processes and Attributes	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SoilCover	SWIM	UNSAT-H	VS2DT
Hydraulic Conductivity Function									
Non-applicable (saturated flow only)		●							
Tabular data						●			●
Polynomials (Bond et al., 1984)								●	
Brooks-Corey (Brooks and Corey, 1964)			●				●	●	
Brooks-Corey (Brooks and Corey, 1964) and Burdine (1953)			●				●	●	●
Brooks-Corey (Brooks and Corey, 1964) and Mualem (1976)			●				●	●	
Modified Brooks-Corey (Fayer and Simmons, 1995) and Mualem (1976)								●	
Campbell (1974) and Burdine (1953)	●		●	●	●			●	
Havercamp (Havercamp et al., 1977)								●	●
van Genuchten (1980) and Burdine (1953)								●	
van Genuchten (1980) and Mualem (1976)			●				●	●	●
Modified van Genuchten (Fayer and Simmons, 1995)								●	
Modified van Genuchten (Vogel and Císlerová, 1988)			●						
Fredlund et al. (1994)						●			
Rossi-Nimmo sum model (Rossi and Nimmo, 1994) and Mualem (1976)								●	
Rossi-Nimmo junction model (Rossi and Nimmo, 1994) and Mualem (1976)								●	
One-parameter exponential function (Ross and Smettem, 1993) and Mualem (1976)							●		
Richards' equation solution technique									
Finite difference									
Newton-Raphson					●		●		●
Crank-Nicholson				●				●	
Modified Picard								●	
Finite element			●			●			

Table 3.1: Characteristics of Water Balance Computer Models (cont.).

Model Processes and Attributes	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SoilCover	SWIM	UNSAT-H	VS2DT
Vegetation									
ET within specified depth	●	●							
Above-ground biomass growth									
Constant plant cover				●	●		●		
Tillotson et al. (1980)				●					
User specified growth						●	●		
User specified LAI function								●	
LAI is a function of total biomass, considering water and temperature stresses	●								
LAI is a function of total biomass considering water, nutrient, temperature, aeration, and radiation stresses		●							
Sigmoidal growth/decay							●		
Above-ground biomass not considered			●						●
Root growth									
Constant root distribution				●	●		●		
Verhulst-Pearl logistic growth function with exponential root distribution			●						
Root biomass is a function of total biomass	●								
Root biomass is a function of total biomass, soil temperature, soil strength, and aluminum toxicity		●							
Tillotson et al. (1980) with relative root depth factor				●					
User specified root depth and density or activity function						●	●	●	●
Root growth model	●	●							
Positive feedback between plant growth and growth limiters	●	●							

Table 3.1: Characteristics of Water Balance Computer Models (cont.).

Model Characteristics	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SoilCover	SWIM	UNSAT-H	VS2DT
Other Processes/Effects									
Soil erosion		●							
Surface crust							●		●
Lateral drainage	●	●							●
Potential lateral flow (informational only, not included as a sink term)							●		
Heat flow	●	●	●	●	●	●		●	
Snow storage and melt	●	●			●				
Soil freezing and thaw	●	●		●	●	●			
Temperature effect on hydraulic conductivity			●						
Hysteresis			●				●	●	
Preferential flow		●	●	●			●		
Inverse solution of hydraulic properties			●						
Solute transport		●	●	●	●		●		●
Multiple plant species					●		●		
Dimensions									
One-dimension			●	●	●	●	●	●	
Quasi two-dimension with lateral drainage from drainage layer	●	●							
Two-dimension									●
Initial Conditions									
Water Content	●	●	●	●	●	●	●		●
Head			●	●	●	●	●	●	●
Static Equilibrium									●
Upper Boundary									
Constant head			●	●		●	●	●	●
Variable head			●						
Constant flux			●						
Variable flux			●						
No flow			●	●					●
Variable gradient			●						
Meteorological forcing	●	●	●	●	●	●	●	●	●
Meteorological forcing with ponding			●						●
Meteorological forcing with ponding/runoff relationship							●		

Table 3.1: Characteristics of Water Balance Computer Models (cont.).

Model Characteristics	HELP	EPIC	HYDRUS-1D	LEACHM	SHAW	SoilCover	SWIM	UNSAT-H	VS2DT
Lower Boundary									
Constant water content						●			
Final water content					●				
Constant head			●	●		●	●	●	●
Variable head			●	●			●		●
Constant flux			●					●	●
Variable flux			●					●	●
No flow			●	●			●	●	●
Unit gradient	●	●	●	●	●		●	●	
Variable gradient			●				●		
Seepage face			●	●			●		●
Horizontal drains			●						

It can be very useful to be able to review the source code to better understand how the water balance model works. There are often assumptions used to develop the model that are not included in the model documentation. For example, in multi-year simulations conducted with UNSAT-H, the base year is actually a calendar year from which the leap year is calculated. If the specified base year is 1, UNSAT-H will require a leap year at year 4. UNSAT-H also does not allow precipitation on the last day of a leap year. If there is significant precipitation on the last day of a leap year, it will not be included in the water balance.

The information contained in Table 3.1 was developed by reviewing the model documentation listed above, examining the computer code to some extent (if it was available), and exploring the options in the graphical user interface (GUI) provided with some of the models. Just because a process is discussed in the documentation, it does not necessarily follow that the process has been implemented that way in the model. For example, Berger (2002) found that the vegetation growth and decay algorithm described in the HELP documentation was not fully incorporated into HELP.

3.4 Selection of Water Balance Computer Models for Study

Based on a comparison of the characteristics of the above water balance models, and on the past use of these models to evaluate evapotranspirative cover systems, HELP, LEACHM, and UNSAT-H were selected to analyze the three evapotranspirative cover systems in this study. HELP is the most commonly used computer model for water balance analysis of landfills, is frequently used for cover system design, and is required by some states, e.g., New Mexico, for cover system design. UNSAT-H currently appears to be the most commonly used computer model to design evapotranspirative cover systems in the U.S. There have been a number of studies that have compared the measured water balances for evapotranspirative cover systems to water balances predicted using UNSAT-H and HELP. Though LEACHM is currently used in practice to design evapotranspirative cover systems in the southwest U.S., published studies that compared the measured water balance for any type of cover system to the water balance simulated using LEACHM were not identified. Therefore, LEACHM was also used to analyze the water balances of the three evapotranspirative cover systems. LEACHM has historic use in the U.S. because it is based on Richards' equation, but requires less computation time than UNSAT-H.

The models that were screened but not selected for this study are either similar to HELP, LEACHM and UNSAT-H in terms of water balance approach (e.g., EPIC, which is similar to HELP), are currently not as well documented (HYDRUS-1D), or are not in the public domain (SWIM and SoilCover). SHAW would have been selected if the evapotranspirative cover systems in this study were located at sites in colder regions with significant snow. SHAW is one of the few models that considers snow accumulation, snow melt, and frozen soil and uses Richards' equation for water redistribution.

Chapter 4: Description of Study Sites

4.1 Overview of Study Sites

This chapter describes the three test sites with evapotranspirative cover systems that were evaluated for this study: (i) a test plot within a 4.5-ha cover system constructed over a pre-Subtitle D landfill in Yucaipa, California; (ii) a 0.11-ha test plot within a cover system research facility at Sandia National Laboratories near Albuquerque, New Mexico that was developed in support of the closure of a mixed waste landfill containing low-level radioactive waste and minor amounts of mixed waste; and (iii) a 0.06-ha test plot within a cover system research facility in Sierra Blanca, Texas that was developed in support of a proposed low-level radioactive waste landfill. All three test plots are located in the arid or semi-arid southwest U.S (Figure 4.1).

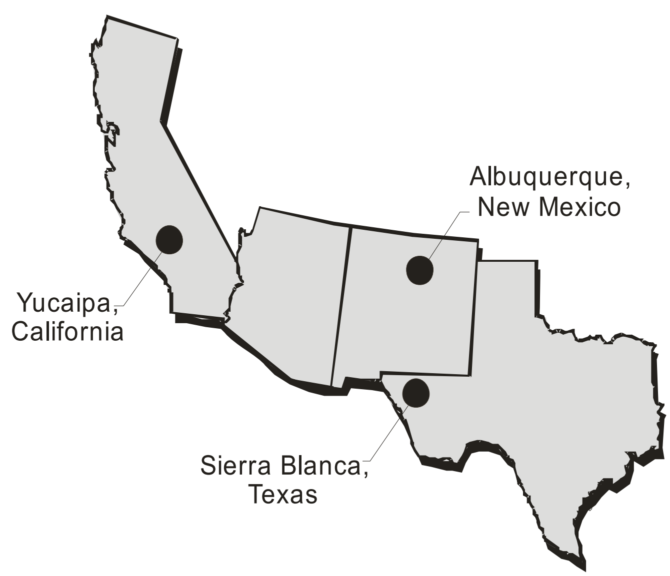

Figure 4.1: Locations of Cover System Test Plots Evaluated in this Study.

Information on site setting and on the construction and monitoring of the evapotranspirative cover systems at the Yucaipa, Albuquerque, and Sierra Blanca sites is provided in the remainder of this chapter. More information is provided on the Yucaipa site than the Albuquerque and Sierra Blanca sites because details on these latter two sites are available in the technical literature, i.e., Dwyer, 1997, 2003; Dwyer et al., 1998, 2000; and Scanlon et al., 2001, 2002, 2005.

4.2 SITE SETTING

4.2.1 Yucaipa Site Setting

The Yucaipa site is located in San Bernardino County, California, about 120 km east of Los Angeles, and is situated on the eastern edge of the Los Angeles basin in an area known as the Yucaipa plain. The site is in the California Coastal Range Open Woodland - Shrub - Coniferous Forest - Meadow Province of the Mediterranean Ecoregion Division (Bailey, 1995). This biogeographic zone, located in the transition between the wet west coast and the dry west coast desert, experiences a climate with wet, mild winters and hot, dry summers. Dominant plant communities are California chaparral, which consists of fire-adapted shrubs, and sclerophyll forest, which is characterized by evergreen trees. The estimated humidity index for the Yucaipa vicinity is approximately 0.35 (Mooreland, 1970); thus, the site is classified as semi-arid.

Based on data from the Beaumont, California weather station (Beaumont 1E), located about 15 km south of the site and at a similar elevation (approximately 820 m versus 800 m for Yucaipa), the 30-year (1971-2000) mean annual monthly precipitation at the site is approximately 490 mm (Southern Regional Climatic Center, 2004). About 80% (391 mm) of annual precipitation occurs from November through March (Figure 4.2). During these months, solar radiation and temperature, and thus, potential evapotranspiration, are relatively low compared to the average values for these parameters during April to October. For example, on average, the site receives only about 28% of its annual solar radiation from November through March when the site is the wettest [based on 30-yr (1961-1990) mean monthly solar radiation for Daggett, California (Renewable Resource Data Center, 2004)]. Consequently, at the Yucaipa site, the potential for water to infiltrate soil and percolate beyond the root zone is greatest during the winter and early spring. There would be an even greater potential for drainage at this site if precipitation in the winter occurred as snow and resulted in snowmelt. However, the Yucaipa site has mild winters. Essentially all of the precipitation at the site occurs as rain (Mendez et al., 2001).

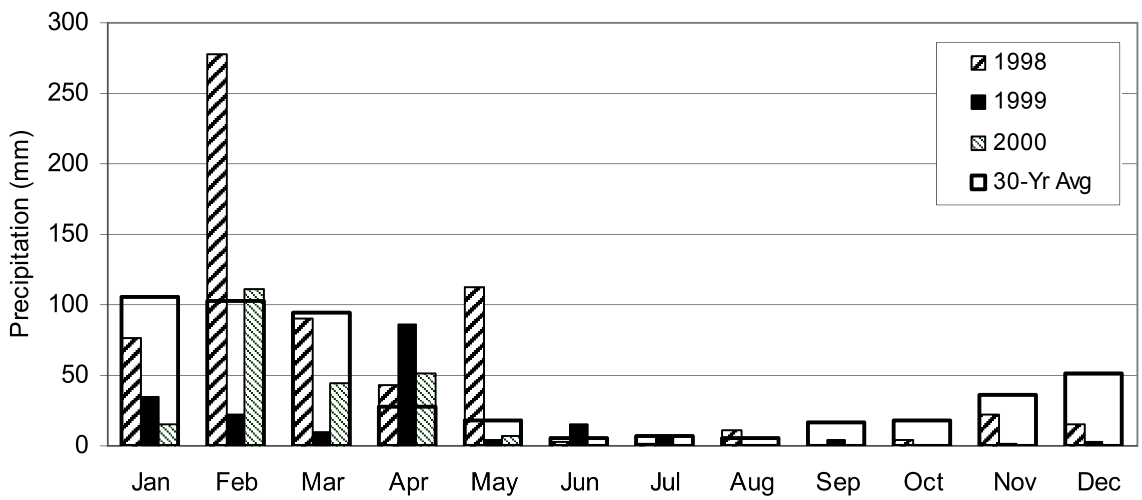

Figure 4.2: Average Monthly Precipitation at Yucaipa Site during Monitoring Period (January 1998 through June 2000) and 30-Year (1971-2000) Average Monthly Precipitation at Beaumont, California Weather Station.

4.2.2 Albuquerque Site Setting

The Albuquerque site is located in Technical Area 3 at Sandia National Laboratories on Kirkland Air Force Base, Bernalillo County, New Mexico. The site is in the Colorado Plateau Semidesert Province of the Tropical/Subtropical Steppe Ecoregion

Division (Bailey, 1995). The climate in this biogeographic zone is characterized by cold winters and by summers that experience a significant variation in diurnal temperatures, with hot days and cool nights. In the winter, precipitation can occur as snowfall; however, there is generally little accumulation and the accumulation that does occur does not last very long. Using the total precipitation (1.69 m) and potential evapotranspiration (17.31 m) values for the Albuquerque, New Mexico weather station (Albuquerque WFSO Airport) from 1991 though May 1999 reported by Dwyer et al. (1999), the calculated humidity index for the Albuquerque site is approximately 0.10; thus, the site is classified as arid.

Based on data for the Albuquerque WFSO Airport weather station, located about 11 km northwest of the site, the 30-year (1971-2000) mean annual monthly precipitation at the site is approximately 241 mm (Southern Regional Climatic Center, 2004). Unlike the Yucaipa site, which experiences the majority of its rainfall in the winter and spring, the Albuquerque site receives approximately 43% (103 mm), on average, of its annual precipitation in the summer (July to September) (Figure 4.3), when evapotranspiration is the highest. Average monthly precipitation is also more evenly distributed throughout the year at the Albuquerque site than at the Yucaipa site.

The average annual snowfall recorded at the Albuquerque weather station over the period of record (September 1931 to March 2005) is about 249 mm, with average daily snow accumulations during the winter months of 2 to 5 mm when snow occurs and average monthly snow depths of less than 1 mm, i.e., snow does not tend to accumulate. There are uncommon events of snow accumulation recorded at the weather station, e.g., peak daily snow depth of 280 mm. The impact of snow accumulation and frozen ground on the water balance of the evapotranspirative cover system at the Albuquerque site could be evaluated as an extreme event. However, it will not be discussed herein because the topics of frozen ground and snowmelt have been excluded from this dissertation. These topics were also not covered by Dwyer (2003) or Scanlon et al. (2005) in their studies of the Albuquerque site, probably because extended snow accumulation is not expected to be a regular occurrence at the site.

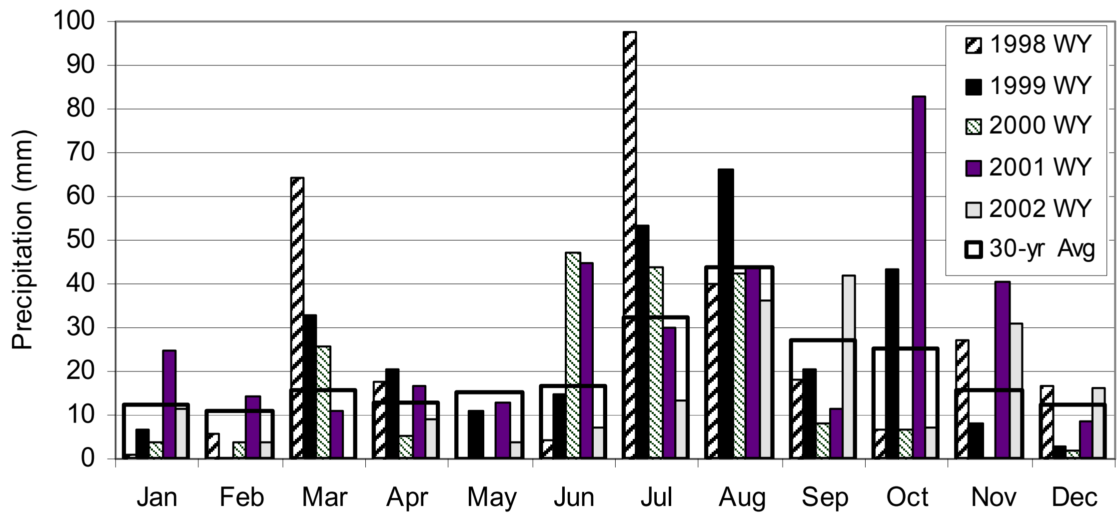

Figure 4.3: Average Monthly Precipitation at Albuquerque Site during Monitoring Period and 30-Year (1971-2000) Average Monthly Precipitation at Albuquerque Weather Station. (WY = Water Year, from October to September, i.e., 1998 WY = October 1997 - September 1998).

Plant communities near Technical Area 3 consist primarily of mesa and desert grassland with some sandsage and desert shrubland (Sandia National Laboratories, 1999).

Based on the presence of caliche at shallow depths, typically 0.8 to 1.5 m below ground surface, at the site and on local studies of chloride profiles in the shallow and deep vadose zone soils, annual average recharge to groundwater is estimated to be less than 1 mm/yr (Sandia National Laboratories, 1996). Further, the accumulations of chloride in the upper 3 m of soil suggest that drainage below 3 m has been negligible over the past 10,000 years.

4.2.3 Sierra Blanca Site Setting

The Sierra Blanca site is located in Hudspeth County, Texas, about 150 km southeast of El Paso and 8 km east of the town of Sierra Blanca. The site is located in the Chihuahuan Desert Province of the Tropical/Subtropical Desert Ecoregion Division (Bailey, 1995). The climate in this biogeographic zone is characterized by short winters, with temperatures occasionally falling below freezing, and long, hot summers. Summer rains are generally localized torrential storms, and fall rains are more gentle and widespread. Precipitation in the region can exhibit large inter-annual variations. The plant community at the site is primarily creosote-tarbush desert shrub. Vegetation observed adjacent to the site includes black grama grass (*Bouteloua hirsuta*), mesquite (*Prosopis* sp.), and soaptree yucca (*Yucca elata*). Using the average annual precipitation (224 mm) and calculated potential evapotranspiration (2087 mm) values for El Paso, Texas from 1961 through 1990 reported by Keese et al. (2003), the calculated humidity index for the Sierra Blanca site is approximately 0.11; thus, the site is classified as arid.

Based on data for the Sierra Blanca weather station (Sierra Blanca 2 E), located about 10 km east of the site, the 30-year (1971-2000) mean annual monthly precipitation at the site is approximately 303 mm (Southern Regional Climatic Center, 2004). The Sierra Blanca site has a precipitation pattern that is somewhat similar to the Albuquerque site, but with higher precipitation in the summer. It receives most of its rainfall in the summer: on average, 55% (167 mm) of annual precipitation occurs from July through September (Figure 4.4). During the remainder of the year, the mean precipitation for the Albuquerque and Sierra Blanca sites is 137 and 136 mm, respectively.

Similar to the Albuquerque site, the Sierra Blanca site has been undergoing long-term (more than 10,000 years) drying based on the presence of thick caliche layers at shallow depths, chloride profiles in the vadose zone, and measurement and modeling of matric potential and bomb chloride concentrations at the site (Scanlon et al., 2005).

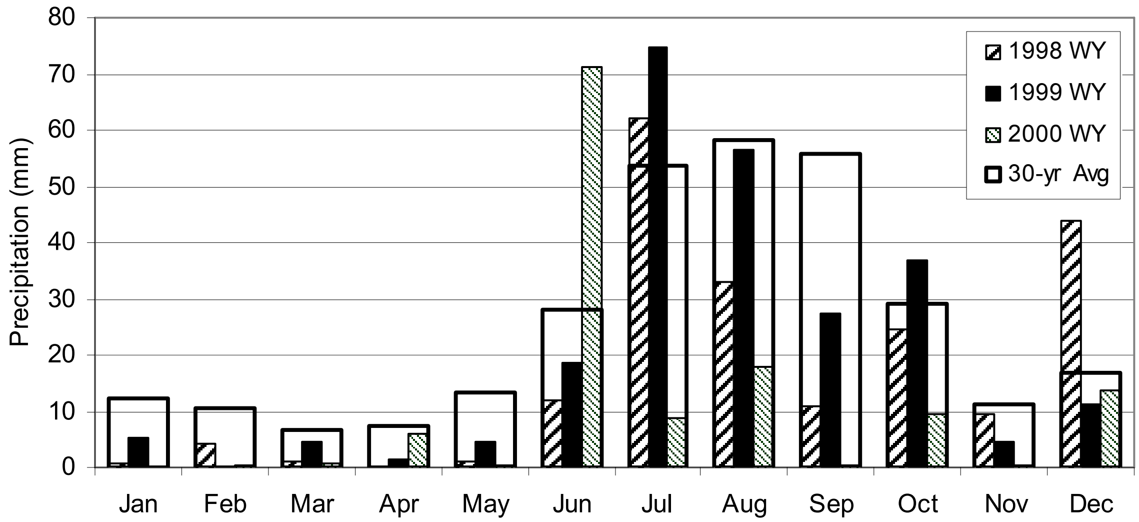

Figure 4.4: Average Monthly Precipitation at Sierra Blanca Site during Monitoring Period and 30-Year (1971-2000) Average Monthly Precipitation at Sierra Blanca Weather Station. (WY = Water Year, from October to September, i.e., 1998 WY = October 1997 - September 1998).

4.2.4 Weather Record Observations

Interestingly, all of the sites were being monitored during the strong "El Niño" weather pattern that began during spring 1997 and caused higher than normal precipitation and lower than normal temperatures in the southwest U.S. from the winter of 1997 through the spring of 1998. For example, Mendez et al. (2001) noted that February 1998 was the wettest February on record for southern California. The El Niño weather pattern was followed by the "La Niña" weather pattern the following year, and the southwest U.S. experienced drier and warmer conditions than normal in the winter and early spring.

4.3 DESIGN, CONSTRUCTION, AND MONITORING OF YUCAIPA SITE

4.3.1 Design of Yucaipa Site

A 1.2-m thick monolithic cover system (Figure 4.5) was constructed over 4.5 ha of side slopes on a pre-Subtitle D municipal solid waste landfill in Yucaipa, California. The monolithic cover system was designed to perform equivalent to or better than a 1.2-m thick cover system that meets the minimum standards for municipal solid waste landfills contained in Section 20190(a) of the California Code of Regulations. This "minimum standard" cover system consists of, from top to bottom:

- 0.3-m thick erosion layer capable of sustaining native or other suitable vegetation having a rooting depth no greater than the thickness of the erosion layer;
- 0.3-m thick barrier layer with a maximum saturated hydraulic conductivity of 1×10^{-8} m/s; and
- 0.6-m thick foundation layer.

As described by GeoSyntec Consultants (2001), the cover system performance mandated by California regulations was demonstrated by:

- monitoring the field water content of the monolithic cover system for 30 months;
- comparing the measured field water contents to water contents predicted using the computer models LEACHM and UNSAT-H (which was considered a validation of the model and input parameters);
- estimating the drainage during the monitoring period using the two models; and

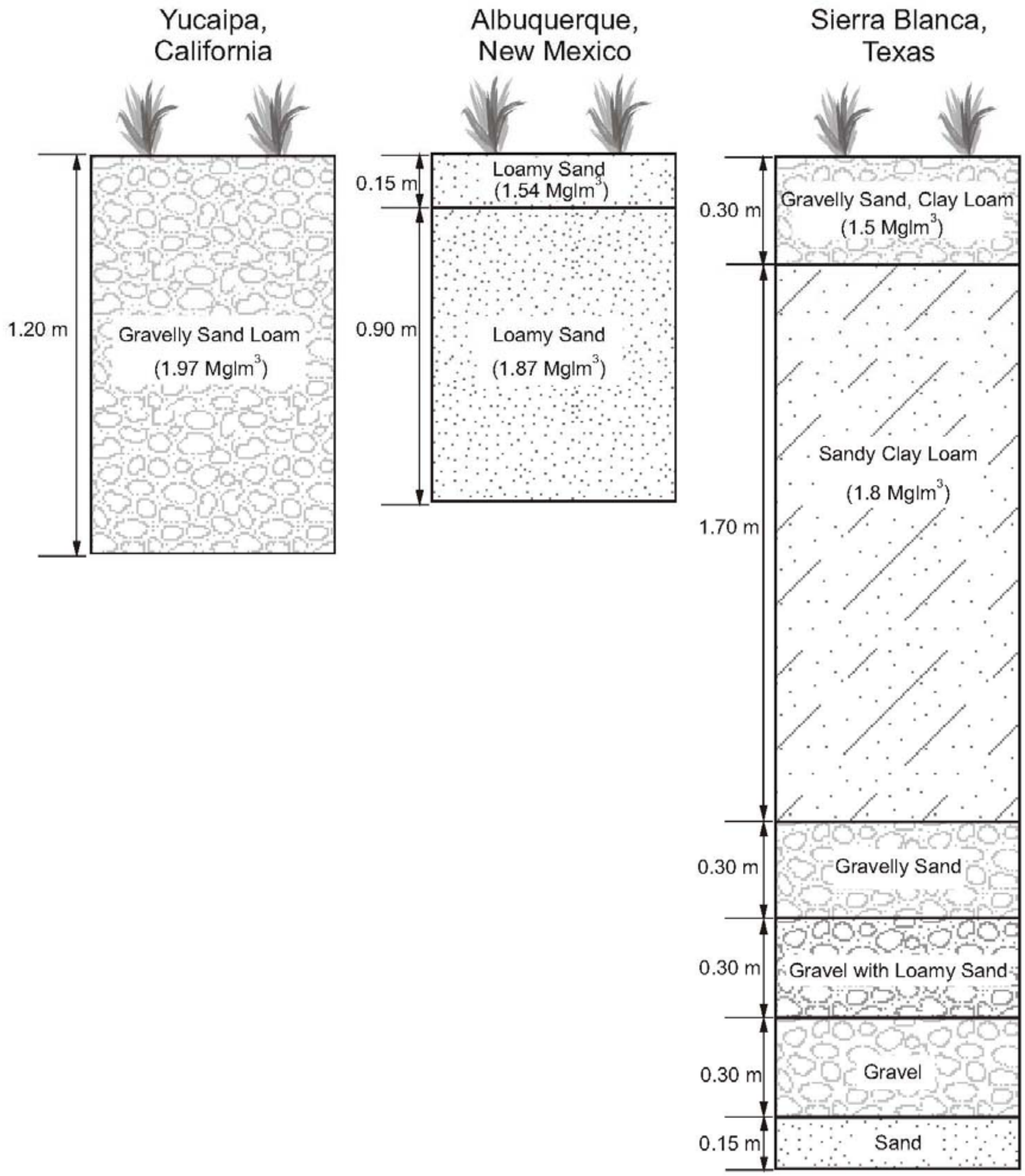

Figure 4.5: Profiles of Evapotranspirative Cover Systems Evaluated in this Study and Used in Simulations.

- predicting drainages from the monolithic cover system and minimum standard cover system over the wettest recorded 10-year interval (1974-1983) using the two models, a water retention curve developed from a pressure plate test, a specified saturated hydraulic conductivity of 1×10^{-7} m/s, and historic weather data taken from nearby weather stations [(Beaumont 1E) for precipitation and temperature data and a weather station located about 90 km north-northwest of the site (Daggett FAA Airport) for dew point temperature, solar radiation, and wind speed data].

For simulations with LEACHM, daily precipitation was applied between 0.3 and 0.5 day; thus, precipitation intensity varied with daily rainfall. For simulations with UNSAT-H, daily precipitation was applied at an intensity of 10 mm/hr.

The water content versus time trends calculated with the LEACHM and UNSAT-H models bounded the water contents measured at various depths at two monitoring stations. Simulated drainage through the monolithic cover system was less than drainage through the minimum standard cover system, indicating satisfactory performance of the monolithic cover system. Cumulative drainage during the first 18-months of the monitoring period calculated using LEACHM and UNSAT-H was 5.4 and 0.1 mm, respectively, for the monolithic cover system and 59.2 and 6.7 mm, respectively, for the minimum standard cover system (GeoSyntec Consultants, 2001). Significantly higher rates of drainage were simulated with LEACHM than UNSAT-H. The drainage predicted with LEACHM was considered an upper bound for the site during the monitoring period.

The average annual drainage predicted using LEACHM and UNSAT-H with 10-years of historic weather data was 12.1 and 0.5 mm, respectively, for the monolithic cover system and 20.7 and 2.8 mm, respectively, for the minimum standard cover system (GeoSyntec Consultants, 2001). Both models predicted no significant change in water content at depths greater than 0.6 m. These results were considered consistent with the field monitoring results.

4.3.2 Construction of Yucaipa Site

Construction details presented herein for the monolithic cover system at the Yucaipa site are based on the construction quality assurance report for the cover system (GeoSyntec Consultants, 1998) and discussions with the design engineer. Details on vegetation of the cover systems are from GeoSyntec Consultants (2001).

The cover system was constructed on the east and south side slopes of the landfill from August 25, 1997 to November 21, 1997. The landfill slopes are relatively steep, with inclinations up to 2 horizontal: 1 vertical (26.6°) (Figure 4.6). Soil for the cover system was excavated from an on-site borrow pit, placed in 0.15 to 0.20-m thick loose lifts with a scraper, moisture conditioned as needed, and then compacted with a sheeps-foot roller. The project specifications required that the soil conform to the following:

- maximum particle size ≤ 64 mm;
- percent particles finer than 0.074 mm (percent fines): ≥ 20% by weight for any individual test and ≥ 25% by weight for any 10 consecutive tests;
- as compacted, minimum bulk (dry) density ≥ 90% of the maximum dry density obtained from the modified Proctor compaction test (ASTM 1557) and water content within 0 to -4 percentage points of the optimum water content; the target dry density and gravimetric water content for the in-place soil were, for the most part, 4 to 8% (0.08 to 0.15, by volume) and ≥ 1.93 Mg/m^3 (19.0 kN/m^3), respectively; and
- saturated hydraulic conductivity ≤ 1×10^{-7} m/s for field BAT® well point tests and ≤ 2.5×10^{-7} m/s for laboratory tests.

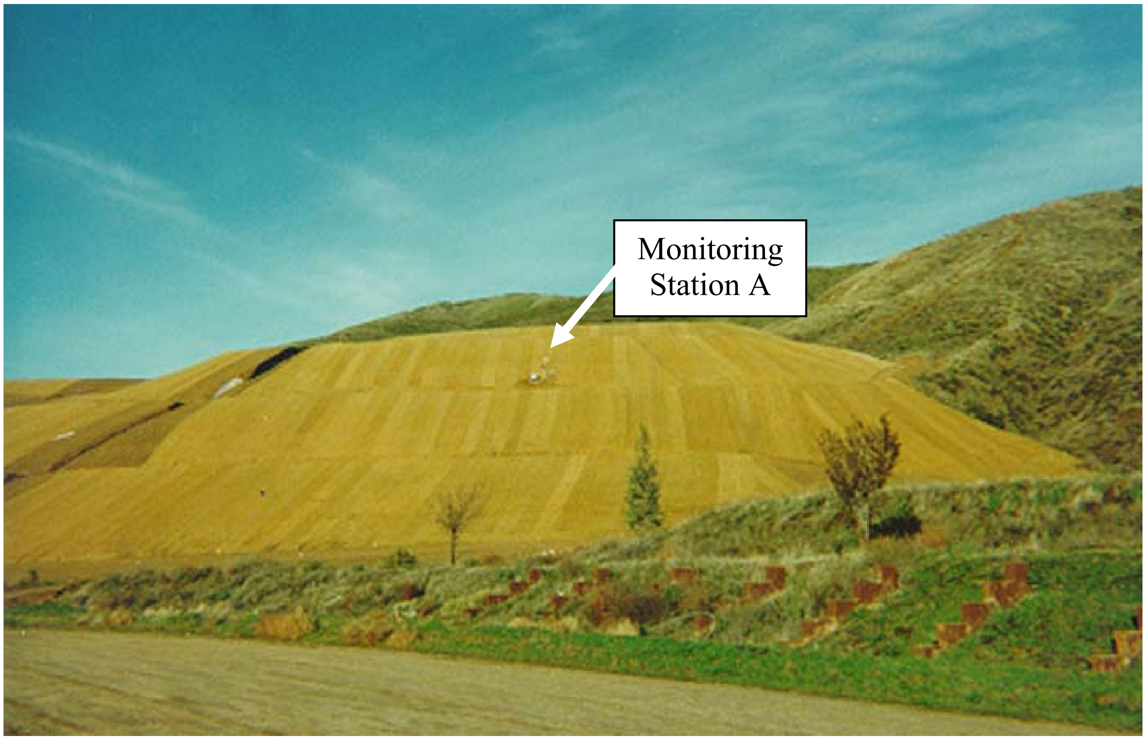

Figure 4.6: Steep Slopes of the Monolithic Cover System at the Yucaipa Site.

The minimum bulk density specified for this monolithic cover system is relatively high; however, this design density was required to ensure seismic and static slope stability. The site is located south of the San Andreas Fault zone. Although a well-graded soil compacted to such a high bulk density would likely have a relatively low hydraulic conductivity, at least in the short term, it would also likely be difficult for roots to penetrate. Based on the USDA NRCS guidance presented in Table 2.1, soil bulk densities greater than 1.80 Mg/m^3 (17.7 kN/m^3) will restrict plant root growth for any soil type. Data on the density of the native soil (alluvial fan deposits) at the site were not available. However, from the NRCS descriptions of the soil series in the site vicinity (Ramona and Greenfield series), at least the Ramona series is dense. As described by NRCS (2004), the upper 2-ft of soil in this series is hard to very hard after considerable cultivation or cattle trampling.

To verify that the soil used to construct the monolithic cover system was relatively consistent in its properties and that the above specifications were achieved, a number of laboratory and field tests were performed during construction (Table 4.1). From the test results, the as-built cover system at the Yucaipa site consists of a dense, gravelly sand loam classified as an SM-SC material under the Unified Soil Classification System.

The hydraulic conductivities of thin-walled tube samples measured in the laboratory were, on average, one order of magnitude higher than the hydraulic conductivities determined in the field using the BAT® probe. The design engineer primarily attributed the difference between the field and laboratory hydraulic conductivities to sample disturbance that occurred during pushing of the thin-walled tube sampler. Field personnel noted that, during sampling, the soil expanded in the tube up to about 20 mm above ground surface (Figure 4.7). Dry, compacted sandy loam soils are difficult to sample because they are generally brittle and fracture easily during sampling. In addition, in gravelly soil, gravel particles near the edge of a thin-walled tube sampler may move into the tube and disturb the soil as the sampler is being pushed.

The dry densities of the extruded samples were relatively low, ranging from 1.72 to 1.92 Mg/m^3 (16.9 to 18.8 kN/m^3) and averaging 1.79 Mg/m^3 (17.6 kN/m^3). In comparison, the dry densities of the cover system soil determined from nuclear gauge and sand cone tests ranged from 1.93 to 2.08 Mg/m^3 (19.8 to 20.4 kN/m^3). Fractures were noted on some of the samples when they were extruded from the tubes. Fractures in the samples will create preferential flow paths that may result in higher hydraulic conductivities, depending on the orientation of the fractures. In addition, fractured or disturbed samples can exhibit more sidewall flow when tested in laboratory permeameters at low confining pressures (20 to 30 kPa), leading to higher measured hydraulic conductivity values.

Table 4.1: Summary of Laboratory and Field Tests Results for Yucaipa Cover System During Construction.

Test	Number of Samples	Results
Percent Fines (ASTM D 1140)	24	25% (avg)
Sieve Analysis (ASTM D 422)	37	gravel:sand:fines 20:50:30 (avg) 41:39:20 (coarsest) 10:47:43 (finest)
Particle Size Distribution (ASTM D 422)	3	
Atterberg Limits (ASTM D 4318)	19	SM-SC
In-situ Moisture Content and Bulk Density (on 75-mm diameter, thin-walled tube, undisturbed samples) (ASTM D 2216)	12	water content, by weight: 5.3 - 9.6%, 7.2% (avg); bulk density: 1.72 - 1.92 Mg/m^3 (16.9 - 18.8 kN/m^3), 1.79 Mg/m^3 (17.6 kN/m^3) (avg)
Modified Proctor Compaction (ASTM D 1557)	16	optimum water content, by weight: 7 - 10%, 8.1% (avg); maximum bulk density: 2.10 - 2.18 Mg/m^3 (20.6 - 21.4 kN/m^3), 2.14 Mg/m^3 (19.8 kN/m^3) (avg)
Water Content by Nuclear Gauge (ASTM D 2922)	175	by weight, 5.0 - 10.0%, 6.8% (avg) by volume, 0.10 - 0.21, 0.13 (avg)
Density by Nuclear Gauge (ASTM D 3017)	175	1.93 - 2.08 Mg/m^3 (18.9 - 20.4 kN/m^3), 1.97 Mg/m^3 (19.3 kN/m^3) (avg)
Microwave Water Content (ASTM D 4643)	88	4.7 - 8.3%, 6.7% (avg)
Sand Cone Density (ASTM D 1556)	10	1.94 - 2.07 Mg/m^3 (19.0 - 20.3 kN/m^3), 2.00 Mg/m^3 (19.6 kN/m^3) (avg)
Specific Gravity (ASTM D 854)	2	2.76 - 2.77
Laboratory Saturated Hydraulic Conductivity (on 75-mm diameter, thin-walled tube, undisturbed samples) (ASTM D 5084)	12	7.0×10^{-9} - 2.4×10^{-7} m/s 8.7×10^{-8} m/s (geometric mean)
In-Situ Saturated Hydraulic Conductivity (estimated from BAT® outflow)	15	8.3×10^{-10} - 7.6×10^{-8} m/s 8.7×10^{-9} m/s (geometric mean)

Figure 4.7: Expansion of Soil up to 20 mm above the Ground Surface During Sampling with a Thin-Walled Tube.

The in-situ hydraulic conductivity tests were conducted with a 31-mm diameter Geonordic BAT® porous probe. The probe was driven into the compacted soil, and falling head tests were performed by connecting a test container with approximately 30 mL of water and 5 mL of gas to the probe. As the pressurized water flowed through the 36-mm long probe filter and into the unsaturated soil, the pressure of the gas in the test container was recorded. The test ended when the measured hydraulic conductivity stabilized or when the driving head dissipated. For the latter case, the estimated saturated hydraulic conductivity was always less than 1×10^{-7} m/s when the test was stopped.

Although the BAT® falling head test is a very convenient method for estimating the saturated hydraulic conductivity of low permeability soils, by its nature it only tests a small volume of soil. For soils compacted dry of the line of optimums, rather than wet of the line of optimums, the minimum soil sample size that expresses the overall field structure (representative specimen size) can be large due to the macrostructure that tends to exist in drier compacted soils. For example, the difference between the measured hydraulic conductivity of a small specimen, such as a 75-mm diameter thin-walled tube sample, and a large specimen, such as a 300-mm diameter sample trimmed from a block specimen, may be several orders of magnitude (Benson et al., 1994). The representative specimen size for testing the hydraulic conductivity of the Yucaipa cover system soil is not known. However, given that the soil was compacted dry of the line of optimums and given that the soil contained gravel up to 38-mm in diameter (based on the results of the sieve tests) and that it is desirable to have a specimen with a diameter that is at least six times the maximum particle size, the volume of soil tested by the BAT® test is probably smaller than the representative specimen size.

The desorption soil water characteristic curve (SWCC) of the soil was evaluated by a pressure plate test (ASTM D 2325) (Figure 4.8) conducted at pressures ranging from 0.25 to 70 m (2.4 to 690 kPa). Soil samples for the test were screened of gravel and remolded in the laboratory to a bulk density of 1.80 Mg/m^3 (17.6 kN/m^3) and volumetric water content of 0.35. For this dissertation, the results of the pressure plate test were corrected for 29% gravel by volume (based on 20% gravel by weight measured during construction) by multiplying the measured water content values by the non-gravel fraction (1 - 0.29).

The data from the pressure plate test were fitted to the van Genuchten water retention function (Figure 4.8) using the Solver tool in EXCEL™ to find the smallest root mean squared error between the data and the fitted curves. The residual water content in the van Genuchten function was assumed to be zero. This is a reasonable assumption because, from thermodynamic considerations and experimental data, zero water content should be reached at a matric potential slightly less than -100,000 m (-10^6 kPa) (Fredlund and Xing, 1994). The van Genuchten SWCC was also used to determine the Campbell (1974) SWCC using the Solver tool. The calculated parameters for the van Genuchten

SWCC are α and n of 0.0016 mm^{-1} and 1.21, respectively. The calculated parameters for the Campbell SWCC are h_b and λ of - 393 mm and 0.189, respectively.

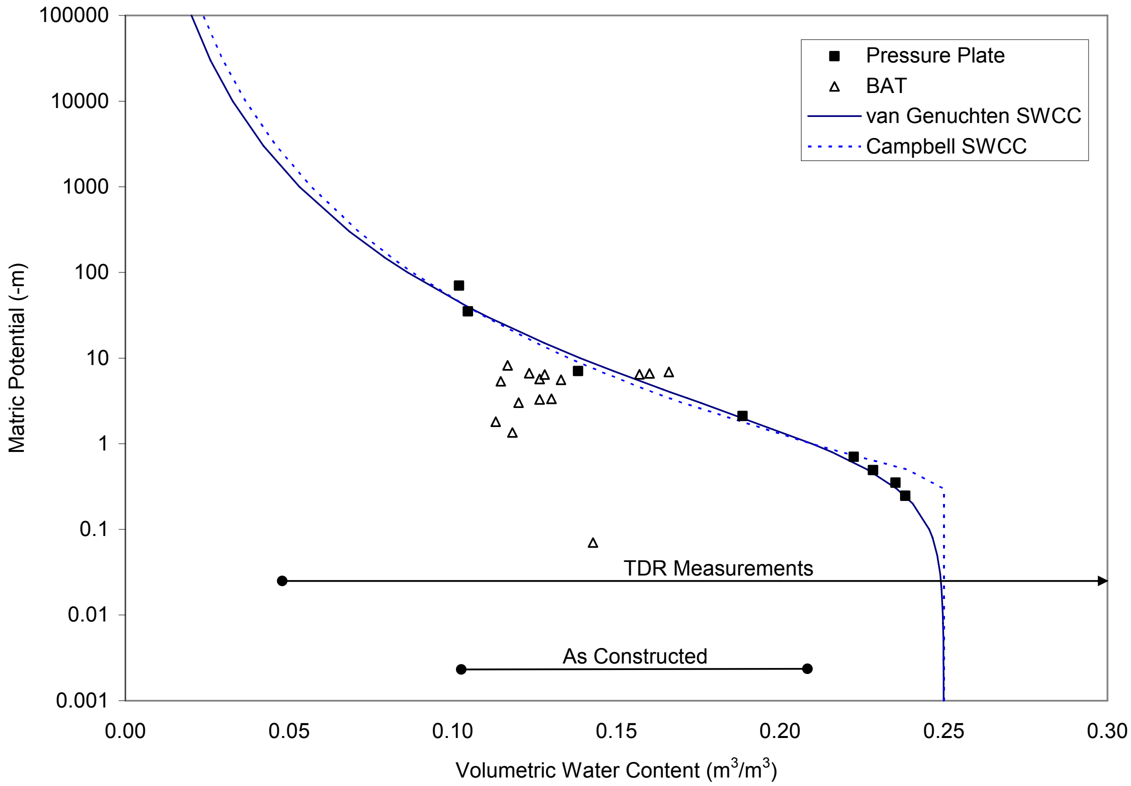

Figure 4.8: SWCCs (Desorption) for Cover System Soil at the Yucaipa Site Based on Pressure Plate Data Fitted to van Genuchten and Campbell Water Retention Functions. [Field Conditions at Start of the BAT® Tests and Volumetric Water Contents Measured during Construction and Monitoring are also Shown].

At the start of each BAT® test, the water potential of the soil was measured with the BAT® pressure transducer. The bulk density and moisture content of soil near each test location was measured with a nuclear density gauge. The measured water potentials and water contents are shown in Figure 4.8. The BAT® data plot to the left of the desorption SWCC. Since the BAT® test is an infiltration test that involved wetting of the soil, the displacement of the BAT® test data relative to the pressure plate test data may be due, in part, to hysteresis.

For this dissertation, van Genuchten-Mualem and Campbell-Burdine hydraulic conductivity functions were developed for the cover system soil (Figure 4.9). Due to the disturbance of the thin-walled tube samples collected for laboratory hydraulic conductivity testing, only the in-situ hydraulic conductivity test results from the BAT® probe were used to estimate the saturated hydraulic conductivity. To reflect that the representative sample size of cover system soil for hydraulic conductivity tests is likely greater than the sample size tested by the BAT® probe, the geometric mean soil hydraulic conductivity of 8.7×10^{-9} m/s measured with the BAT® probe was increased by a factor of 10. The actual relationship between the hydraulic conductivity determined with the BAT® probe and the field hydraulic conductivity may be more or less than this value.

The Yucaipa cover system was hydroseeded in December 1997 with introduced and cultivar annuals. The seed mix was a typical blend used for rapid revegetation in southern California and consisted of:

- 25% Cucamonga brome (*Bromus carinatus*);
- 25% common oats (*Avena sativa*);
- 20% Zorro fescue (*Vulpia myuros* var. *hirsuta*);
- 15% crimson clover (*Trifolium incarnatum L.*);
- 10% Lana vetch (*Vicia villosa* ssp. *dasycarpa*); and
- 5% California field flowers.

With the exception of common oats, which experiences most of its growth in the spring and summer, the above plants have their active growth period from fall to spring (Hitchcock, 1950; USDA, 2004). By January 1998, seed germination was noted.

Vegetation coverage appeared to be nearly 100% by spring, helped by the El Niño precipitation. Because these plants are annuals, they do not have a deep root system.

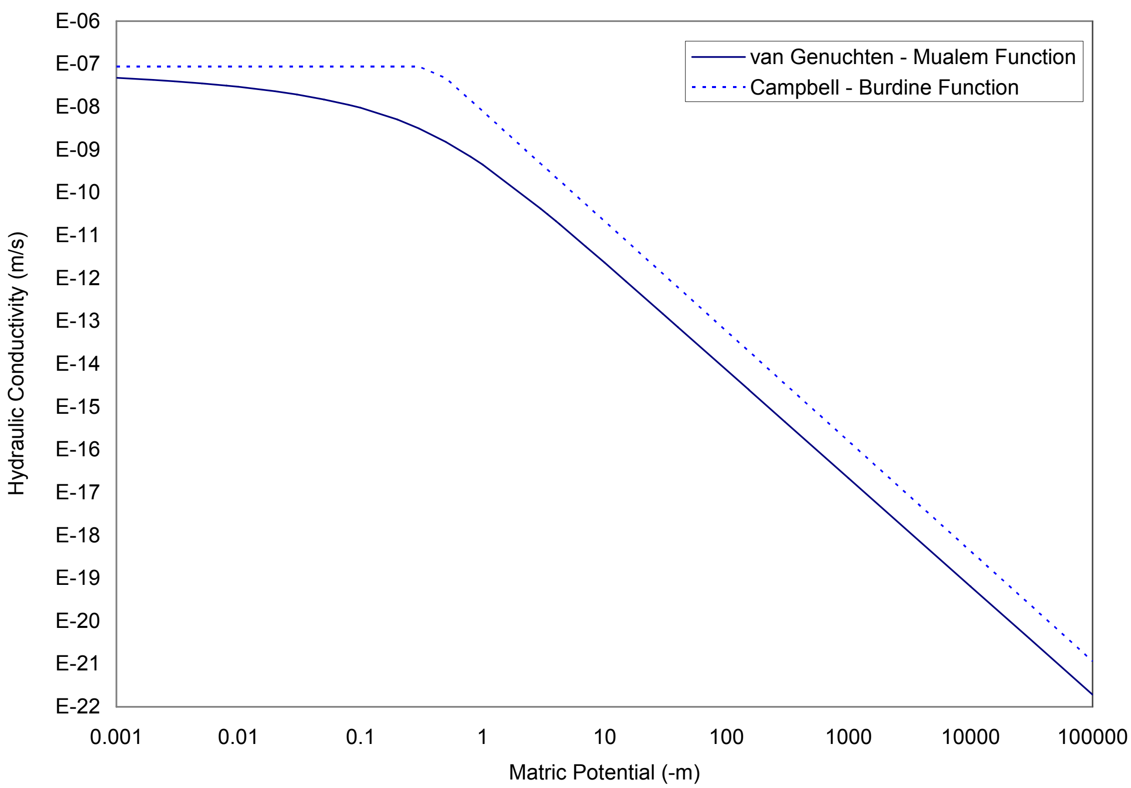

Figure 4.9: van Genuchten-Mualem and Campbell-Burdine Hydraulic Conductivity Functions (Desorption) for Cover System Soil at the Yucaipa Site.

After the annual grasses went to seed and before the rains of winter 1998 to spring 1999, the cover system was drill seeded with perennial species. Data on the specific seed mix was not available.

4.3.3 Monitoring of Yucaipa Site

Cover system performance data were collected at two southeastern facing monitoring points, Station A and B, located approximately 180 m apart on the side slopes of the landfill. The ground slope is 2 horizontal: 1 vertical (2H:1V) at Station A and 2.3H:1V at Station B.

Monitoring instrumentation consisted of a meteorological station (Figure 4.10), main multiplexer, data logger, and two time domain reflectometry (TDR) probes at Station A and satellite multiplexer and two TDR probes at Station B. The instrumentation was installed in December 1997, after the cover system was constructed, and was operational by January 1998. Hourly data were collected for approximately 30 months: from the time the monitoring systems became operational in January 1998 through mid-July 2000. The instruments used and the manufacturer's stated accuracy of each measurement are summarized in Table 4.2. The data collection systems are described below.

Climatologic measurements at the Yucaipa site consisted of precipitation, air temperature, relative humidity, solar radiation, wind speed, wind direction, and wind directional standard deviation. Precipitation recorded at the Yucaipa site during the 30-month monitoring period is compared to 30-year (1971-2000) average precipitation for the Beaumont, California weather station in Figure 4.2. From 1971 to 2000, average annual precipitation at the Beaumont weather station ranged from 184 to 1001 mm and averaged 490 mm, with a standard deviation of 223 mm. This relatively large standard deviation is due to six strong El Niños (some with significant La Niñas) that occurred over the 30-year weather record (National Weather Service, 2005). In southern California, higher than average precipitation is associated with strong El Niños and lower than average precipitation is associated with strong La Niñas. El Niños and La Niñas affect weather in the winter months (November to March).

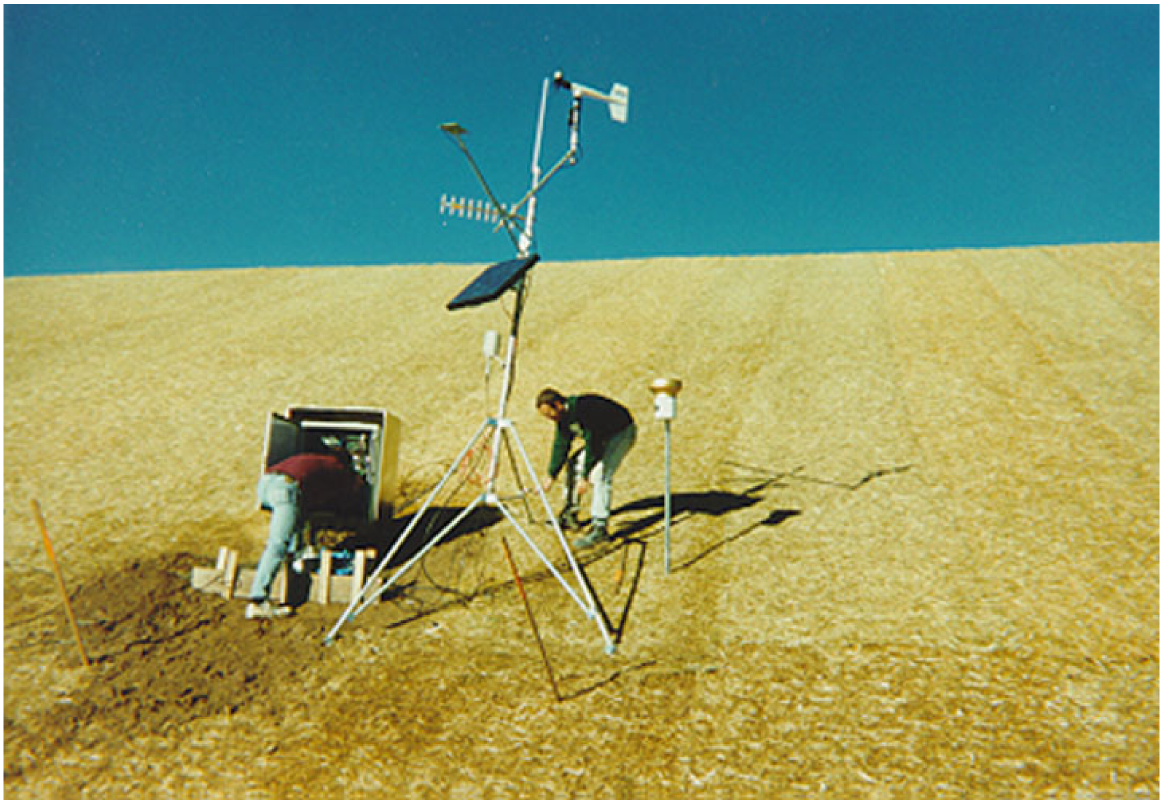

Figure 4.10: Meteorological Station Being Installed at Station A at Yucaipa Site.

Table 4.2: Sensors Used at Yucaipa Site.

Parameter	Instrument	Accuracy (Manufacturer Stated)
Precipitation	Campbell TE525MM tipping bucket rain gauge (0.1 mm tip)	± 1% at rates up to 10 mm/hr -3-0% at rates of 10-20 mm/hr -5-0% at rates of 20-30 mm/hr
Air Temperature and Relative Humidity	Vaisala HMP35C thermistor and capacitive relative humidity sensor	± 0.2-0.3 °C ± 2-3% relative humidity
Solar Radiation	Vaisala 441A pyranometer	± 5% max, ± 3% typical
Wind Speed and Direction	RM Young 03001 anemometer and vane	± 0.5 m/s ± 5°
Soil Water Content	Environmental Sensors, Inc. (ESI) Moisture Point PRB-A/MPX and PRB-A/MPX TDR Probes	± 3 percentage points typical, ± 1.3% percentage points with calibration

The effects of the winter 1997 to spring 1998 El Niño and winter 1998 to spring 1999 La Niña are evident. In 1998, precipitation at the site totaled 658 mm and was over 1.3 times higher than the long-term average of 490 mm for Beaumont, but still within one standard deviation. In contrast, 1999 was a relatively dry year with only 187 mm of precipitation recorded for the site. That year was also the second driest within the 1971-2000 weather record for the Beaumont weather station. Precipitation during the first six months of 2000 totaled 230 mm.

Precipitation data were collected at one-hour intervals at the site meteorological station. Rainfall intensities during the monitoring period ranged from 0.1 to 14.0 mm/hr, with a median intensity of 0.5 mm/hr and an average intensity of 1.0 mm/hr. Daily precipitation from 1998 to 1999, the two years for which a complete year of data are available, ranged from 0.1 to 50.7 mm, with a median of 2.4 mm and an average of 6.1 mm. In comparison, daily precipitation recorded for the Beaumont weather station from 1961 to 1990 ranged from 0.3 to 119.1 mm, with a median of 5.1 mm and an average of 10.0 mm.

Soil water content was measured with TDR probes calibrated by the manufacturer with site-specific soil. Probes were installed vertically through the constructed cover system and into the underlying soil. To reduce the potential for air gaps to form between the probes and the soil during installation, the probes were driven into pilot holes that had been predrilled with a smaller diameter than the probes.

The TDR probes were electrically segmented to allow average water content measurements to be made along discrete sections of each probe. A data logger was used with the manufacturer's calibrated signal processing code to detect and analyze TDR waveforms and output soil water contents. Probes were installed at Stations A and B on December 9, 1997. Data collection began on December 9, 1997 at the Station A probe (Probe A) and January 2, 1998 at the Station B probe (Probe B).

A 1.5-m long probe that provided averaged water content readings at 0.3 m intervals was initially used (Figure 4.11). However, this configuration overestimated water contents along certain segments due to signal attenuation along the long probe. Therefore, the single probe was replaced with two 0.9-m long nested probes (Figure 4.11). When this configuration also gave higher than expected water contents, soil samples were collected adjacent to the probes for water content measurements, and the results of these measurements were used to recalibrate the probes.

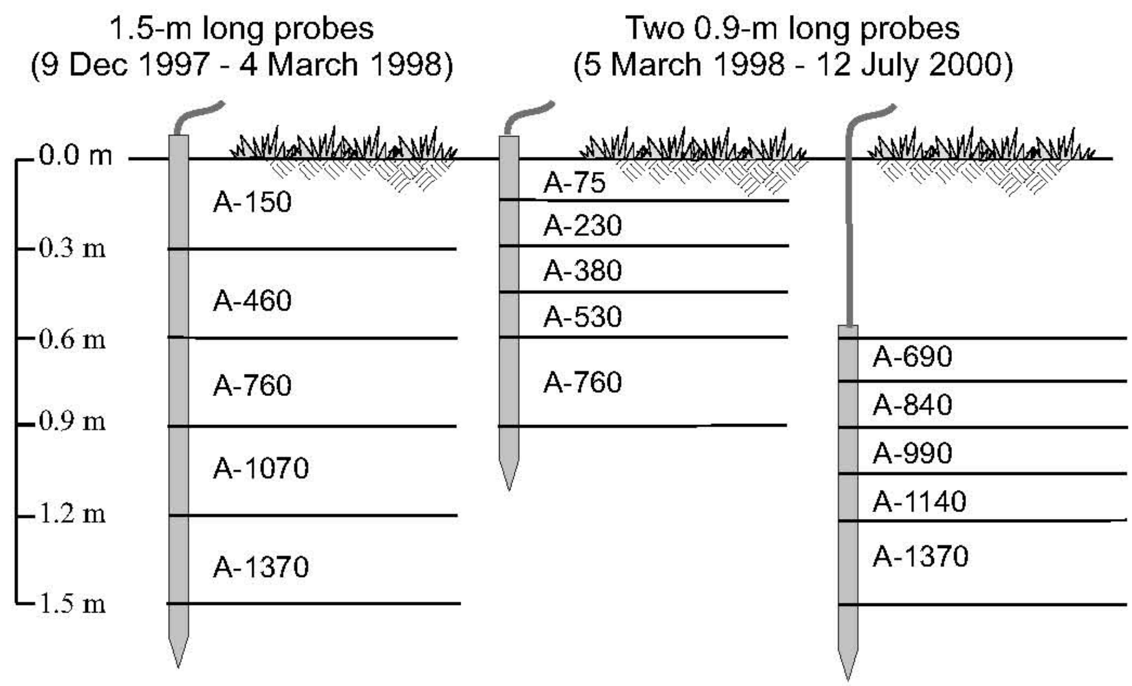

Figure 4.11: Typical TDR Probe Configuration for Yucaipa Test Plot. [Note: Probe Segment Designation Indicates Monitoring Station and Cover System Depth (mm) at the Midpoint of the Segment.]

Meteorological and water content data were generally collected hourly from system start-up until July 12, 2000. Average daily water content measurements from January 1, 1998 to June 30, 2000 at segments 75, 380, 760, 1140, and 1370 on Probes A and B are shown in Figures 4.12 and 4.13, respectively. The segment number represents the cover system depth in millimeters at the midpoint of the segment. The deepest segment (1370) is located within the intermediate soil cover placed below the monolithic cover system. The intermediate soil cover consists of the same soil as the cover system. However, the intermediate soil cover was placed with less compactive effort than the cover system soils. The bulk density of the intermediate soil cover was not required to be measured and is not known.

The variation in measured water content with depth for Probes A and B during the monitoring period are shown in Figures 4.14 and 4.15, respectively. The measured change in soil water storage along Probes A and B is shown in Figure 4.16. Storage on a given day was calculated by integrating the probe water contents over the depth of the cover system. Water contents were assumed to be constant over a probe segment. Where more than one probe segment was used to monitor an interval of the cover system, i.e., at a depth of 0.6 to 0.9 m below ground surface, the average water content measured by the segments along that interval and weighted for segment length was used in the storage calculation. The results of the field monitoring program are summarized in Table 4.3.

Table 4.3: Summary of Measured Components of Water Balance for Yucaipa Monolithic Cover.

	Year[1]	Precipitation (mm)	Storage (mm)	Change in Storage (mm)
Station A			195[2]	
	1998	658	187	-8
	1999	187	171	-16
	2000	230	195	24
Station B			180[2]	
	1998	658	192	12
	1999	187	170	-22
	2000	230	206	36

[1] 2000 = January - June
[2] Measured storage at beginning of monitoring period

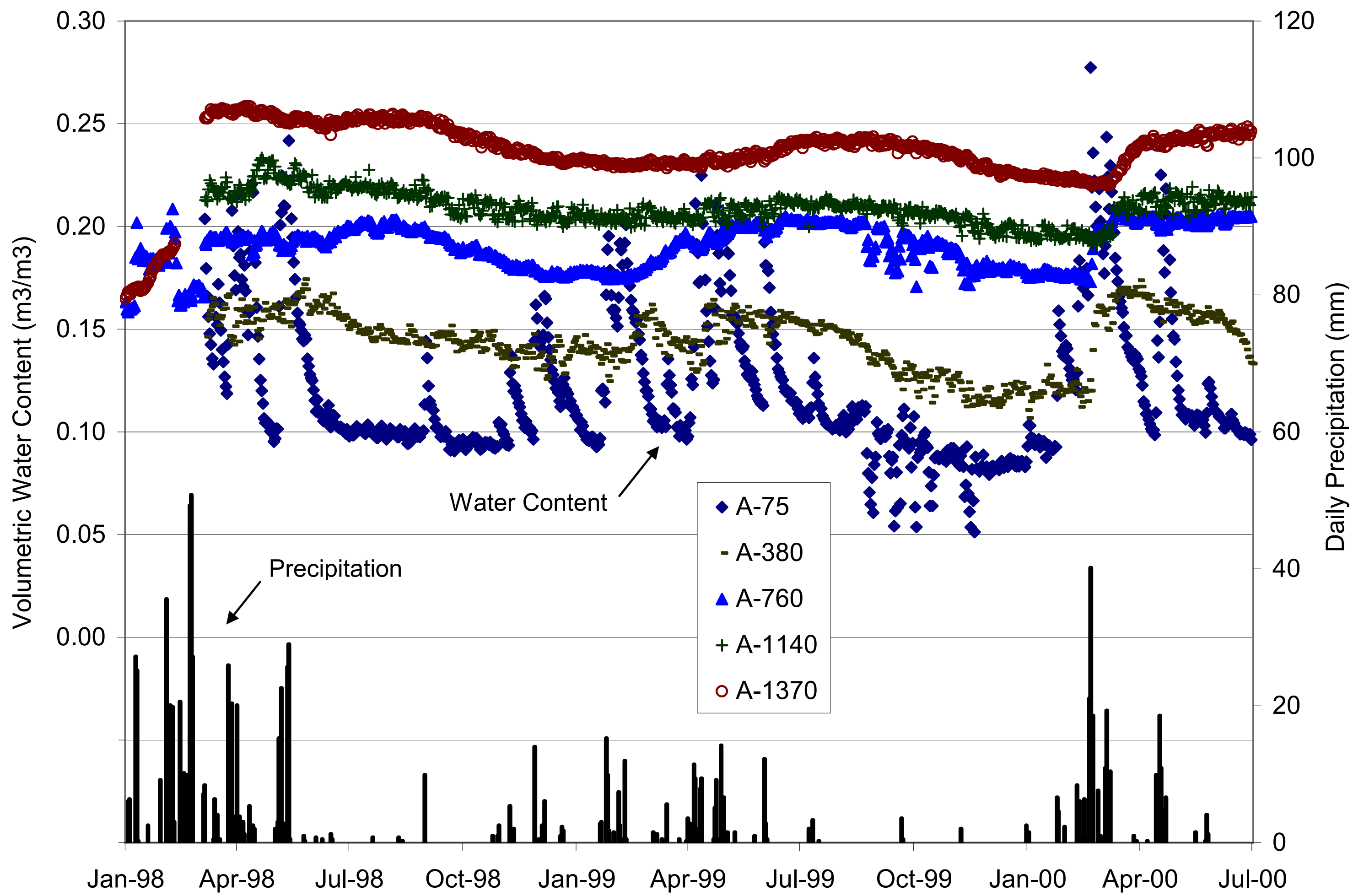

Figure 4.12: Water Content Measurements at Segments 75, 380, 760, 1140, and 1370 on Probe A. [Segment Number Represents Cover System Depth (mm) at the Midpoint of the Segment.]

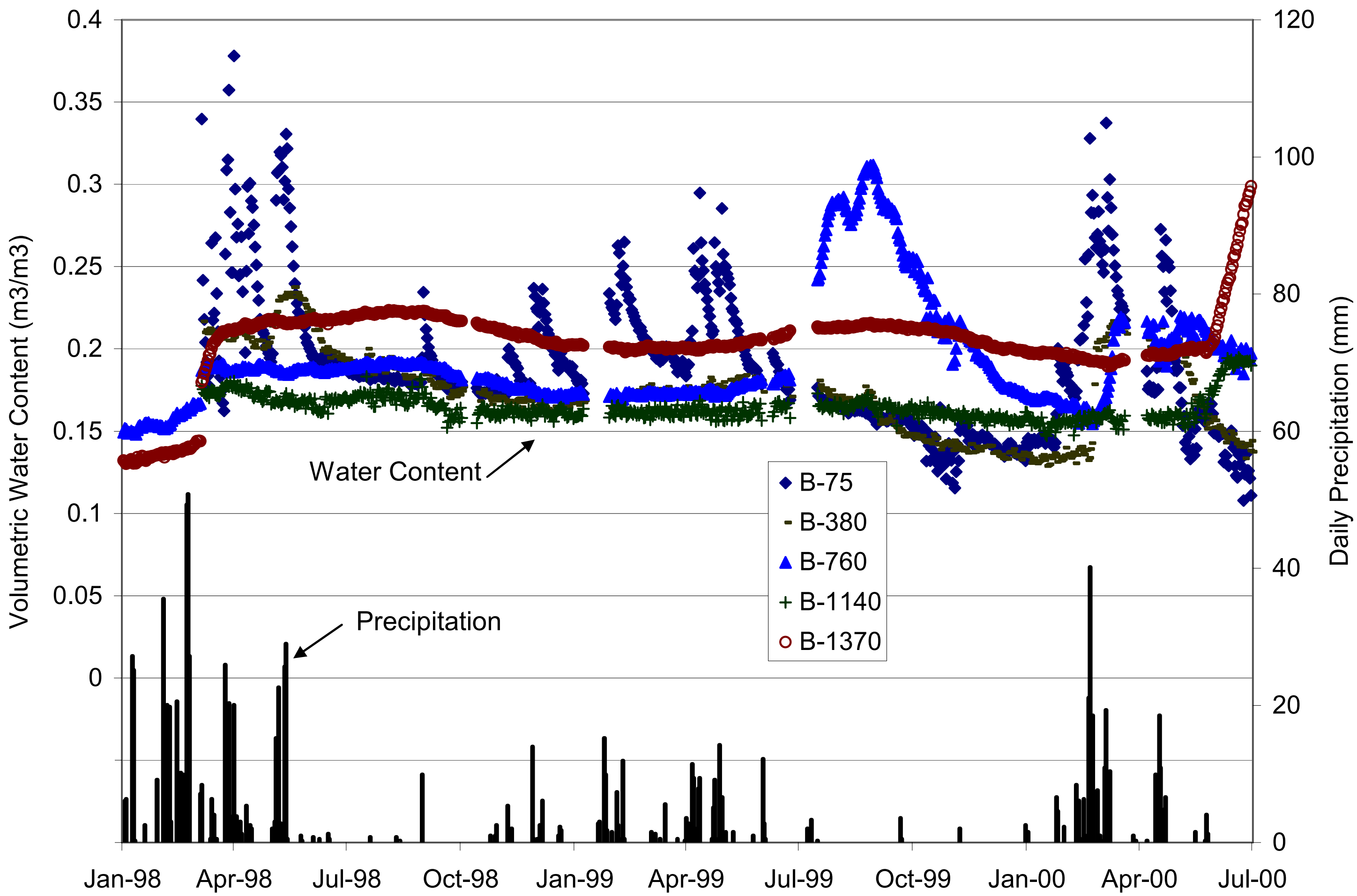

Figure 4.13: Water Content Measurements at Segments 75, 380, 760, 1140, and 1370 on Probe B. [Segment Number Represents Cover System Depth (mm) at the Midpoint of the Segment.]

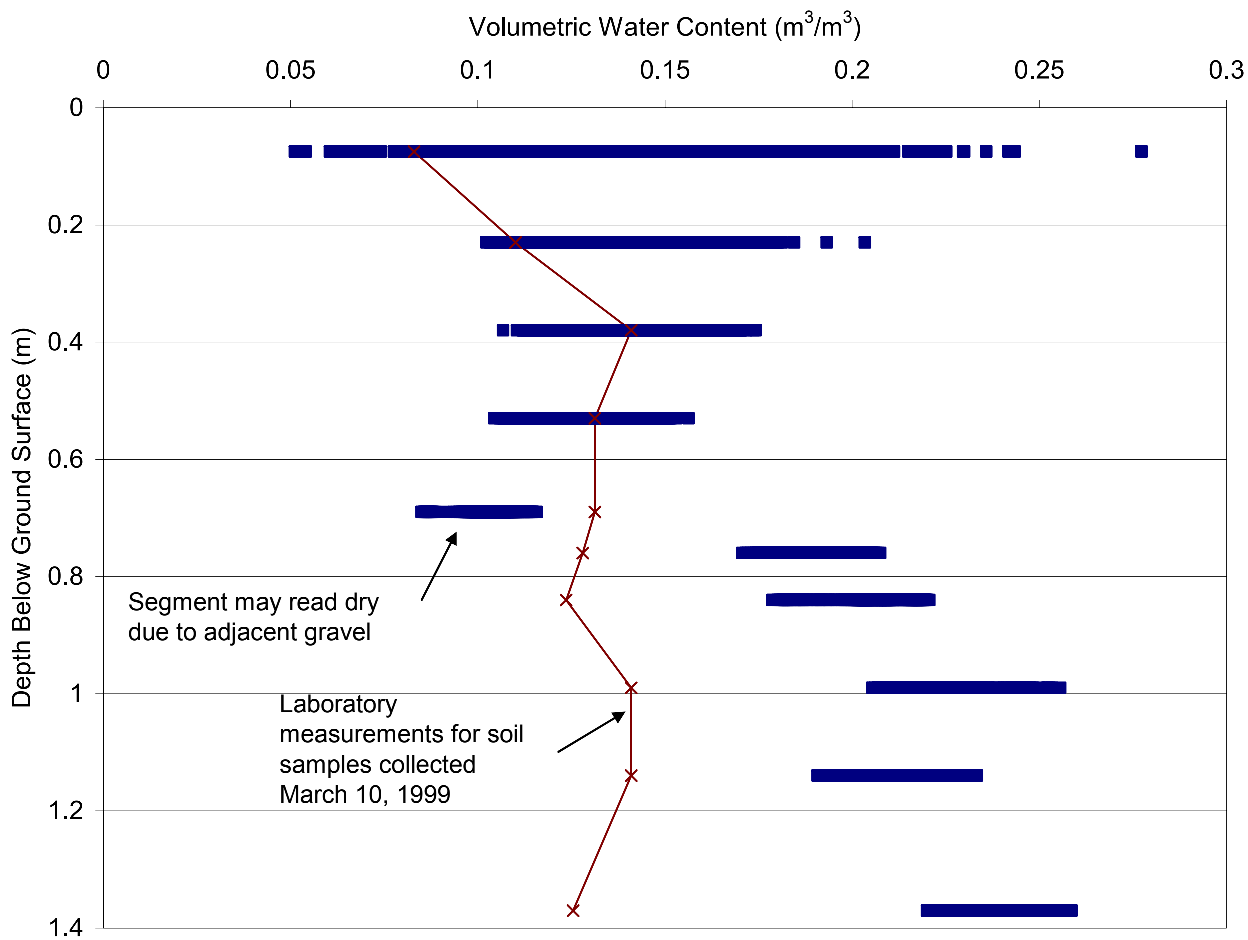

Figure 4.14: Variation in Water Content Measurements with Depth at Probe A Segments. [Segment Number Represents Cover System Depth (mm) at the Midpoint of the Segment.]

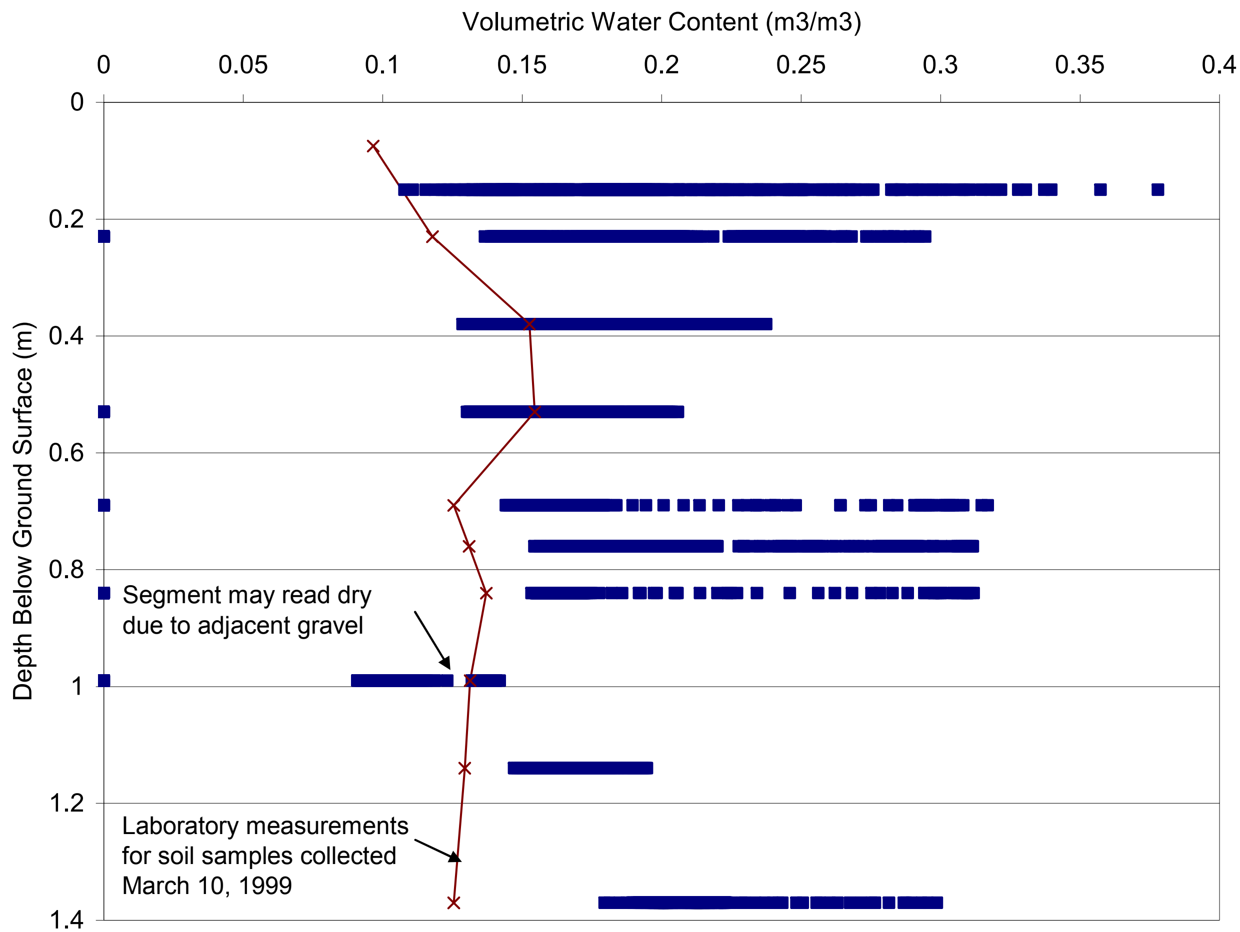

Figure 4.15: Variation in Water Content Measurements with Depth at Probe B Segments. [Segment Number Represents Cover System Depth (mm) at the Midpoint of the Segment.]

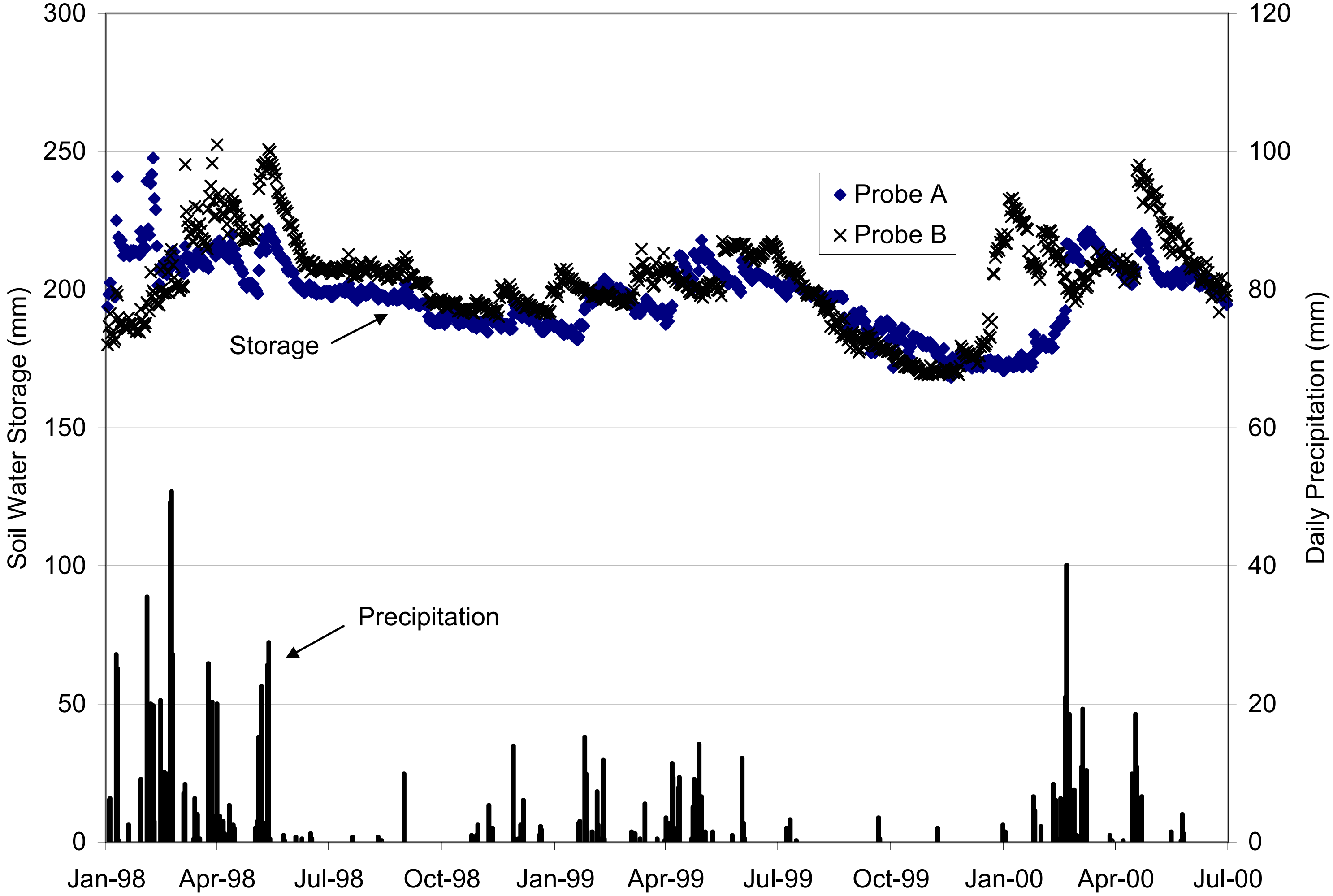

Figure 4.16: Soil Water Storage at Stations A and B Calculated from Measured Water Contents.

The more significant interruptions and issues in water content data collection are summarized below:

- On January 14, 1998, it was discovered that a cemented fence post had been installed within 80 mm of Probe A. For soil water contents below 0.30, the TDR manufacturer indicates that 90% of the field of influence of the probe is located within approximately 30 mm of the probe axis. To ensure that the fence post did not impact probe data, Probe A was relocated about 1 m away from its original position on February 12, 1998. During the installation of the probe at the new location, the probe tip became damaged as it was pushed past an obstruction. As a result, the lower probe segment (A-1370) became inoperable.
- On March 5, 1998, each 1.5-m long probe was replaced with two nested 0.9-m long probes (Figure 4.11) installed about 1 m away from the original probe location. The purpose of this probe reconfiguration was to reduce signal attenuation associated with the longer probe and provide water content measurements that were more accurate.
- On April 13, 1998, the soil surrounding the uppermost probe at Station B was recompacted around the probe. The top two segments on this probe (B-75, B-230) had been exhibiting rapid increases in water content readings in response to precipitation events (Figure 4.13). It was thought that a gap between the probe and the soil had allowed surface water to flow along the probe. After the soil was recompacted around the probe, the apparent preferential flow ceased.
- In May 1998, soil samples were collected adjacent to the probe segments and were tested in the laboratory for volumetric water content. Water contents determined from the TDR probes were found to be too low. The probe calibration

was subsequently adjusted to account for this, and prior TDR water content measurements were corrected.

- In March 1999, soil samples were again collected and tested for volumetric water content. Laboratory water contents ranged from about 0.083 to 0.155 (Figures 4.14, 4.15, and 4.17). With the exceptions of segments A-690 and B-990, which read 0.031 and 0.028 drier, respectively, than the adjacent soil samples, the water contents recorded from the TDR segments were 0.006 to 0.105 higher than the water contents measured for the adjacent soil samples (Figure 4.17). It was speculated that the consistently low water content readings for segments A-690 and B-990 were due to the presence of gravel within the field of influence of the segments.
- While the TDR measurements suggested that the cover system soils were drier near Probe A than around Probe B (Figures 4.12 to 4.16), laboratory measurements of soil water content did not support this inference. The average volumetric water contents measured in the laboratory in March 1999 were approximately the same: 0.125 along Probe A and 0.131 along Probe B.
- During the summer of 1999, the water content reading of probe segment B-760 increased from about 0.18 to 0.30 (Figure 4.13) after rainfall on two days in July. The water content readings of segments B-690 and B-840 on the adjacent nested probe at Station B and the water content readings of the probes at Station A did not increase (Figures 4.12 and 4.13). However, the water contents recorded for segments B-230, B-380, and B-530, all located on the same probe above segment B-760, also increased by up to 0.03 or more. It may be that the area around this probe was being wetted due to preferential flow from upslope or along the probe. The relationship between the July rainfall and the increase in measured water

contents is unclear as data were not collected for the Station B probes from late June 1999 until approximately one week after the July rainfall had occurred.

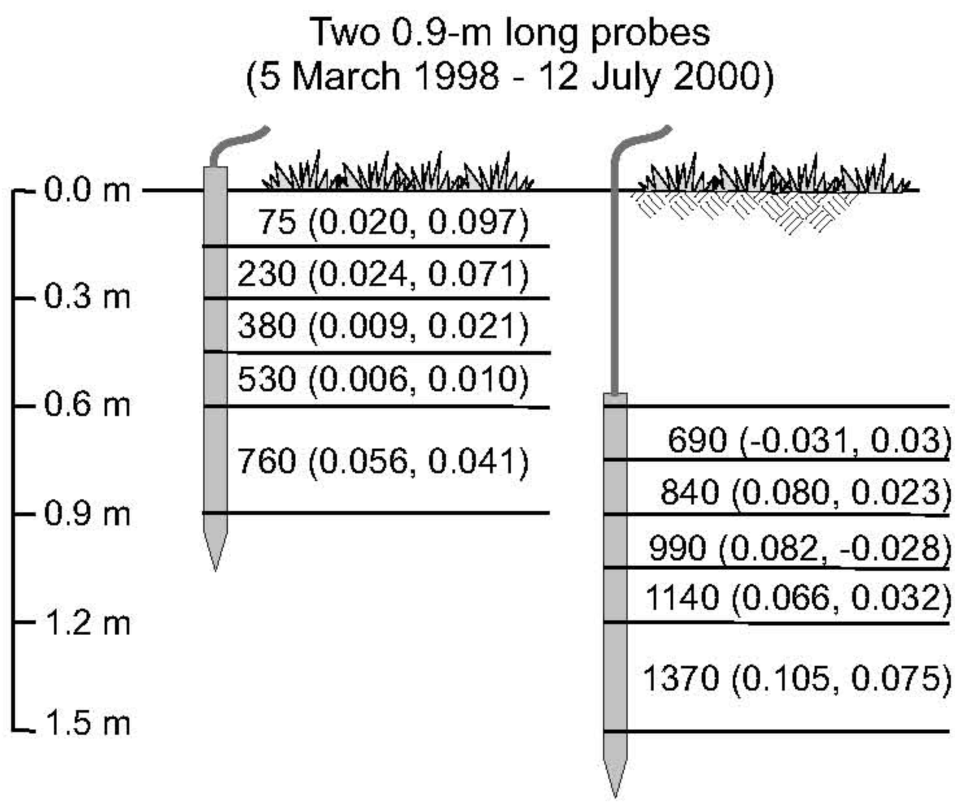

Figure 4.17: Difference between Field and Laboratory Volumetric Water Contents on March 10, 1999. (Numbers Given for Each Probe Segment are Segment Number and Water Content Differences for Probe A and Probe B Segments.)

- In late May through June 2000, the water contents of all segments along the deeper nested probe at Station B rapidly increased by up to 0.13 after three rainfall events in late May (Figure 4.13). The water content readings of the adjacent nested probe at Station B and the water content readings for the nested probes at Station A did not increase (Figures 4.12 and 4.13). On 21 July 2000, soil samples were collected approximately 1 m downslope of the deeper nested probe at Station B. The water contents measured in the laboratory for the samples were approximately the same at those measured on March 10, 1999 for samples collected from similar locations. Because the increase in measured water content at depth occurred relatively fast and did not correspond to increases in water content of shallower probe segments or of soil samples located 1 m away, it appears to be attributable to preferential flow.

- Data interruptions occurred in October 1998, January and June 1999, and March 2000 at Station B after power and data cables had been severed (Figure 4.13).

The significant and varying differences between laboratory and field measured water contents for different probe segments that apparently varied with time make it difficult to assess the absolute water contents of the cover system at the Yucaipa site. These differences can be caused by spatial variability in the cover system soil, e.g., the presence of gravel near some probe segments and not others, preferential flow in the soil and along the probes, and other factors. However, the relative changes in probe readings do suggest water entered the cover system during the winter and moved at least mid-way into the cover system profile. In the summer, water contents decreased.

This seasonal change in water content of the cover system may be more apparent if the effect of soil temperature on the TDR readings, i.e., the decrease in recorded water content with increase in soil temperature, were considered. For example, for soil at a given water content, increasing the temperature of the soil from 10 °C to 25 °C results in a decrease in the dielectric constant of the soil from approximately 84 to 78. Based on Topp's equation (Topp et al., 1980), an empirical relationship between soil dielectric constant and water content, this decrease in dielectric constant results in a decrease of 0.04 in the apparent volumetric water content of the soil. Therefore, if TDR readings are not corrected for temperature, the readings for a soil at a constant water content would be lower in the summer than in the winter. A positive offset would need to be added to the measured water content in the summer, with the magnitude of the offset depending on the change in temperature of the soil.

Except for the uppermost segment (A-75 and B-75) of the TDR probes at each station, probes in the Yucaipa cover system generally measured higher water contents in the early summer than in the winter. This is expected because the site receives most of its precipitation in the winter. If measured water contents were corrected for temperature, the measured water contents of the cover system in the early summer would appear even higher, especially at shallow depths where temperature fluctuations are highest.

Winter precipitation increased the water content in the shallow soils of the cover system (Figures 4.12 and 4.13). At Probe A, infiltrating water appears to have been redistributed through the soil profile, as evidenced by the out-of-phase peaks in measured water content between the different monitoring intervals. Water content increases were first recorded at the shallowest probe segment, A-75, and then were sequentially recorded at deeper probe segments including the deepest segment, A-1370, located in the intermediate cover below the monolithic cover system. The assessment of water movement at Probe A, however, has a high degree of uncertainty. The changes in water contents over time for the lowest segments, i.e., A-1140 and A-1370, were small (less than 0.04) and within the TDR manufacturer's stated accuracy of the measurement (± 1.3% gravimetrically, which is approximately ± 0.025, by volume, for the Yucaipa cover system). In addition, rocks located near the probe segments may have affected the probe readings. As an additional complication, upward flow of water vapor from the underlying municipal solid waste landfill may have occurred. Therefore, it is unclear if infiltrating water moved as deep as 1.14 m into the cover system. Vertical flow is less evident for Probe B than for Probe A because there was generally less variation in water content over time for the segments on Probe B.

Soil water storage at Stations A and B generally showed the same trends with time (Figure 4.16) in 1998 and 1999. In 2000, soil water storage at Station A was generally higher than storage at Station B and exhibited rapid changes, possibly due to preferential flow along the probe.

While it may appear that the TDR system for the Yucaipa test plot had an excessive number of problems, instrumentation often requires a significant amount of care while in use. There were also instrumentation issues at the Albuquerque and Sierra Blanca sites. However, instrumentation issues for these sites were not required to be documented in an external report as was done for the Yucaipa site. Therefore, detailed information on problems with instrumentation at the Albuquerque and Sierra Blanca sites and information on how the problems were resolved is not presented herein.

The Yucaipa test plot differs significantly from the Albuquerque and Sierra Blanca test plots in the robustness of its instrumentation. Only one type of measurement was made to assess cover system performance, and data were only collected at two stations. However, the Yucaipa study was developed to support the numerical modeling of a monolithic cover system for a small municipal solid waste landfill, not to support the design of an evapotranspirative cover system for a landfill containing low-level radioactive waste, as was purpose of the Albuquerque and Sierra Blanca studies.

4.4 DESIGN, CONSTRUCTION, AND MONITORING OF ALBUQUERQUE SITE

4.4.1 Design of Albuquerque Site

Six different large-scale (12.2 m × 91.4 m) cover systems (Figure 4.18), including three evapotranspirative cover systems, were installed during the summers of 1995 and 1996 in Technical Area 3 at Sandia National Laboratories near Albuquerque, New Mexico (Dwyer, 1997, 1998, 2003). The test plots were constructed and monitored to support the design of a cover system for an on-site mixed waste landfill containing low-level radioactive waste and minor amounts of mixed waste.

Figure 4.18: Six Cover System Test Plots in Albuquerque, New Mexico (from Dwyer, 2003).

Based on a Corrective Measures study (U.S. Department of Energy, 2003), it appears that the cover system for this landfill was intended to be equivalent to a RCRA Subtitle C (hazardous waste) cover system. A drainage standard for the cover system was not identified. The recommended corrective measure is an evapotranspirative cover system; however, this remedy has not yet been approved by the New Mexico Environmental Department.

Only the monolithic cover system constructed at the Albuquerque site is discussed in this section. The approximately 1.05-m thick monolithic cover system consisted of a single soil type, loamy sand, installed with a 0.90-m thick compacted lower component and a 0.15-m thick loosely placed upper component (Figure 4.5). The surface of the cover system was mulched with a 20 to 40-mm thick gravel veneer. The test plot was divided into two 45.7-m long subplots, one facing east and one facing west, both with 5% slope inclinations.

4.4.2 Construction of Albuquerque Site

The monolithic cover system was constructed from May through August 1996. Unless noted, the information presented below is taken from Dwyer (1997, 2003), Dwyer et al. (1998, 2000), and Sandia National Laboratories (1999).

The project specifications required that the cover system soil conform to the following:

- maximum particle size ≤ 50 mm;
- percent particles finer than 0.074 mm (percent fines): ≥ 20% by weight;
- percent particles coarser than 4.75 mm (percent gravel): ≤ 10% by weight;
- plasticity index ≤ 35%; and
- as compacted, lower soil component: minimum bulk (dry) density = 95-110% of the maximum dry density obtained from the standard Proctor compaction test (ASTM D 698) and water content dry of the line of optimums; the target dry density was approximately 1.81 to 2.10 Mg/m^3 (17.8 to 20.6 kN/m^3).

Unlike the monolithic cover system at the Yucaipa site, a saturated hydraulic conductivity for the cover system at the Albuquerque site was not specified.

The lower compacted component of the monolithic cover system was placed and compacted in six 0.15-m thick lifts with an 18,200-kg smooth-drum vibratory compactor.

Interlift bonding was provided by scarifying the surface of each compacted lift to a depth of 20 to 50 mm prior to placing the next lift. In other words, it was placed like a compacted clay liner, except drier. The average bulk density of the in-place soil was 1.87 Mg/m^3 (18.3 kN/m^3), which is considered root restricting when compared to the soil bulk densities in Table 2.1. The actual impact of the relatively high level of compaction of the lower soil layer on root growth is not known because plant root depth was not evaluated. In addition, data on the density of the native soil at the site were not available. Therefore, it is not known if the native soils are naturally dense.

The upper 0.15 m of soil was placed loose to provide a good substrate for vegetation. The average bulk density of this soil layer was 1.54 Mg/m^3 (15.1 kN/m^3), which is considered ideal based on the soil bulk densities in Table 2.1.

To verify that the soil used to construct the cover system was relatively consistent in its properties and that the above specifications were achieved, standard laboratory and field tests were required to be performed during construction. From the test results, the as-built cover system at the Albuquerque site consists of a dense loamy sand classified as an SM material under the Unified Soil Classification System. Though not required by the specifications, the hydraulic properties of the monolithic cover system were also measured.

During construction, the saturated hydraulic conductivity and water retention properties of the uncompacted and compacted soil were measured in the laboratory. As described by Dwyer (2003), the laboratory tests were conducted on soil samples compacted to the specified minimum densities for the cover system. Dwyer (2003) did not indicate if moisture was controlled. Hydraulic conductivity tests were conducted in rigid wall permeameters (ASTM D 5856). Water retention properties were determined from hanging water column and pressure plate tests, and the test data were fitted to the van Genuchten water retention function. At the end of the five-year monitoring period, the soil hydraulic properties, both saturated hydraulic conductivities and water retention curves, were evaluated in the field by tension infiltrometer tests. The van Genuchten parameters and SWCCs developed from the laboratory and field data are presented in Dwyer (2003). The reported hydraulic conductivities and van Genuchten parameters for the laboratory and field tests are summarized in Table 4.4.

Table 4.4: Summary of Measured Saturated Hydraulic Conductivities and van Genuchten Parameters Determined for the Monolithic Cover System at the Albuquerque Site by Dwyer (2003).

Soil	Test Method	Hydraulic Conductivity (m/s)	Saturated Water Content (-)	Residual Water Content (-)	van Genuchten Parameters	
					α (mm^{-1})	n (-)
Uncompacted	Laboratory	1.0×10^{-5}	0.433	0.06	0.0106	1.36
	Field	1.2×10^{-5}	0.390	0.045	0.0105	1.45
Compacted	Laboratory	4.3×10^{-7}	0.359	0.06	0.0033	1.36
	Field	4.7×10^{-7}	0.323	0.065	0.0321	1.44

For this dissertation, the van Genuchten parameters reported by Dwyer for the tension infiltrometer tests were modified to use a residual moisture content, θ_r, of zero. As previously discussed, it is reasonable to assume that the residual moisture content is zero because, from thermodynamic considerations and experimental data, zero water content should be reached at a matric potential slightly less than -100,000 m (-10^6 kPa) (Fredlund and Xing, 1994). The modified van Genuchten water retention functions were calculated using the Solver tool in EXCEL™ to find the smallest root mean squared error between the van Genuchten SWCCs determined using the parameters presented in Dwyer (2003) and the modified SWCCs with a residual water content of zero. This fitting was performed over the range of matric potentials considered in the laboratory tests (-1500 to 0 m (150 to 0 kPa)). The modified van Genuchten SWCCs were then used to determine the Campbell (1974) SWCC using the Solver tool. The calculated parameters for the modified van Genuchten SWCCs and the Campbell SWCCs are presented in Table 4.5 and the SWCCs are shown in Figure 4.19.

Table 4.5: Summary of van Genuchten and Campbell Parameters Calculated Using Dwyer (2003) Data.

Soil	Saturated Water Content (-)	Residual Water Content (-)	van Genuchten Parameters		Campbell Parameters	
			α (mm^{-1})	n (-)	h_b (mm)	λ (-)
Uncompacted	0.39	0.0	0.00723	1.37	-70.7	0.302
Compacted	0.32	0.0	0.00269	1.26	-226	0.236

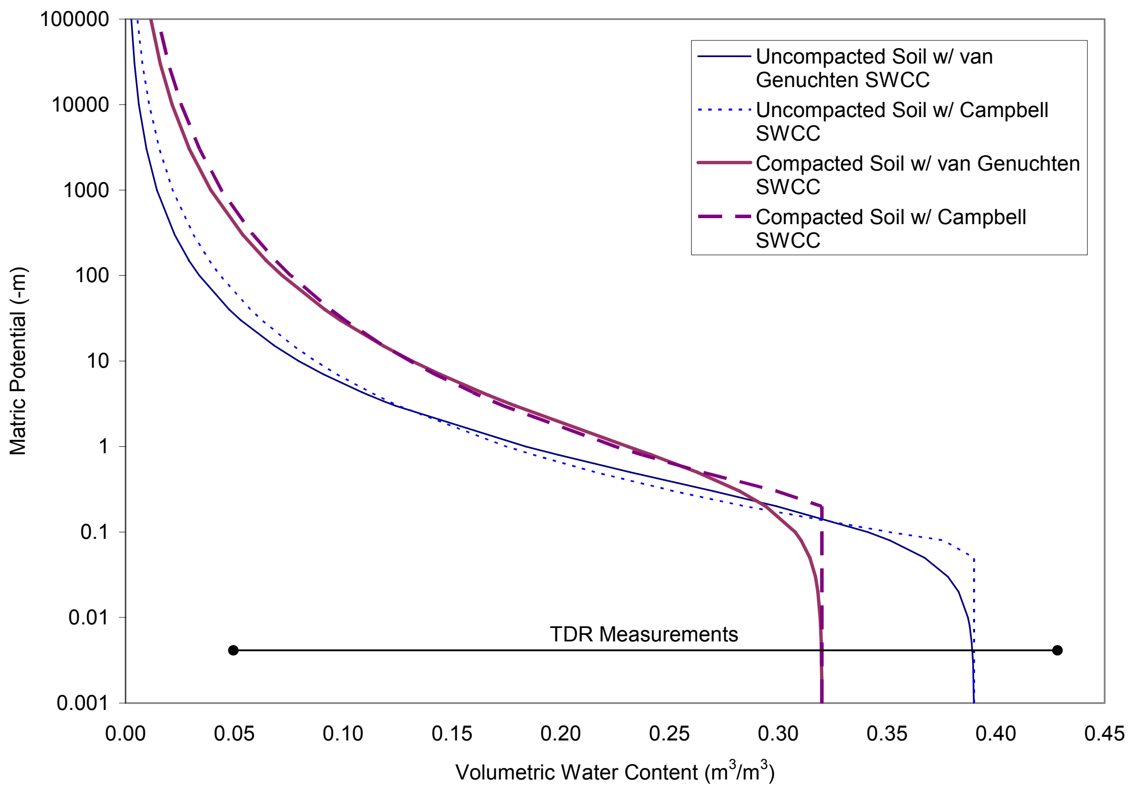

Figure 4.19: SWCC (Desorption) for Cover System Soil at Albuquerque Site Based on Tension Infiltrometer Tests Fitted to the van Genuchten Function.

van Genuchten-Mualem and Campbell-Burdine hydraulic conductivity functions were also developed for the cover system soils (Figure 4.20). From comparison of the plotted functions for the uncompacted and compacted soils, the effect of soil compaction is seen. Compaction reduced the larger pore spaces in the compacted soil and decreased its saturated hydraulic conductivity. Compaction, however, did not affect the size of the smaller pores. As a result, the difference in hydraulic conductivity between the uncompacted and compacted soil at a given matric potential is greatest at lower matric potentials than at higher matric potentials.

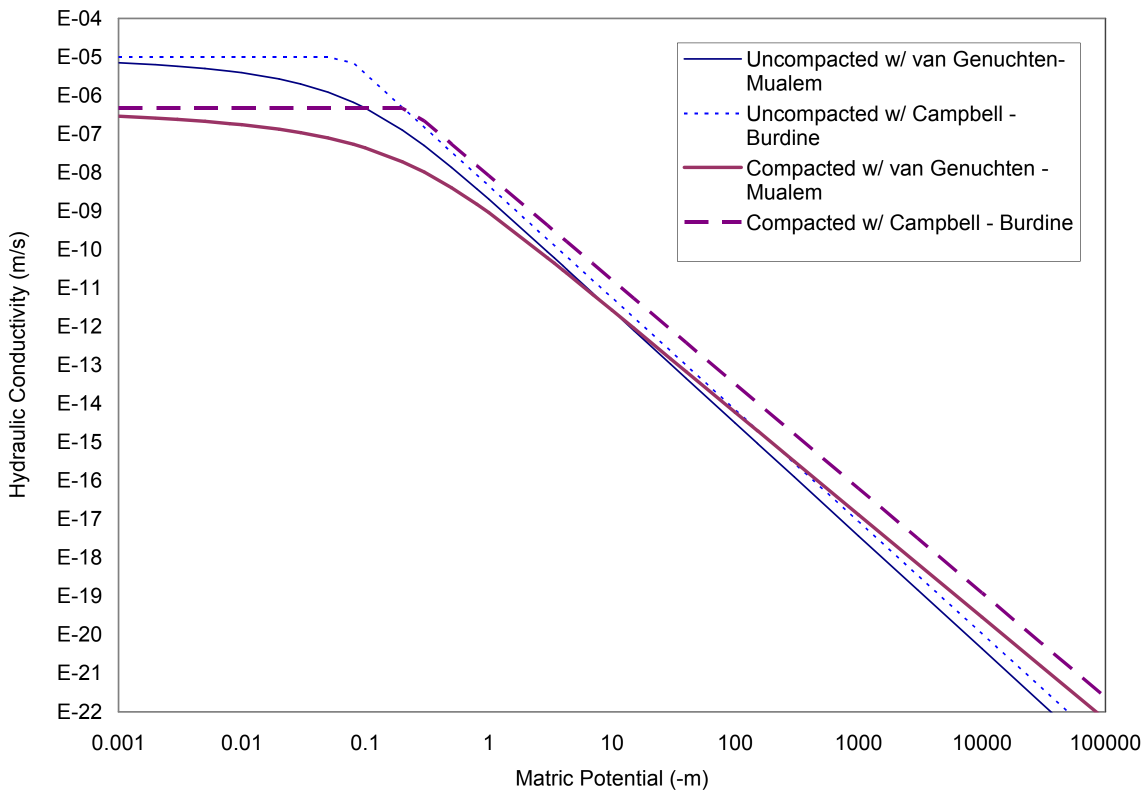

Figure 4.20: van Genuchten-Mualem and Campbell-Burdine Hydraulic Conductivity Functions (Desorption) for Cover System Soil at Albuquerque Site.

In the fall of 1996, the cover system was drill seeded with a native rangeland seed mix that is used by the New Mexico Highway Department for roadsides and is considered to provide adequate coverage during warm and cool growing seasons. Warm season grasses consisted of blue grama (*Bouteloua gracilis*), sideoats grama (*Bouteloua* *curtipendula*), galleta grass *(Hilaria jamesii*), and sand dropseed (*Sporobolus cryptandrus*). The cool season grass consisted of Indian ricegrass (*Oryzopsis hymenoides*). In addition to the grasses, the cover was seeded with the shrub four-wing saltbush (*Atriplex canescens*). After the cover was seeded, a thin veneer of gravel (20 to 40-mm thick) was placed on the cover to promote the establishment of vegetation and minimize erosion. The cover system was subsequently irrigated to promote plant growth.

Based on the USDA Plants database (USDA, 2004), the grasses require a minimum soil depth of 0.3 to 0.45 m for good growth and the shrub requires a minimum soil depth of 0.5 m. With only 0.15 m of uncompacted soil available for roots, it would seem difficult for the plants to become established. During the monitoring period, cover system vegetation consisted primarily of invasive weeds, such as fireweed (*Epilobium angustifolium*), a perennial, and Russian thistle (*Salsola kali*), an annual (Dwyer, 2000). The seeded grasses were only a small component of the cover system vegetation and then only towards the end of the monitoring period.

4.4.3 Monitoring of Albuquerque Site

Meteorological, water balance, and vegetation data were collected at the Albuquerque site from May 1, 1997 to September 24, 2002. The sensors used and the manufacturer's stated accuracy of each measurement are summarized in Table 4.6. The east subplot was monitored under ambient conditions, and the west subplot was stressed in January and February 2002 by applying water (110 mm) with a calibrated sprinkler system. The purpose of this stress was to be representative of snowmelt occurring in the winter when potential evapotranspiration is relatively low.

Table 4.6: Sensors Used at Albuquerque Site.

Parameter	Instrument	Accuracy (Manufacturer Stated)
Precipitation	Met One 385 tipping bucket rain and snow gauge (0.25 mm tip)	± 0.5% at rates up to 12 mm/hr ± 1% at rates of 25-75 mm/hr
Air Temperature and Relative Humidity	Vaisala HMP35C thermistor and capacitive relative humidity sensor	± 0.2-0.3 °C ± 2-3% relative humidity
Solar Radiation	Li-Cor LI200X pyranometer	± 5% max ± 3% typical
Wind Speed and Direction	RM Young 05305 anemometer and vane	± 0.2 m/s ± 3°
Soil Water Content	Campbell Scientific CS610	from calibration ± 1.3% (avg.)
Soil Temperature	Type-E Themocouples	Not specified
Drainage	Tipping Bucket	Not specified
Runoff	Omega FP-540 Flow Meter	± 5%

An on-site weather station collected hourly precipitation (with a heated tipping bucket), wind speed and direction, relative humidity, solar radiation, and air temperature data.

Surface-water runoff was collected in concrete channels located at the toe of the east and west slopes. Runoff from each section was conveyed in pipes to the water collection manhole where it was measured with a flow meter.

Drainage through each subplot of the cover system was collected in a pan lysimeter and conveyed though pipes to a concrete water collection manhole, where it was measured with a tipping bucket. The lysimeters were lined with a 1-mm thick linear low-density polyethylene geomembrane overlain by a geonet drainage layer and then a geotextile filter. The cover system was constructed directly on top of the geotextile, thus the geotextile and underlying geonet served as a capillary break beneath the cover system.

Soil temperature and water content data were also collected. Thermocouples were installed to measure soil temperature to 0.6-m depths, and data were collected every hour.

Water content measurements were made using calibrated 3-prong TDR probes (0.3-m long). Probes were installed at ten monitoring stations that were equally spaced along the cover system in the west-east direction. Thus, five stations were located on the east slope of the cover system and five stations were located on the west slope. At each station, three TDR probes monitored soil water content. The probes were installed horizontally in the cover system during construction and were spaced between soil lifts at depths of 0.15, 0.45, and 0.90 m. Therefore, the total number of TDR probes for the monolithic cover system is 30. TDR probe readings (Figures 4.21 to 4.24) were recorded every two hours. Probe readings were not corrected for soil temperature.

The cumulative precipitation, cumulative runoff, cumulative drainage, soil water storage (calculated by integrating the average TDR readings at the three monitored depths over the total monitoring depth), and calculated evapotranspiration (calculated as the residual of the water balance components, Equation 3.1) for the east and west subplots of the monolithic cover system are shown in Figures 4.25 and 4.26. The water balances for the east and west subplots are summarized in Table 4.7.

Table 4.7: Summary of Measured Water Balance for Albuquerque Monolithic Cover System.

Subplot	Water Year[1]	Precip. (mm)	Irrigation (mm)	Runoff (mm)	Storage (mm)	Change in Storage (mm)	Drainage (mm)	Evapotrans. (mm)
East					184[2]			
	1998	299	0	0.8	110	-75	0.0	373
	1999	280	0	0.6	102	-7	0.0	286
	2000	189	0	0.2	121	19	0.0	170
	2001	341	0	0.8	113	-8	0.0	349
	2002[3]	181	0	0.4	127	14	0.0	166
West					166[2]			
	1998	299	0	22	96	-71	0.4	347
	1999	280	0	0.8	96	-0.1	0.0	279
	2000	189	0	0.2	134	38	0.0	150
	2001	341	0	0.6	88	-46	0.0	387
	2002[3]	181	110	0.6	116	28	0.0	262

[1] Water Year = 12-month period from October to September
[2] Measured storage at beginning of monitoring period
[3] Water Year 2002 ends on September 24, 2002

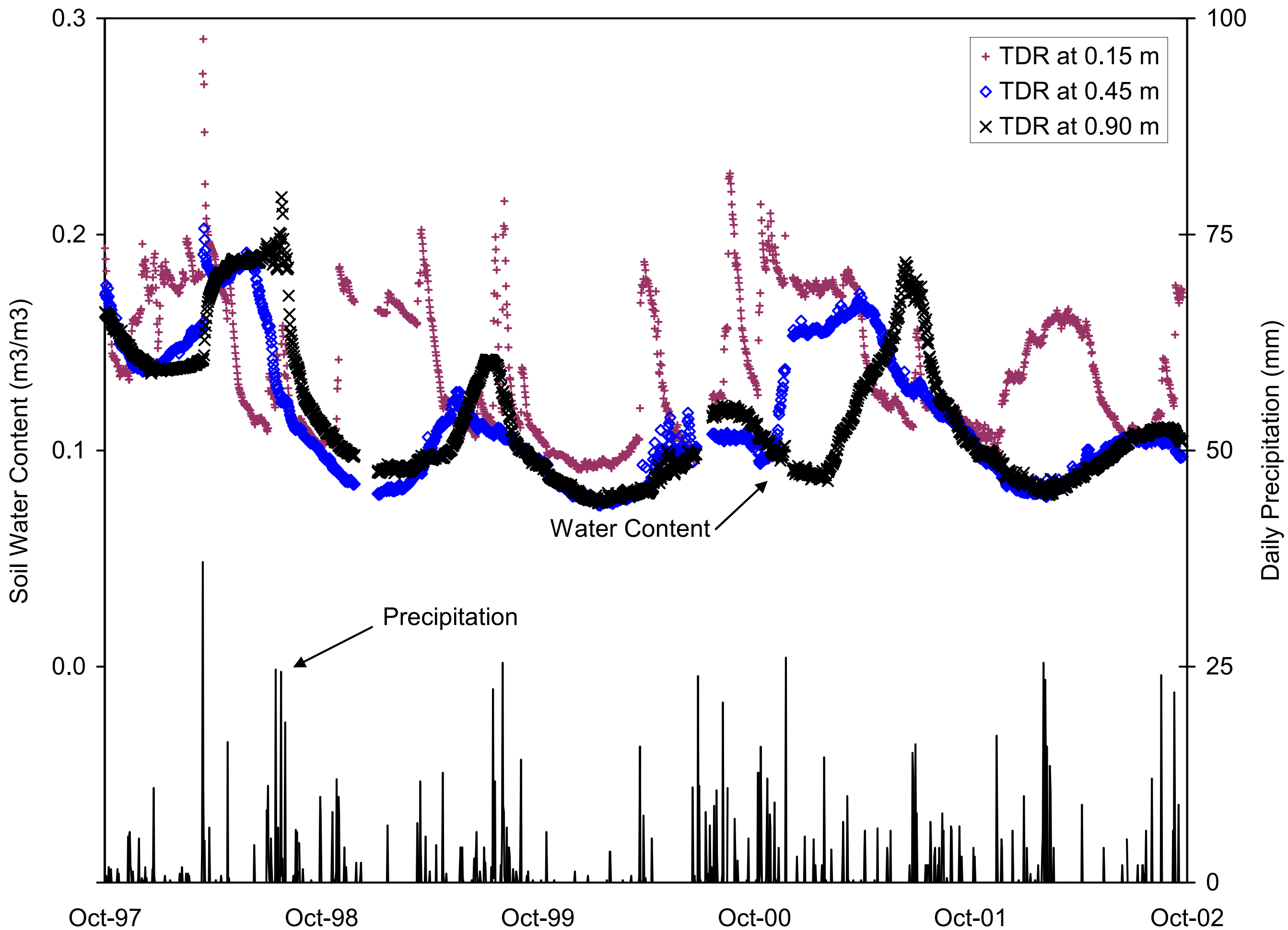

Figure 4.21: Average Water Content Measurements at Depths of 0.15, 0.45, and 0.90 m with TDR Probes on the East Subplot of the Monolithic Cover System at the Albuquerque Site.

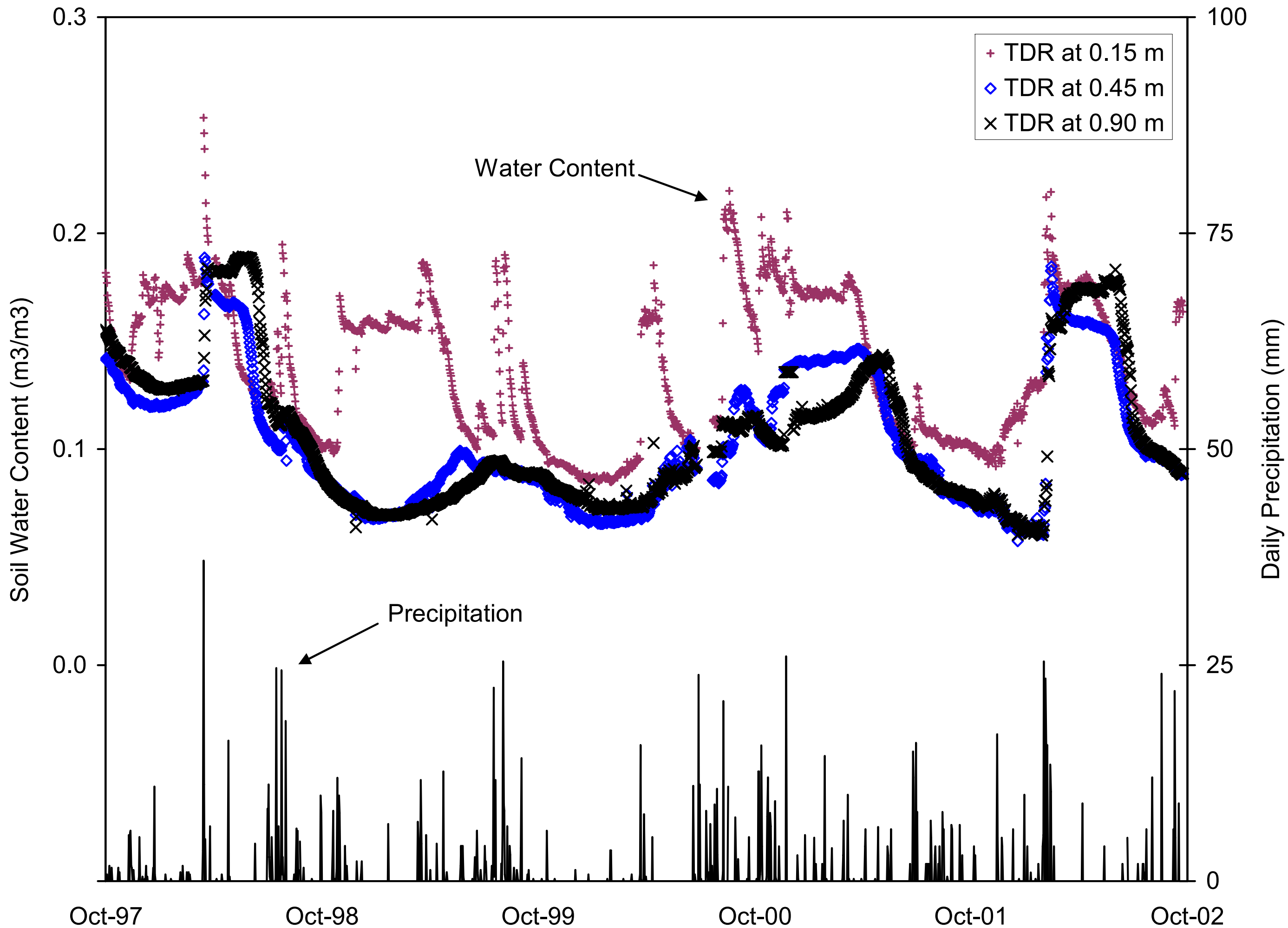

Figure 4.22: Average Water Content Measurements at Depths of 0.15, 0.45, and 0.90 m with TDR Probes on the West Subplot of the Monolithic Cover System at the Albuquerque Site.

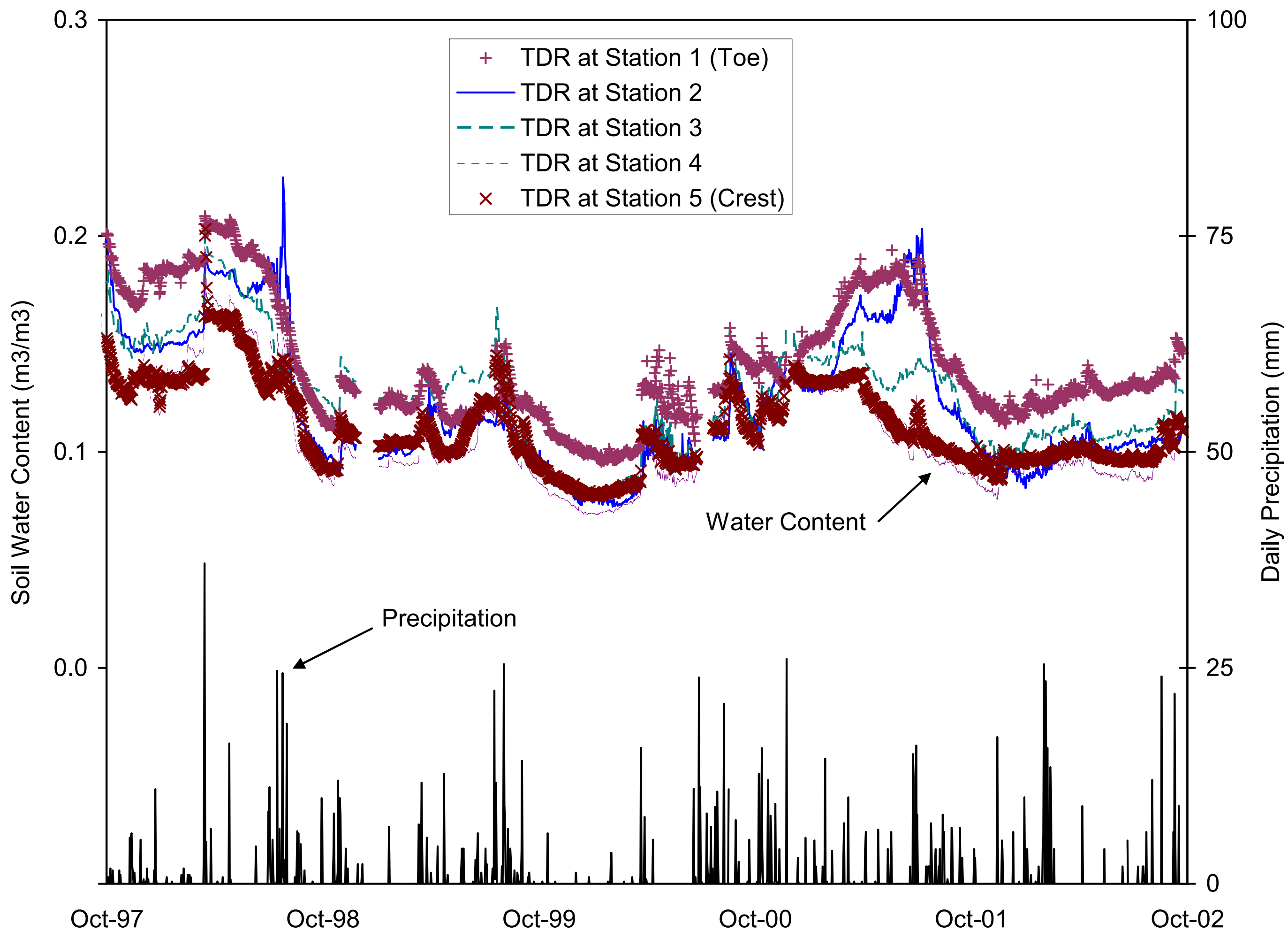

Figure 4.23: Variation in Average Water Content Along the Slope of the East Subplot of the Monolithic Cover System at the Albuquerque Site.

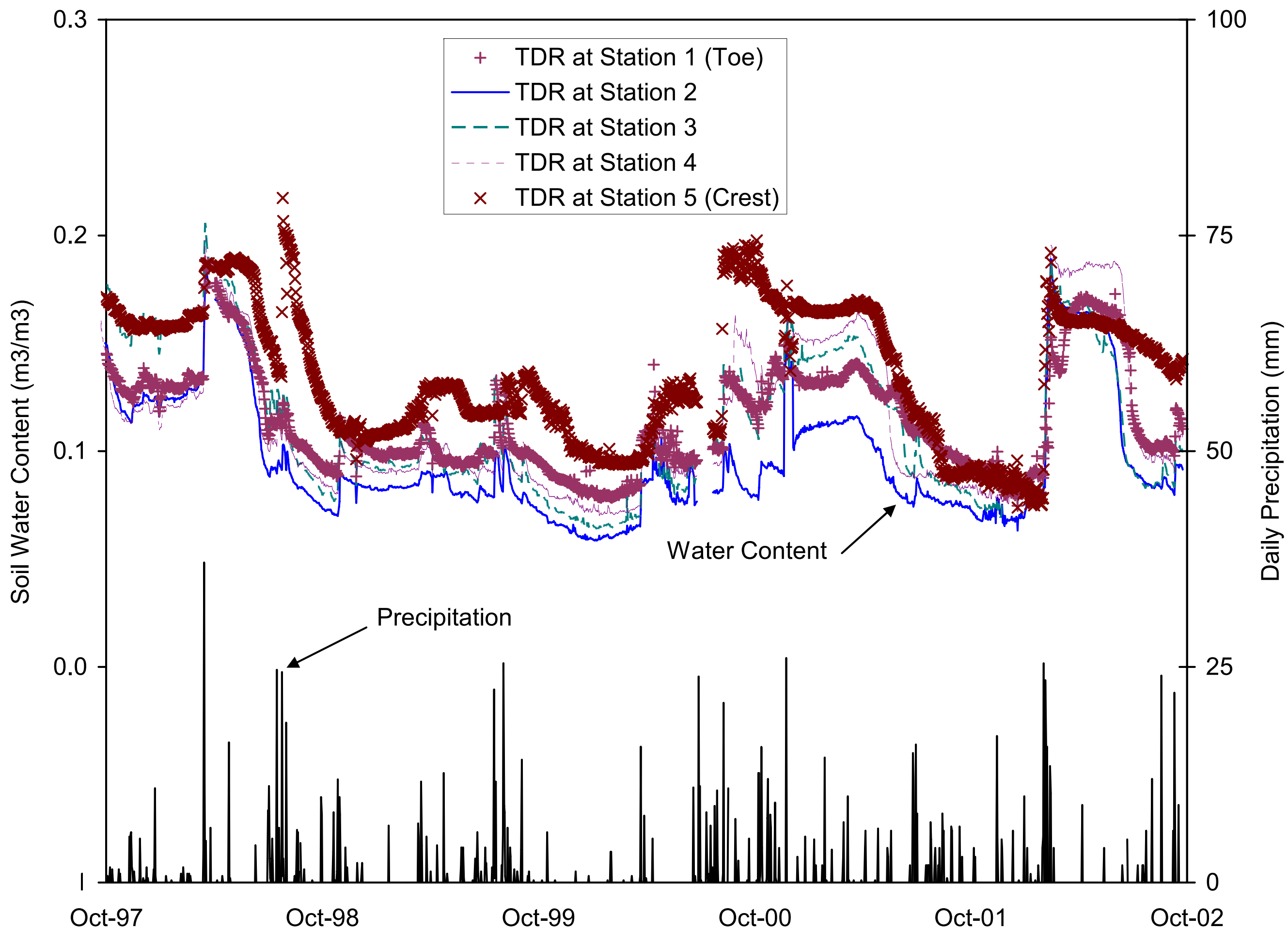

Figure 4.24: Variation in Average Water Content Along the Slope of the West Subplot of the Monolithic Cover System at the Albuquerque Site.

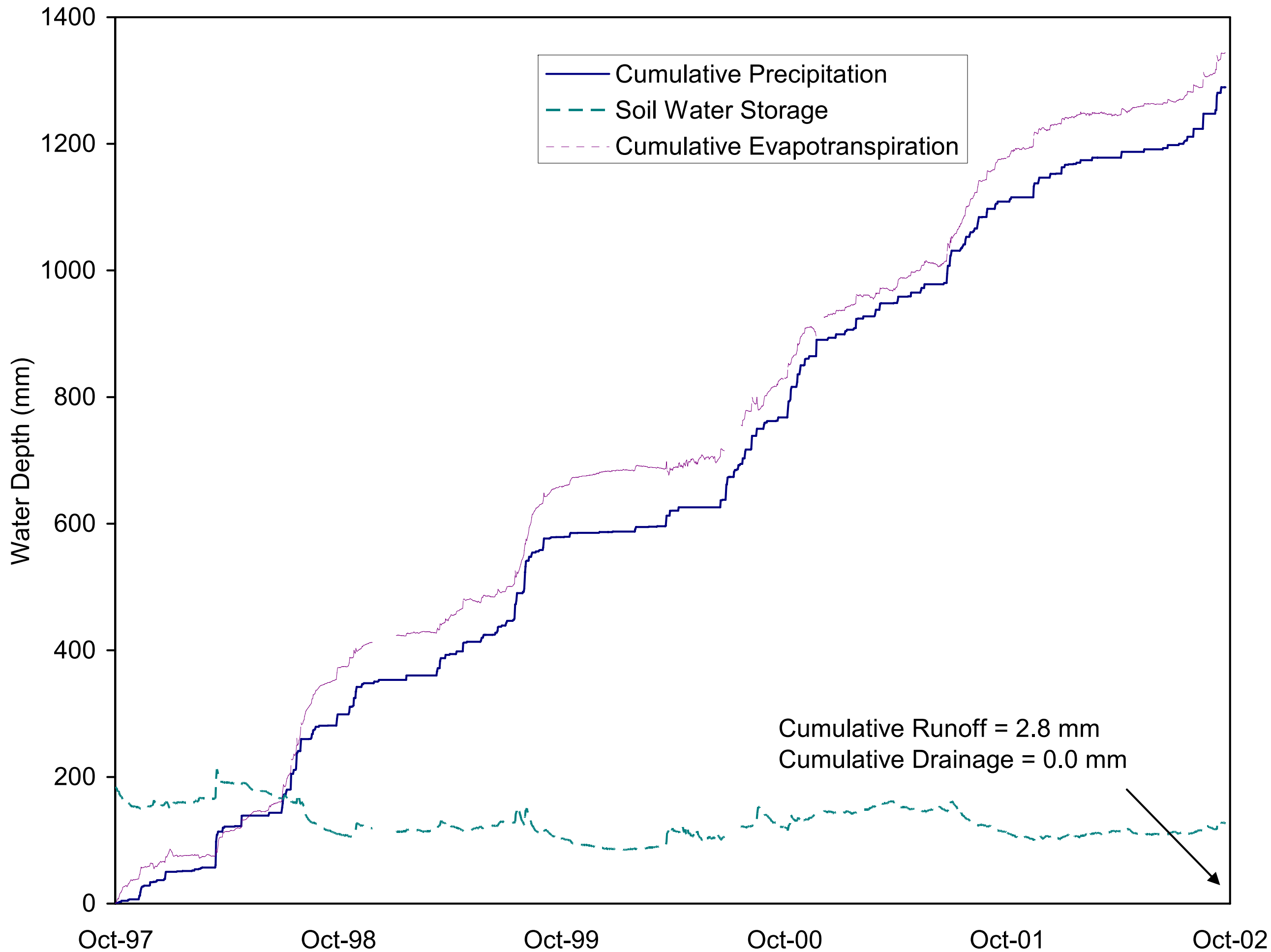

Figure 4.25: Water Balance Components for the East Subplot of the Monolithic Cover System Determined from the Field Monitoring Program at the Albuquerque Site.

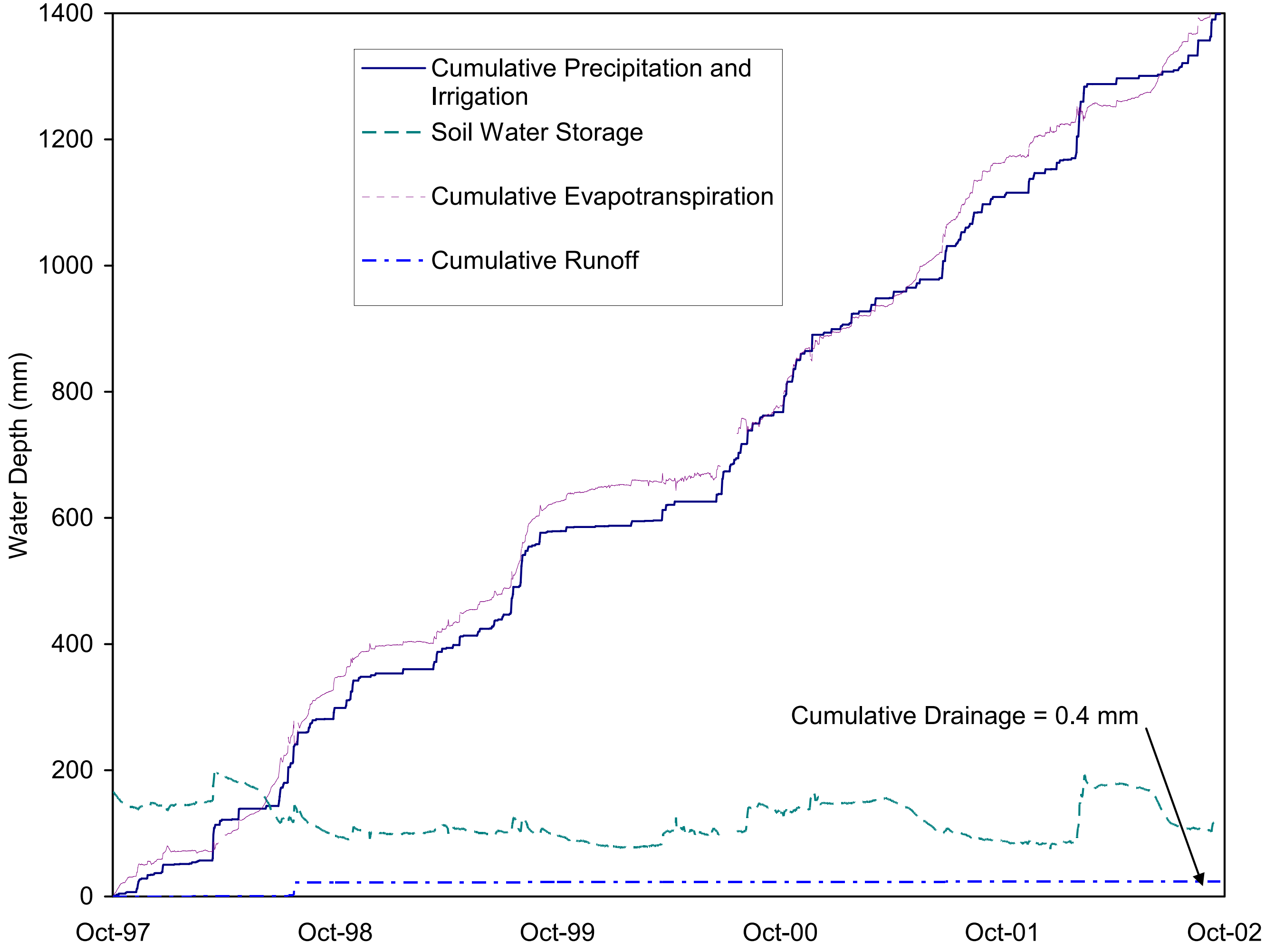

Figure 4.26: Water Balance Components for the West Subplot of the Monolithic Cover System Determined from the Field Monitoring Program at the Albuquerque Site.

Precipitation recorded at the Albuquerque site during the 60-month monitoring period is compared to 30-year (1971-2000) average precipitation for the Albuquerque, New Mexico weather station in Figure 4.3. From 1971 to 2000, average annual precipitation at the Albuquerque weather station ranged from 137 to 333 mm and averaged 240 mm, with a standard deviation of 55 mm. In comparison to precipitation at the Yucaipa site, precipitation at the Albuquerque site shows less relative variance. One standard deviation of the 30-year precipitation record is approximately 46% of the mean at the Yucaipa site and only 23% of the mean at the Albuquerque site.

The Albuquerque site was monitored during several relatively wet years. In water year 1998 (defined for the Albuquerque site as the 12-month time period from October 1, 1997 to September 30, 1998), which was affected by the 1997 to 1998 El Niño, precipitation at the site totaled 303 mm and was over 1.2 times higher than the 30-year average. Much of the excess precipitation in 1998 occurred in two months, March (65 mm) and July (98 mm), which had unusually high rainfall compared to the 30-year average for these months or even other months in the year. At the Albuquerque, New Mexico weather station, the March 1998 precipitation total is the highest March rainfall recorded over 88 years of monitoring (Western Regional Climatic Center, 2004). Water year 2001 was even wetter than water year 1998, with an annual precipitation over 1.4 times higher than the long-term average. Water year 2000 was the driest year monitored, with only 189 mm of rain, but still within one standard deviation of average annual rainfall.

Precipitation data were collected at 1-hour intervals at the site meteorological station. Hourly data during the considered monitoring period (October 1, 1997 to September 24, 2002) were available from October 1, 1997 to October 14, 2001. Rainfall intensities during this time ranged from 0.3 to 21.8 mm/hr, with a median intensity of 0.8

mm/hr and an average intensity of 1.6 mm/hr. Daily precipitation during the monitoring period ranged from 0.3 to 50.8 mm, with a median of 2.8 mm and an average of 4.9 mm. In comparison, daily precipitation recorded for the Albuquerque weather station from 1961 to 1990 ranged from 0.3 to 44.5 mm, with a median of 1.8 mm and an average of 3.6 mm.

For the east and west subplots, the shallowest (0.15 m) TDR probe exhibited significant increases in water content readings that corresponded to precipitation (Figures 4.21 and 4.22). Based on the out-of-phase and corresponding increases in water content recorded by deeper (0.45 and 0.9 m) probes, it appears that water moved into the cover system to a depth of at least 0.9 m. Average water contents recorded at the stations of nested probes varied between stations (Figures 4.23 and 4.24). For the east subplot, the highest water contents were measured by probes located near the toe of the cover system slope, and relatively low water contents were measured by probes located near the crest of the slope (Figure 4.23). This trend was not observed for the west subplot (Figure 4.24). The highest water contents were generally recorded for probes at the slope crest.

The field water balance determined for the site (Table 4.7 and Figures 4.25 and 4.26) indicates that cumulative evapotranspiration plus runoff exceeded cumulative precipitation and irrigation for most of the monitoring period. This climatic pattern kept the cover system soils relatively dry. During periods when precipitation exceeded evapotranspiration plus runoff, soil water storage increased. However, these periods were followed by relatively dry periods that resulted in decreased soil water storage. The most significant increase in storage occurred in February 2002, when the cover system on the west subplot was irrigated (Figure 4.26). In June 2002, the combination of high evapotranspiration and low precipitation led soil water storage to decrease almost back to pre-irrigation levels.

Except for the 22 mm of cumulative runoff recorded for the west subplot during the 1998 water year, annual runoff for the east and west subplots ranged from 0.2 to 0.8 mm. Most (21.1 mm) of the runoff from the west subplot during water year 1998 occurred during July 16 to 27, 1998, following several storms of up to four hours in duration. Runoff of 0.8 mm was recorded on July 16, 1998 after four hours of precipitation totaling approximately 25 mm. Runoff of 0.6, 14.0, and 5.7 mm, respectively, was recorded on July 25 to 27, 1998. Precipitation measured during those days was 24.6 mm over three hours, 0.8 mm over two hours, and 2.8 mm over one hour, respectively. The recorded runoff during July 25 to 27, 1998 lags the measured precipitation by more than a day and is a significant fraction of measured precipitation (72%). Runoff of this magnitude was not recorded for the west subplot during the remainder of the monitoring period. In addition, runoff recorded from the east subplot was only 0.1 mm on July 16, 1998 and a total of 0.04 mm on July 25 to 27, 1998. It is unclear if the recorded runoff values for the west subplot on July 25 to 27, 1998 are correct or it there was a measurement error. For example, Dwyer (2003) noted that the flow meter used to measure the volume of collected runoff would occasionally become clogged with sediment.

Drainage was only recorded for one subplot (west subplot) (Table 4.6) and only during the early part of the monitoring period (prior to October 1, 1997, the start date for the monitoring data presented herein, and during July 25 to August 6, 1998) before the soils were dewatered by evapotranspiration, as evidenced by the decrease in soil water storage. Based on a review of data from the five TDR stations on this subplot, it appears that the drainage during 1998 may have been related to preferential flow (Figure 4.24). During the late July 1998 precipitation events, the water contents recorded by the shallowest TDR probes on the west subplot increased (Figure 4.22). Prior to the July

1998 precipitation, the average water contents at each station of probes on the west subplot had been decreasing (Figure 4.24). For all stations, except Station 5, average water contents generally continued a decreasing trend. At Station 5, the water content recorded by the shallow probe abruptly increased from 0.19 to 0.26 on July 25, 1998, the day that the 1998 drainage event started. The following day, readings from the two lower probes at the station also indicated rapidly increasing water contents (0.14 to 0.20 for the probe at 0.45 m and 0.17 to 0.20 for the probe at 0.9 m). It may be that a crack in the cover system developed upslope of Station 5 on the west subplot, allowing water to preferentially wet the soil by Station 5 and recharge the underlying lysimeter. None of the readings from the lower probes at the other four stations indicated a similar increase in soil water content. Water contents for these probes remained relatively low until the summer rains of 2000.

Vegetation on the monolithic cover was monitored annually in the fall from 1997 to 2001 and in spring 1998. Measurements included an assessment of leaf area index and bare area. Fractional bare area recorded from the fall of 1998 to the fall of 2000 ranged from 0.38 to 0.87, with the lowest bare area recorded in the fall of 1998. The average fractional bare area and leaf area index for the monolithic cover system during the monitoring period were 0.82 and 1.8, respectively (Dwyer, 2003).

4.5 Design, Construction, and Monitoring of Sierra Blanca Site

4.5.1 Design of Sierra Blanca Site

The Sierra Blanca test plots were constructed during April and September 1997 on a tract of land known as Faskin Ranch and monitored from October 1997 to September 2002 to support the development of a low-level radioactive waste landfill at the site. Only the data from October 1, 1997 to September 30, 2000 were evaluated in this dissertation. The performance objective for the cover system was to limit cover system drainage to an average of 10 mm/yr over the 500-year evaluation period for the facility (Radian Corporation and MK Environmental Services, 1993).

The test facility included two heavily instrumented 34 m × 17 m cover systems (four 17 m × 17 m subplots) (Figure 4.27). Each subplot was sloped at 2% towards the east or the west, from an approximately north-south running ridgeline to a runoff collection channel located along the perimeter of the test plot. Only the two subplots constructed with a capillary barrier are addressed in this dissertation.

The capillary barrier cover system consisted of, from top to bottom (Figure 4.5):

- 0.3-m thick loosely placed gravelly sand clay loam (24% gravel by weight, 15% by volume);
- 1.7-m thick compacted sandy clay loam;
- 0.3-m thick gravelly sand;
- 0.3-m thick gravel with loamy sand;
- 0.3-m thick gravel; and
- 0.15-m thick sand.

The gravelly sand layer at a depth of 2 m created the capillary break beneath the overlying finer-grained soil.

4.5.2 Construction of Sierra Blanca Site

The project specifications required that the upper 2 m of soil in the cover system conform to the following (Morrison Knudsen Corporation and Radian Corporation, 1996):

- maximum particle size ≤ 76 mm;
- Unified Soil Classification System designation (ASTM D 2487): SC or CL material;

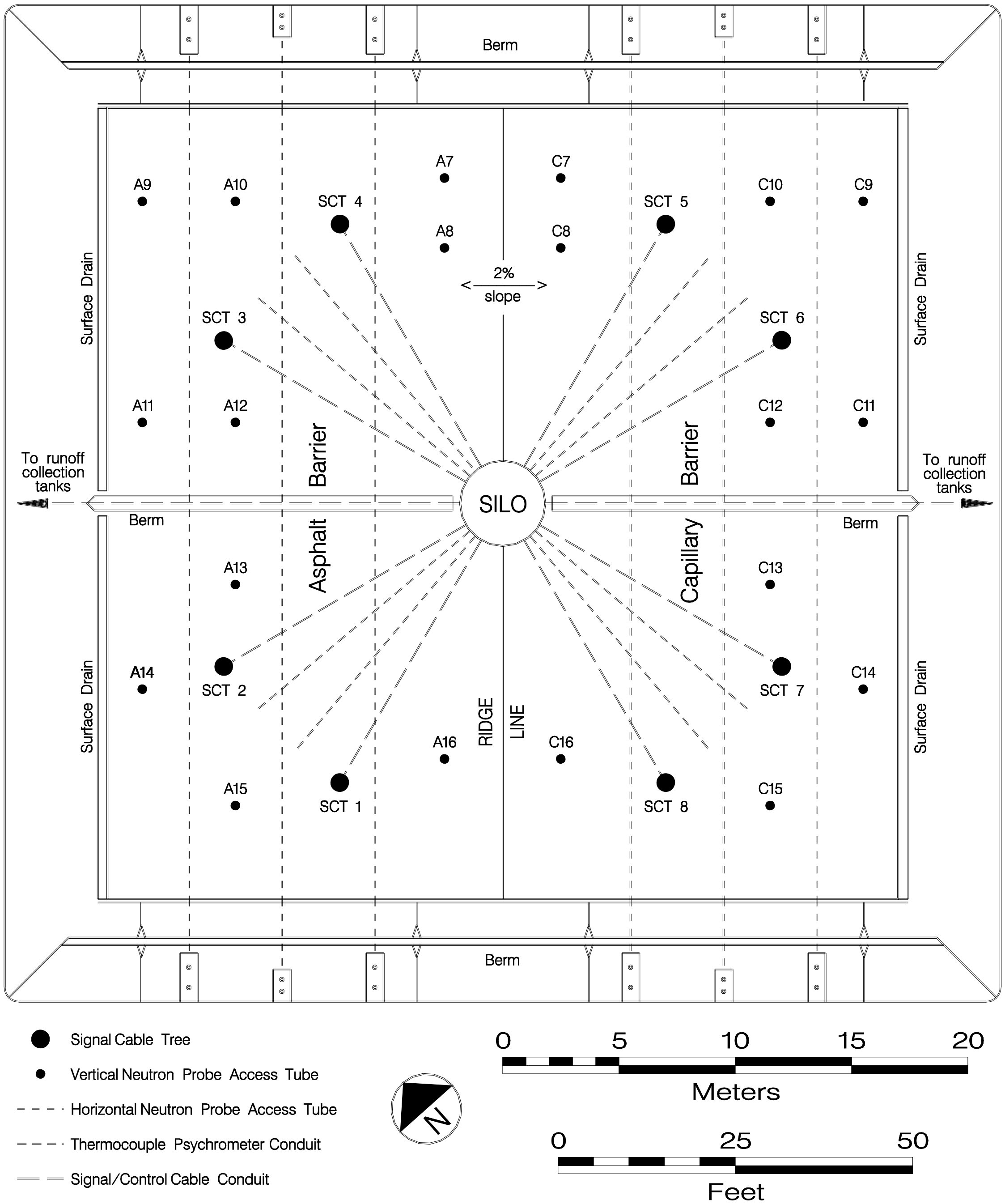

Figure 4.27: Plan View of Sierra Blanca Test Facility (courtesy of the Texas Bureau of Economic Geology).

- uncompacted soil: minimum dry density ≥ 85% of the maximum dry density obtained from the modified Proctor compaction test (ASTM 1557) and water content within ±2 percentage points of the optimum water content; the target gravimetric water content and dry density for the in-place soil was, for the most part, 10 to 14% (0.16 to 0.22, by volume) and ≥ 1.72 Mg/m^3 (16.8 kN/m^3); and
- compacted soil: minimum dry density ≥ 90% of the maximum dry density obtained from the modified Proctor compaction test (ASTM 1557) and water content within ±2 percentage points of the optimum water content; the target gravimetric water content and dry density for the in-place soil was, for the most part, 10 to 14% (0.16 to 0.22, by volume) and ≥ 1.62 Mg/m^3 (15.9 kN/m^3).

Similar to the other cover systems described herein, the minimum soil bulk density specified for this cover system is relatively high and may impede growth of plant roots. However, it is within the range of bulk densities measured for the in-situ soils in the footprint of the test plot before they were excavated. During a soil boring program conducted at the site (described below), four soil samples were collected and analyzed for bulk density. The densities ranged from 1.65 to 1.81 Mg/m^3 (16.2 to 17.6 kN/m^3) and averaged 1.70 Mg/m^3 (16.7 kN/m^3).

The tests plot for the capillary barrier was constructed as part of a field demonstration program at the site, which included the advancement of eight soil borings, excavation of a prototype landfill cell, hydrologic studies of the cell excavation, construction of compacted soil liner test pads on the side slopes and floor of the cell, and construction of cover system test plots. Prior to excavation of the test cell, eight borings located within the cell footprint were advanced approximately 11 m deep into the test area to collect soils for geotechnical testing (Dames & Moore, 1996, 1997). Twenty samples were collected and tested for percent fines (ASTM D 1140), grain size (ASTM D

422), Atterberg limits (ASTM D 4318), classification (ASTM D 2487), and in-situ moisture content and density (ASTM D 2216). Soils in the upper 3.7 to 4.0 m of the borings were predominantly silty and poorly graded sands (SM to SP), inter-layered with lesser amounts of clayey sands and sandy clays (SC to CL). Deeper in the soil profile, the SC and CL materials become more predominant and were inter-layered with lesser amounts of SM to SP materials. The soils were dry and most of the soils had varying degrees of caliche cementation.

The test plot area was excavated to a depth of approximately 3.7 m below final grade. The lower sands and gravels, obtained from an off-site source, were placed. Then the overlying finer-grained soils were installed. The soil preparation and construction methods used to place the compacted soil component of the capillary barrier were similar to those employed during construction of on-site test pads for a compacted soil liner. Soil was hauled from a stockpile, placed in approximately 200-mm thick loose lifts, disked or moisture conditioned, and then compacted using walk-behind compactors (jumping jacks), a vibratory sheeps-foot compactor, and a vibratory smooth-drum roller. From June to August 1997, while the cover systems were being constructed, the site received over 140 mm of rain. This contributed to the relatively high initial water content of the capillary barrier. The average bulk density of the in-place compacted soil was approximately 1.8 Mg/m^3 (18 kN/m^3).

A 0.3-m thick uncompacted soil layer was placed above the completed compacted soil layer. The specifications originally called for this soil layer to be compacted to 85% of its maximum modified Proctor dry density and at a gravimetric water content within ±2 percentage points of the optimum water content. However, shortly before soil placement began, the density requirement was dropped (though the water content requirement remained) because there was concern that, if compacted, the soil would not support the desired quality of vegetation. The average bulk density of the in-place uncompacted soil was approximately 1.5 Mg/m^3 (15 kN/m^3).

The desorption soil water characteristic curves (SWCCs) of the uncompacted and compacted soils and the underlying sand were evaluated in the laboratory. Samples were compacted to bulk densities representative of field conditions. Water retention properties were determined from hanging water column tests conducted at matric potentials of -0.01 to -2 m (-0.1 to -20 kPa) and pressure plate tests conducted at pressures of 1 to 50 m (10 to 500 kPa). For this dissertation, the results of the pressure plate test were corrected for 15% gravel by volume (based on 24% gravel by weight measured during construction) by multiplying the measured water content values by the non-gravel fraction (1 - 0.15). The test data were fitted to the van Genuchten water retention function (Figure 4.28) using the Solver tool in EXCEL™ to find the smallest root mean squared error between the data and the fitted curves. The residual water content in the van Genuchten function was assumed to be zero. The van Genuchten SWCC was also used to determine the Campbell (1974) SWCC using the Solver tool. The calculated parameters for the van Genuchten SWCCs and the Campbell SWCCs are presented in Table 4.8 and the SWCCs are shown in Figure 4.28.

Table 4.8: Summary of van Genuchten and Campbell Parameters Fit to Laboratory Data.

Material	Saturated Water Content (-)	Residual Water Content (-)	van Genuchten Parameters		Campbell Parameters	
			α (mm^{-1})	n (-)	h_b (mm)	λ (-)
Uncompacted Soil	0.45	0.0	0.0026	1.276	237	0.243
Compacted Soil	0.35	0.0	0.0020	1.166	294	0.149
Sand	0.40	0.0	0.0020	1.464	265	0.373

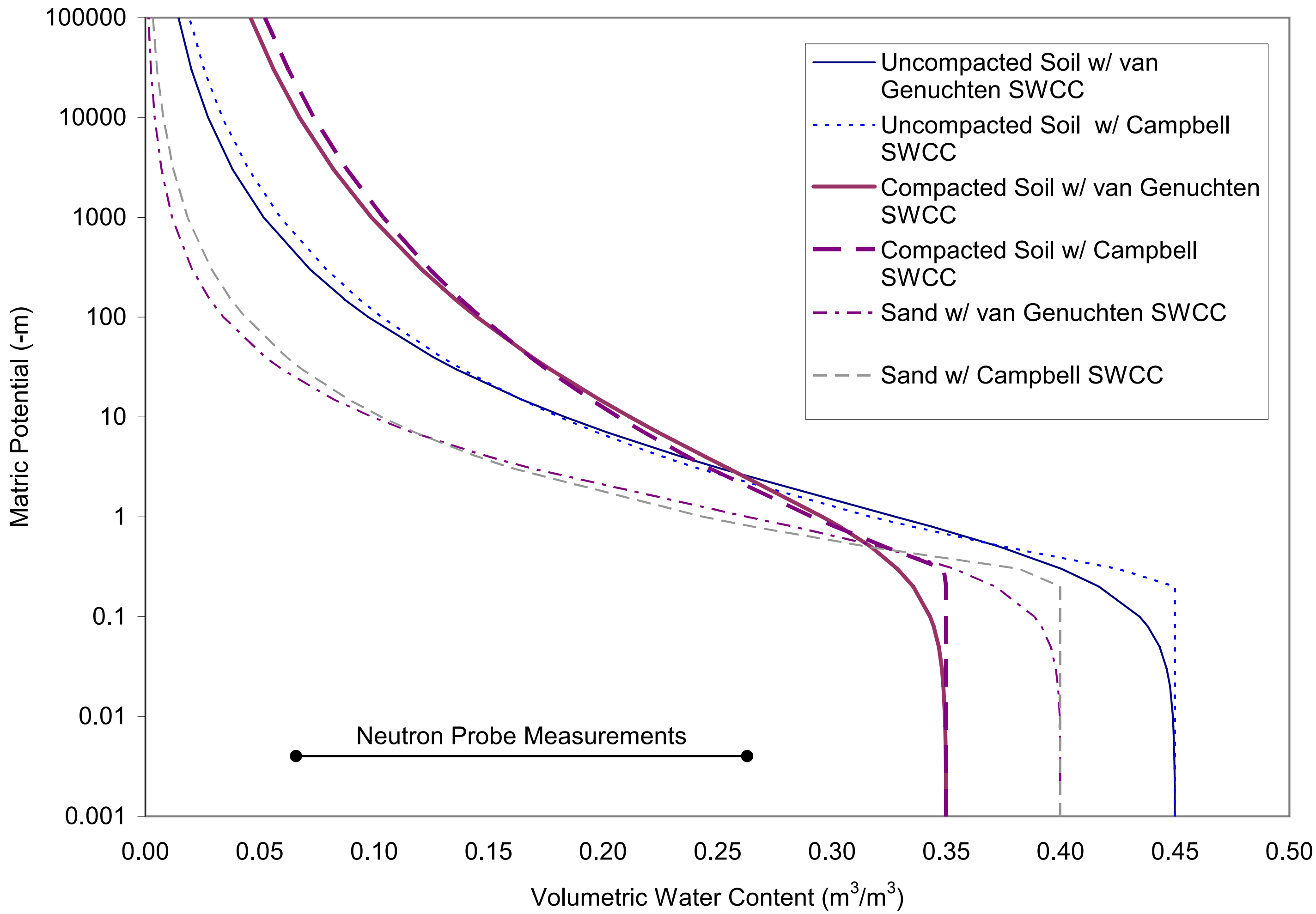

Figure 4.28: SWCC (Desorption) for Cover System Soil at Sierra Blanca Site Based on Laboratory Hanging Column and Pressure Plate Tests Fitted to the van Genuchten Function.

The saturated hydraulic conductivities of the uncompacted and compacted sandy clay loam and the underlying sand were determined by laboratory tests on soil samples remolded approximately to the as-built bulk densities and by field tests (Table 4.9). In the laboratory, the hydraulic conductivities of the uncompacted soil and the sand were evaluated using a rigid wall permeameter (ASTM D 2434), and the hydraulic conductivity of the compacted soil was evaluated using a flexible wall permeameter (ASTM D 5084).

Table 4.9: Saturated Hydraulic Conductivity Measurements of Cover System Soils at Sierra Blanca Site.

Material	Test Type	Number of Tests	Saturated Hydraulic Conductivity (m/s)	
			Range	Geometric Mean
Uncompacted Soil	Rigid Wall Permeameter	2	8.6×10^{-6} - 9.4×10^{-6}	9.0×10^{-6}
	Guelph Permeameter	2	1.8×10^{-6} - 2.0×10^{-6}	1.9×10^{-6}
Compacted Soil	Flexible Wall Permeameter	3	1.3×10^{-9} - 4.8×10^{-9}	2.1×10^{-9}
	Guelph Permeameter	5	1.2×10^{-8} - 3.9×10^{-8}	2.1×10^{-8}
	Open Double Ring Infiltrometer	8	7.8×10^{-9} - 1.1×10^{-7}	2.9×10^{-8}
	Sealed Double Ring Infiltrometer	2	1.9×10^{-8} - 2.5×10^{-8}	2.2×10^{-8}
Sand	Rigid Wall Permeameter	1	7.4×10^{-5}	7.4×10^{-5}

Field hydraulic conductivity tests were conducted on soil test pads that had been constructed at the site to be representative of a compacted soil liner. The test pads had been constructed with the same soil and compaction criteria and methods as used for the uncompacted and compacted soils in the capillary barrier. Therefore, the tests performed on the tests pads were considered representative of the capillary barrier. The hydraulic conductivities of the uncompacted soil and upper portion of the compacted soil were assessed using a Guelph permeameter installed in shallow boreholes (0.15 to 0.66 m) in the test pads. Open and sealed double ring infiltrometer tests were also performed on the compacted soil in the test pads.

The saturated hydraulic conductivities of the uncompacted and compacted soils measured in the laboratory were about one order of magnitude smaller than hydraulic conductivities determined in the field. This effect may be attributed to the small sample size of the laboratory samples that do not capture the macrostructure of a soil compacted dry in the field.

Representative saturated hydraulic conductivities were selected for the capillary barrier soils and used to develop the van Genuchten-Mualem and Campbell-Burdine hydraulic conductivity functions (Figure 4.29) for this dissertation. The geometric mean value determined from the Guelph permeameter test (9.0×10^{-6} m/s) was assumed representative of the uncompacted soil. The geometric mean value determined from the sealed double-ring infiltrometer test (2.2×10^{-8} m/s) was assumed representative of the compacted soil.

For the first year after construction, the capillary barrier remained essentially unvegetated. This allowed the water balance of the cover system to be evaluated without the added complications of vegetation. In early August 1998, a 0.3-m grid drip irrigation system and mulch pad (20-mm thick aspen shavings) were installed on the cover system, and seedlings were then transplanted on a nominal 0.8-m square grid. The planted vegetation consisted of five perennial warm season bunchgrass species:

- Blue grama (*Bouteloua gracilis*);
- Plains bristlegrass (*Setaria leucopila*);
- Sand dropseed (*Sporobolus cryptandrus*);
- Green sprangletop (*Leptochloa dubia*); and
- Lehmann lovegrass (*Eragrostis lehmanniana*).

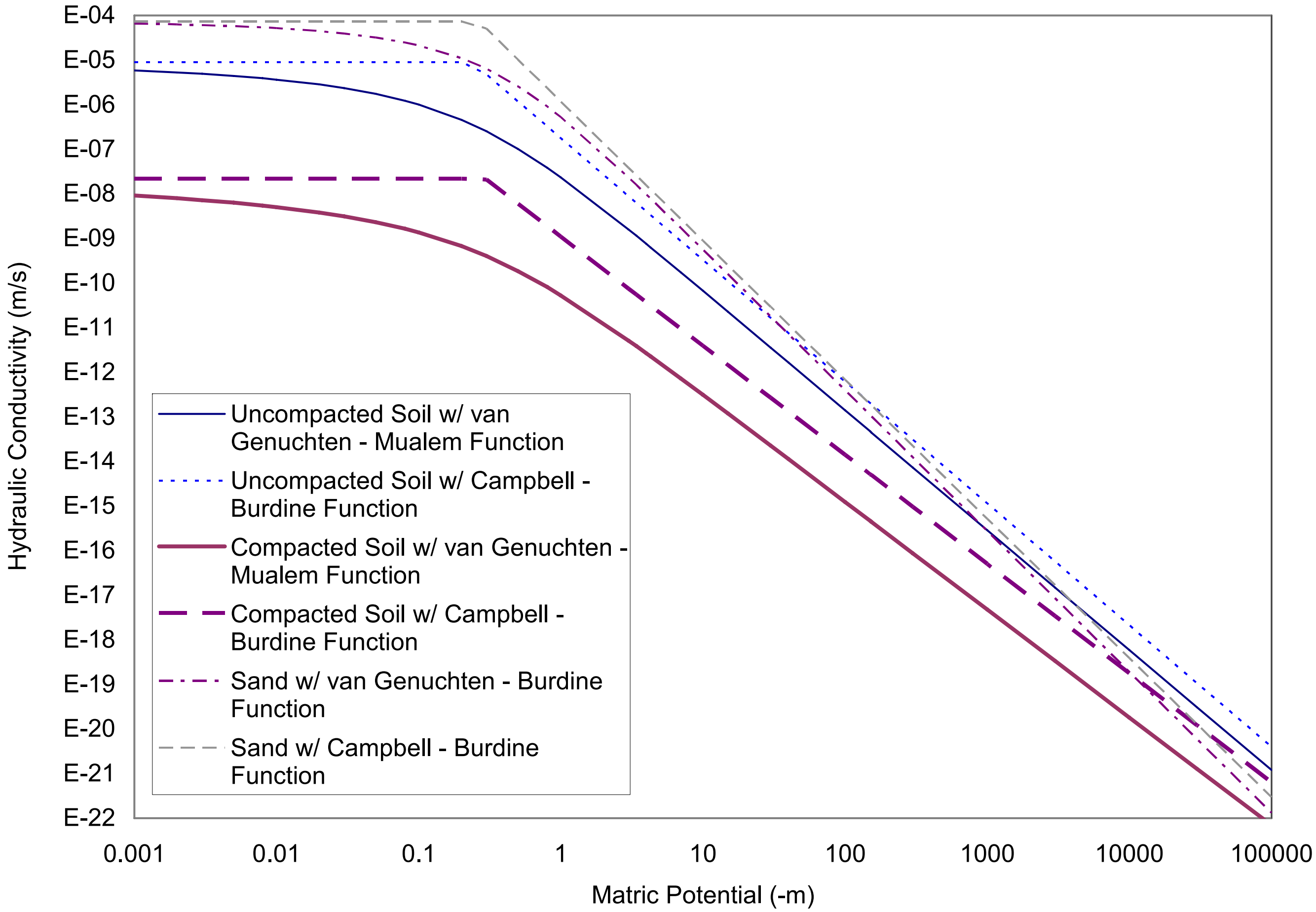

Figure 4.29: van Genuchten-Mualem and Campbell-Burdine Hydraulic Conductivity Functions (Desorption) for Cover System Soil at Sierra Blanca Site.

Blue grama, plains bristlegrass, and sand dropseed all occur naturally in the immediate vicinity of the site, while green sprangletop can be found in the mountains and hills located near the site. Lehmann lovegrass is introduced from Africa and is commonly used by highway departments throughout the southwest to stabilize topsoil along highways. During August and September 1998, the capillary barrier was irrigated to establish vegetation. As described by Scanlon et al. (2005), the vegetation was anticipated to have a negligible effect on the water balance in 1998 because plant roots did not have time to become established before the end of the growing season.

4.5.3 Monitoring of Sierra Blanca Site

Of the three evapotranspirative cover systems evaluated herein, the Sierra Blanca site had the most extensive and intensive monitoring program. The monitoring system was designed to operate for 30 years (Scanlon et al., 1997). Most of the monitoring systems were installed by October 1997, and five years of water balance data were collected before the systems were shut down. The sensors used and the manufacturer's stated accuracy of each measurement are summarized in Table 4.10.

Except for irrigation water (226 mm) that was applied to the capillary barrier in August and September 1998 to establish vegetation, the capillary barrier was monitored under ambient conditions from October 1997 to September 2000.

Climatologic measurements at the site meteorological station, located about 40 m from the test plot, consisted of precipitation, wind speed and direction, relative humidity, solar radiation, air temperature, and atmospheric pressure. Weather data were generally collected at 15-minute intervals during the monitoring period.

Table 4.10: Sensors Used at Sierra Blanca Site.

Parameter	Instrument	Accuracy (Manufacturer Stated)
Precipitation	Campbell Scientific TE525MM tipping bucket rain and snow gauge (0.1 mm tip)	± 1% at rates up to 10 mm/hr -3-0% at rates of 10-20 mm/hr -5-0% at rates of 20-30 mm/hr
Air Temperature and Relative Humidity	Vaisala HMP45AC thermistor and capacitive relative humidity sensor	± 0.2-0.3 °C ± 2-3% relative humidity
Solar Radiation	Li-Cor XL200 pyranometer	± 5% max, ± 3% typical
Wind Speed and Direction	MetOne 034A Windset	± 0.12-1.1 m/s ± 4°
Atmospheric Pressure	Setra Systems 270 barometer	± 0.02 kPa
Soil Temperature	Thermistors	± 0.1 °C
Soil Heat Flux	Heat flux plate	not provided
Soil Water Content	Campbell Pacific Nuclear International Hydroprobe 503DR neutron probe (with vertical access tubes)	soil specific
	FLUT SeaMist neutron probe (with horizontal access tubes)	soil specific
	Campbell Scientific 610 (300-mm long) TDR probe (installed vertically)	soil specific
	Soilmoisture Equipment 6005 (200-mm long) TDR probe (installed vertically)	soil specific
	Soilmoisture Equipment 6005C (200-mm long) TDR probe (installed horizontally) coated with a special plastic to reduce signal attenuation in high salinity soils	soil specific
Soil Matric Potential	Campbell Scientific 229 heat dissipation sensor	soil specific
	Merrill Specialty Equipment thermocouple psychrometers	soil specific
Drainage	Infrared drop sensor, tipping bucket rain gauge (5-mL tip), and a graduated cylinder in 114-L collection drums (Scanlon et al., 2005)	≤ 0.5% (Scanlon et al., 2005)
Runoff	Pressure transducer	± 0.004 and ± 0.06 mm for runoff events ≤ 2 and ≤ 400 mm, respectively (Scanlon et al., 2005)

The test facility had four subplots with two cover system designs (Figure 4.27). The capillary barrier subplots were separated from the adjacent two subplots by a vertically installed 1.5-mm thick very flexible polyethylene geomembrane. The capillary barrier subplots were separated from each other at the ground surface by a small berm (Figure 4.27). Only the capillary barrier subplots will be discussed further.

All of the major water balance components were monitored at the site (Scanlon et al., 2005). Runoff from each subplot was collected in a geomembrane-lined ditch (Figure 4.30) at the toe of the east slope and conveyed through a pipe to an underground tank. Each tank had a calibrated pressure transducer that was used to calculate water level. Runoff volume was then determined from the relationship between water level and water volume developed from a tank calibration.

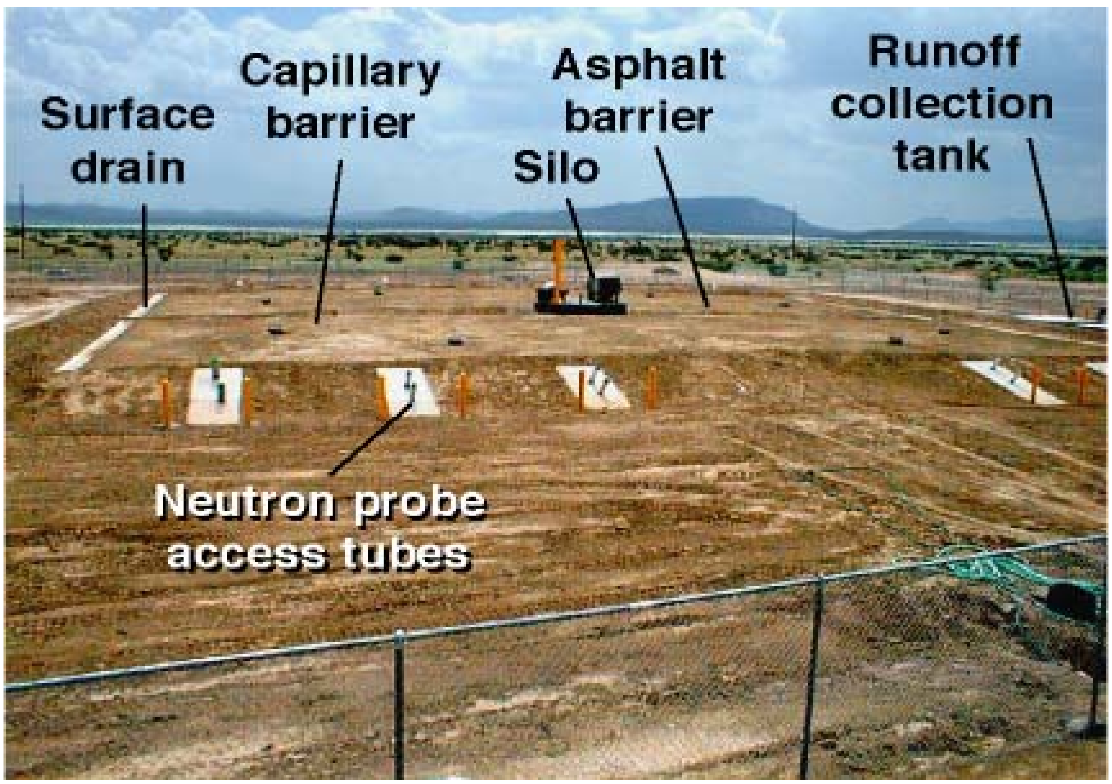

Figure 4.30: Runoff Collection System at Sierra Blanca Site.

A 12 m × 12 m pan lysimeter was centered beneath each subplot at a depth of approximately 3 m below ground surface to collect drainage (Figure 4.31). The lysimeters were constructed of 1.5-mm thick very flexible polyethylene geomembrane overlain by a geocomposite drainage layer. Thus, the lysimeter created a capillary break beneath the lowest sand layer of the capillary barrier. Zero drainage was collected. However, if drainage had been collected in a lysimeter, it would have conveyed by pipe to an instrument silo (Figures 4.30 and 4.31) for measurement using one of three systems (infrared drop sensors, tipping bucket rain gauges, or graduated cylinders in a collection drum), depending on flow rate.

Figure 4.31: Pan Lysimeters and Instrument Silo Installation at Sierra Blanca Site.

Soil water content data were collected using a calibrated neutron probe and TDR probes. Both vertical and horizontal access tubes for the neutron probe were installed at the site. Ten vertical access tubes (Figure 4.27) were placed approximately 2 m into the cover system, to the top of the sand capillary break, in June 1998. Water content was monitored on a monthly basis at approximately 0.15-m depth intervals to a depth of approximately 1.8 m. Measured water contents in the upper 0.15 m of the cover system were calculated from neutron probe data using an empirical correction factor to adjust for the loss of neutrons at the soil surface (Scanlon et al., 2005). Water contents were not monitored at depths greater than 1.8 m because the measured water content of the compacted soil would be affected by water in the underlying sand layer. The average water contents recorded at depths of 0.15, 0.3, 0.6, 1.2, and 1.8 m below ground surface are shown in Figure 4.32. The range of water contents recorded during the monitoring period at each of these depths are shown in Figure 4.33.

Six horizontal neutron probe access tubes (Figure 4.27) were installed during construction at depths of 0.3, 1.3, 1.8, and 3.0 m. The horizontal access tubes were monitored at 0.3 m intervals on a semi-annual to annual basis. In addition to monitoring water content at specific depths, these water content data were used to monitor spatial variability of water content. The neutron probe data from the horizontal access tubes were not evaluated in this dissertation.

One hundred twenty-eight TDR probes were also installed in the cover system to measure water content. Eighty probes (0.3-m long prongs) were placed vertically into the compacted soil during construction. Forty-eight probes (0.2-m long prongs) with a special plastic coating were placed horizontally on the compacted soil during construction. The coating on the probes was used to mitigate the TDR signal attenuation that occurs in the site soils, due to their high salinity and high clay content. Daily monitoring of TDR probes began in March and April 1998. As described by Scanlon et al. (2005), the TDR signals from uncoated probes below the uncompacted soil were generally attenuated, displaying little or no reflection. In addition, the coated probes generally overestimated water content. Therefore, the TDR data were not evaluated in this dissertation.

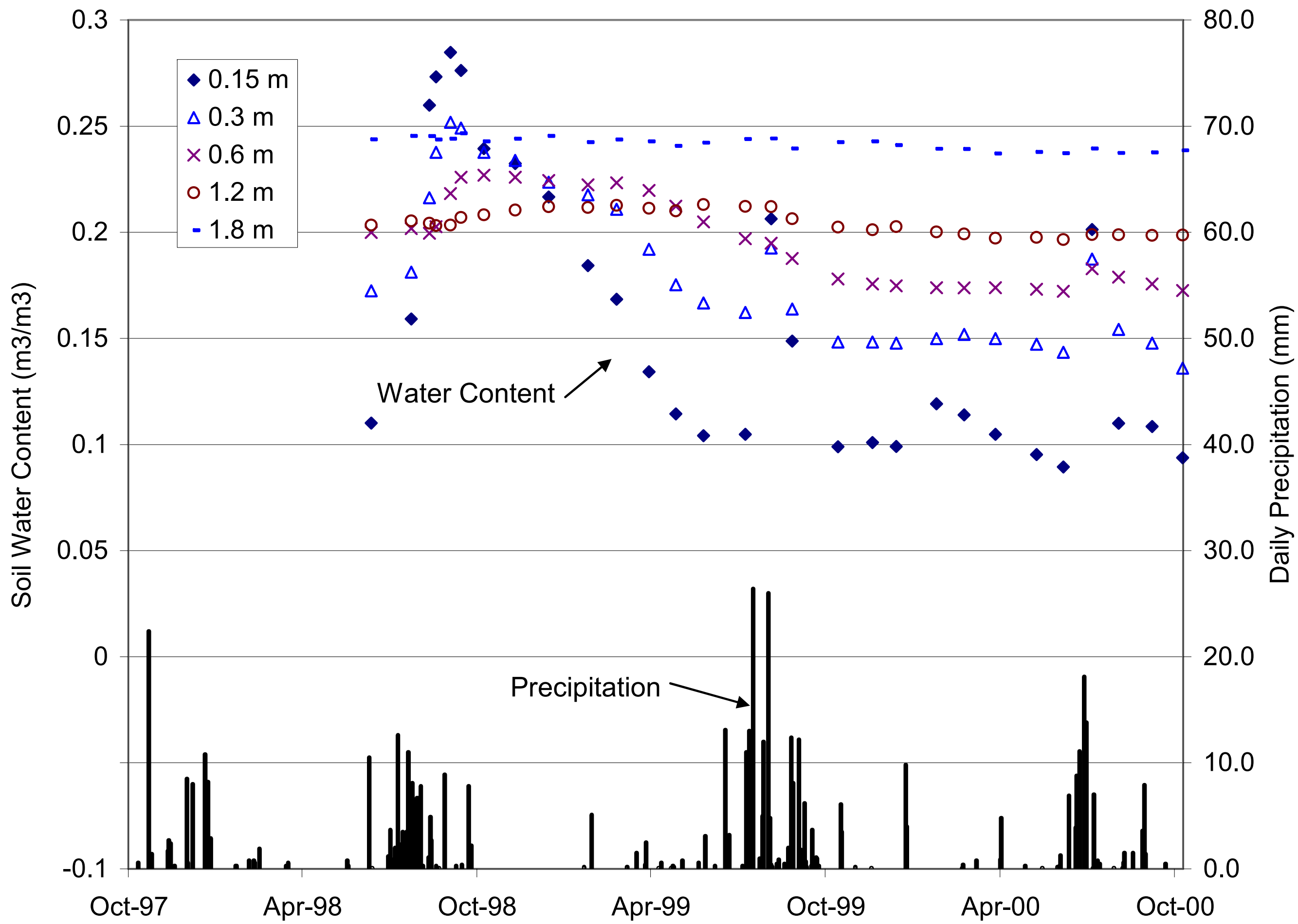

Figure 4.32: Average Water Content Measurements at Depths of 0.15, 0.3, 0.6, 1.2, and 1.8 m with Neutron Probes at the Sierra Blanca Site (Precipitation Includes Irrigation in August and September 1998).

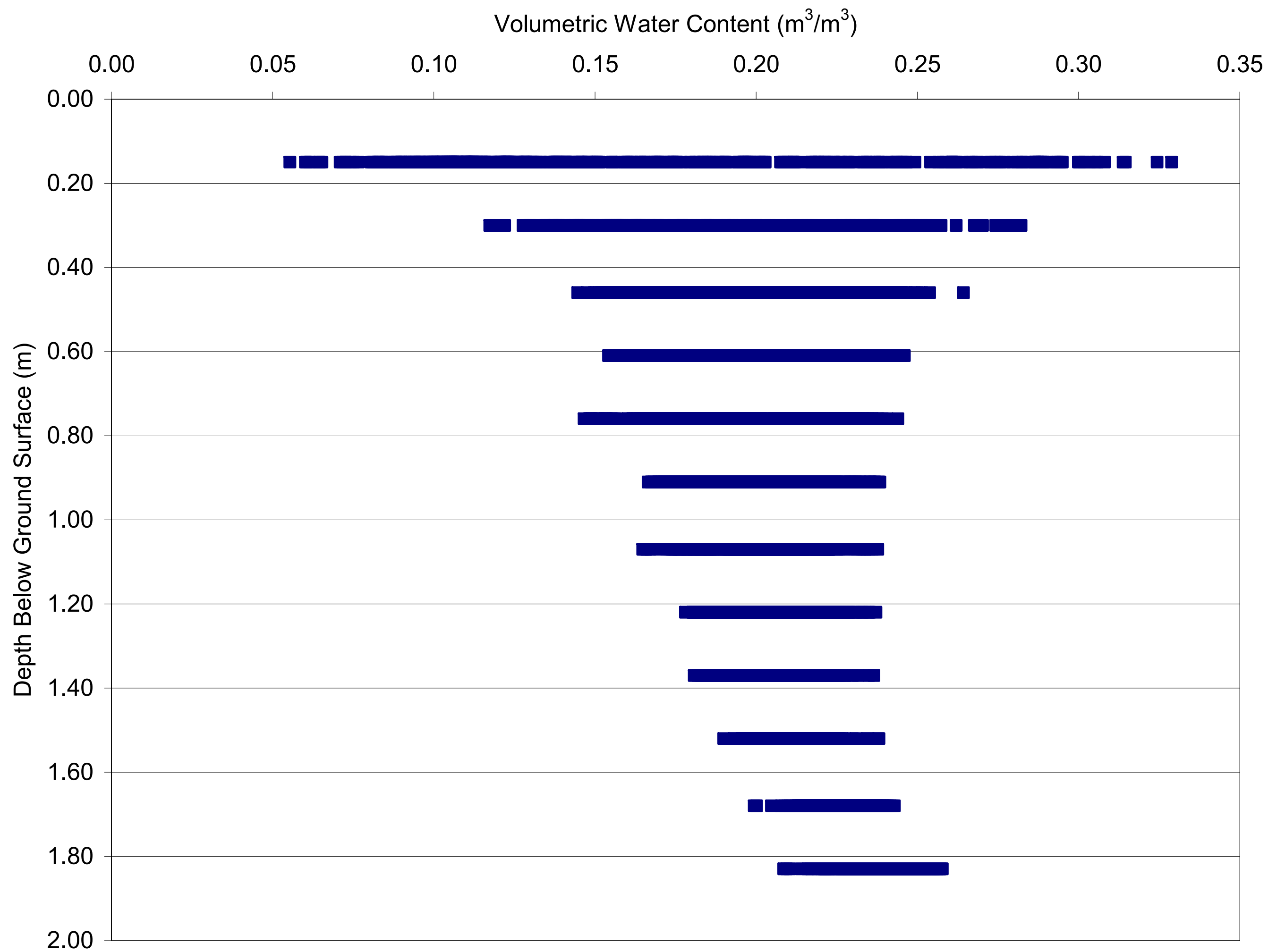

Figure 4.33: Variation in Water Content Measurements with a Neutron Probe at the Ten Neutron Probe Access Tubes.

Fifty-six heat dissipation sensors were installed during cover system construction at the same depths and locations as the horizontal TDR probes (0.15, 0.3, 0.6, 0.9, 1.2, 1.5, and 2 m). The measured matric potentials at two of the eight locations with a vertical array of sensors are shown in Figure 3.4. With these matric potentials and the water content measurements from the horizontal TDR probes, it should have been possible to develop field water retention curves for the uncompacted and compacted soils. However, the TDR probe measurements were not accurate enough to be used for this purpose.

One-hundred twenty thermocouple psychrometers were installed in December 1997 to provide an additional method to measure matric potential. Because psychrometers are relatively fragile compared to other sensors used to monitor water content and matric potential and because psychrometers do not have to be placed in intimate contact with the soil they are monitoring, the psychrometers were installed in 25-mm diameter PVC conduits placed within the cover system (Figure 4.27). By using the conduits, the psychrometers could be retrieved if they needed to be replaced. The psychrometer data were not available for this dissertation.

Soil water storage for the upper 2 m of the capillary barrier, i.e., for the uncompacted and compacted soil layers above the capillary break, was calculated by integrating the soil water content measurements from the neutron probes over the measurement depth. Because neutron probe data were not available until June 1998, water contents from October 1997 to May 1998 were estimated from matric potential measurements made with heat dissipation sensors and using SWCCs (desorption) measured in the laboratory (Scanlon et al., 2005).

A 3.7-m diameter by 6.1-m high steel instrument silo was installed on a concrete foundation in the center of the test facility (Figure 4.31). The silo housed the main data acquisition system and collected information from the 0.3-m diameter PVC instrument trees (two per subplot) located within the cover system approximately 12 m from the silo (Figure 4.34). A 10-mm thick, 6-m diameter flange was installed on each instrument tree at 0.45 m below the ground surface as an anti-seep collar. The instrument trees were used to collect the cables from different instruments installed at the site before they were routed to a multiplexer (Figure 4.34).

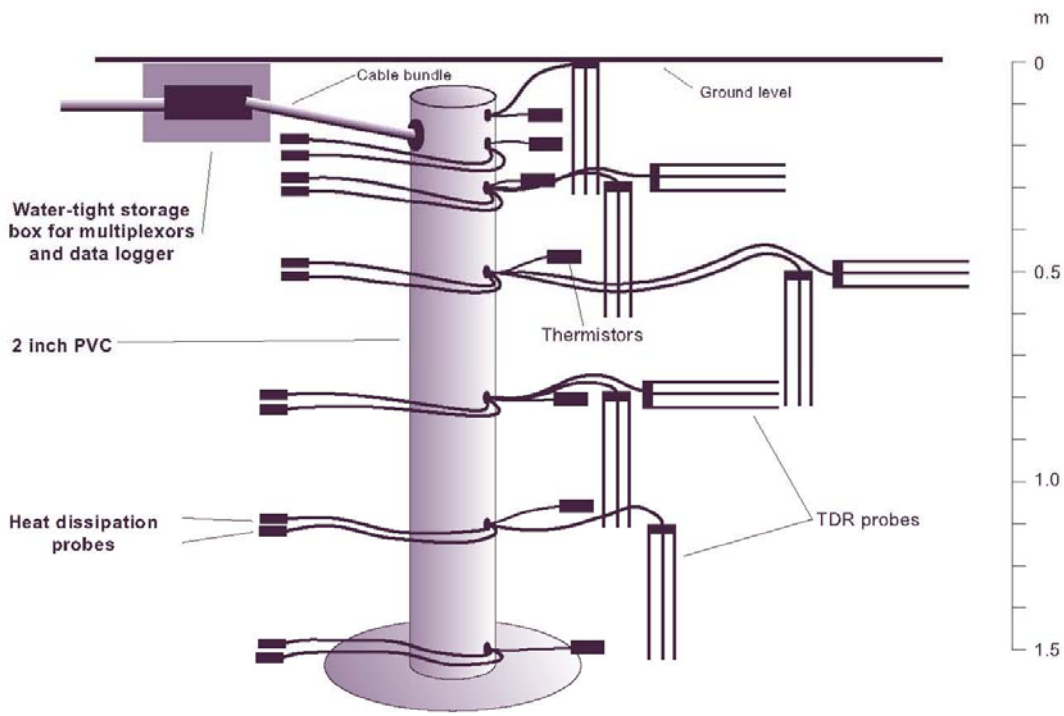

Figure 4.34: Instrument Tree at Sierra Blanca Site (from Scanlon et al., 1997).

The cumulative precipitation, cumulative runoff, soil water storage, and calculated evapotranspiration (calculated as the residual of the water balance components, Equation 3.1) for the capillary barrier are shown in Figure 4.35. The water balance is summarized in Table 4.11.

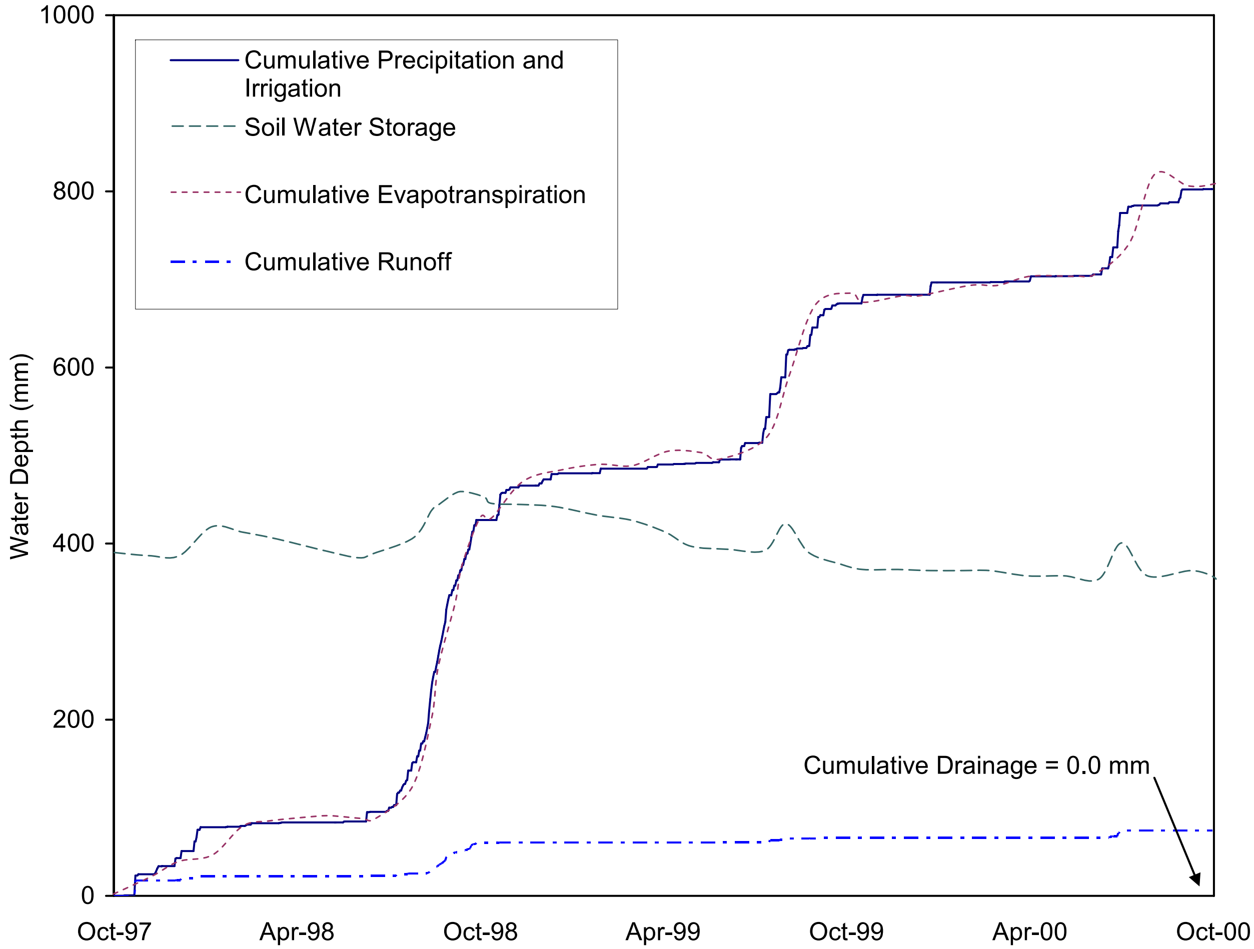

Figure 4.35: Water Balance Components for the Capillary Barrier Determined from the Field Monitoring Program at the Sierra Blanca Site.

Table 4.11: Summary of Measured Water Balance for Capillary Barrier at Sierra Blanca Site.

Water Year[1]	Precipitation (mm)	Irrigation (mm)	Runoff (mm)	Storage (mm)	Change in Storage (mm)	Drainage (mm)	Evapotrans. (mm)
					390[2]		
1998	202	225	60	449	59	0	308
1999	246	0	6	378	-71	0	311
2000	130	0	8	365	-13	0	135

[1] Water Year = 12-month period from October to September
[2] Measured storage at beginning of monitoring period

Precipitation recorded at the Sierra Blanca site during the first three-years of the five-year monitoring period is compared to 30-year (1971-2000) average precipitation (303 mm) for the Sierra Blanca, Texas weather station in Figure 4.4. For all three water years, precipitation was less than average (303 mm) and ranged from 130 to 246 mm. The later winter months to spring months (January to May) were noticeably drier than average. Only 7 to 16 mm of precipitation were measured from January to May during 1998 to 2000. In contrast, the historical average during this timeframe was 50 mm.

Precipitation data were collected at 15-minute intervals at the site meteorological station. Hourly rainfall intensities during the monitoring period ranged from 0.1 to 26.0 mm/hr, with a median intensity of 0.5 mm/hr and an average intensity of 1.5 mm/hr. Daily precipitation ranged from 0.3 to 50.8 mm, with a median of 2.8 mm and an average of 4.9 mm.

Similar to the Yucaipa and Albuquerque cover systems, the largest variations in water content were recorded at the shallowest depths in the capillary barrier (Figures 4.32 and 4.33). The variations were dampened for the Sierra Blanca cover system because water content measurements were only taken monthly. In contrast, water content measurements were collected hourly at the Yucaipa site and every two hours at the Albuquerque site. The damping of water content is apparent when the measured water contents are compared to the water contents calculated using the measured matric potentials and the SWCC. For example, the water contents measured in the ten neutron access probes from July to September 1999 ranged from 0.11 to 0.30. The matric potentials during this time ranged from approximately -70 to -0.2 m (-700 to -2 kPa). Using the measured matric potentials and the SWCCs for the Sierra Blanca soils, the calculated water contents for the soils range from 0.11 to 0.42. The relatively high apparent water contents occurred as a result of summer precipitation, but were not captured by the neutron probe readings.

Another reason for the differences between soil moisture status determined with the neutron probes and with the heat dissipation sensors may be attributed to instrumentation installation. Scanlon et al. (2005) noted that in comparison to the water content data, the matric potential data indicated that water was moving deeper into the profile after infiltration events. They suggested that this might be related to the soil density. Less compactive effort was applied to the soil placed around instruments, such as heat dissipation sensors, which were installed during construction. The vertical access tubes for the neutron probe were installed after construction presumably in soil that was better compacted.

The most significant increase in water content occurred after the site was irrigated in August and September 1998. Based on average water content measurements and on matric potential measurements at two of the eight locations with a vertical array of heat dissipation sensors, the irrigation resulted in downward movement of water to a depth of 0.6 to 1.5 m (Figures 3.4 and 4.32). After the irrigation, water contents generally decreased and matric contents increased over time, with hydraulic gradients directed upward rather than downward. This trend was reversed for a short time during the summer rains, but then was reestablished after the rains ended.

The field water balance determined for the site (Figure 4.35) indicates that storage increased and that small amounts of runoff occurred during summer precipitation. The largest storage increase and runoff amount occurred after the cover system irrigation in August and September 1998 to establish vegetation. After the irrigation event, storage trended downward over the next two years of monitoring.

Excluding runoff related to irrigation, the Sierra Blanca cover system exhibited more runoff than the Albuquerque cover system (on average, 12 mm/yr versus 3 mm/yr) even though the former site received less rainfall (for water years 1998 to 2000, 578 mm versus 768 mm) and generally had drier surface soils. A primary reason for the higher runoff recorded for the Sierra Blanca cover system may be that the measured saturated hydraulic conductivity of the uncompacted soil layer at the surface of the Albuquerque cover system was about five times greater than that for the Sierra Blanca cover system. Due to its lower saturated hydraulic conductivity, the soil at the surface of the Sierra Blanca cover system would be more likely to impede infiltration and cause runoff. In addition, although the Sierra Blanca site received less rainfall on an annual basis than the Albuquerque site, the Sierra Blanca site received most of its rainfall in the summer months, when runoff was recorded. Precipitation intensities during this time varied, but included some events with relatively high intensities that were generally greater than the highest precipitation intensities measured for the Albuquerque site.

Consistent with the water content and matric potential measurements, zero drainage was recorded for the capillary barrier.

Vegetation on the capillary barrier was evaluated by noting vegetation composition and structure during each site visit (approximately monthly) and photographing the vegetation (Scanlon et al., 2005). In addition, the ecosystem leaf area index (LAI) for the cover system was estimated as 0.09 on October 9, 2000 using a ceptometer.

From a review of photographs of the site vegetation, the grasses did not become well established at the site during the three-year monitoring period. The capillary barrier was intentionally bare essentially the first year. The site was not vegetated and irrigated until August 1998, and plant growth was not observed until the spring of 1999. Vegetation at the site in the spring of 1999 consisted primarily of widely spaced pioneer species (Figure 4.36) characteristic of early successional plant communities in the southwest. The dominant plant was Russian thistle (*Salsola kali*), an annual. Other plants identified in the 1999 photographs include weedy perennial species, such as salt cedar (*Tamarix ramosissima*), silverleaf nightshade (*Solanum elaeagnifolium*), broomweed (*Gutierrezia texana*), and *Amaranthus* sp., and the planted perennial plains bristlegrass. Plant density was higher near the runoff collection channel (Figure 4.37).

In the spring of 2000, salt cedar was the first plant to turn green. Plants that are fast growing, such as salt cedar, can capture the available soil water before other slower growing perennials. Salt cedar was the dominant plant in 2000. Plains bristlegrass was becoming more established (Figure 4.37), and blue grama (*Bouteloua gracilis*) could be seen in the photographs. By the summer of 2000, a honey mesquite (*Prosopis glandulosa*) plant was observed in the photographs. Russian thistle was not found. During the 2000 water year, the site received only 130 mm of water and soil water storage decreased to the lowest level measured during the monitoring period (Figure 4.35 and Table 4.11). At the end of 2000, vegetation was still more shrublike than grasslike and differed from the surrounding vegetation, which appeared grasslike.

Figure 4.36: Vegetation on Capillary Barrier at Sierra Blanca Site in March 1999.

4.6 Summary and Synthesis

The design, construction, and monitoring of the monolithic cover systems at the Yucaipa and Albuquerque sites and the capillary barrier at the Sierra Blanca site were described in this chapter. Observations made from the information presented in the chapter are as follows:

- Design drainage rates for the Yucaipa and Sierra Blanca cover systems were based on maximum average annual values (10-yr and 500-yr, respectively) and ranged from approximately 1 to 10 mm/yr. A design drainage rate was not specified for the Albuquerque cover system.

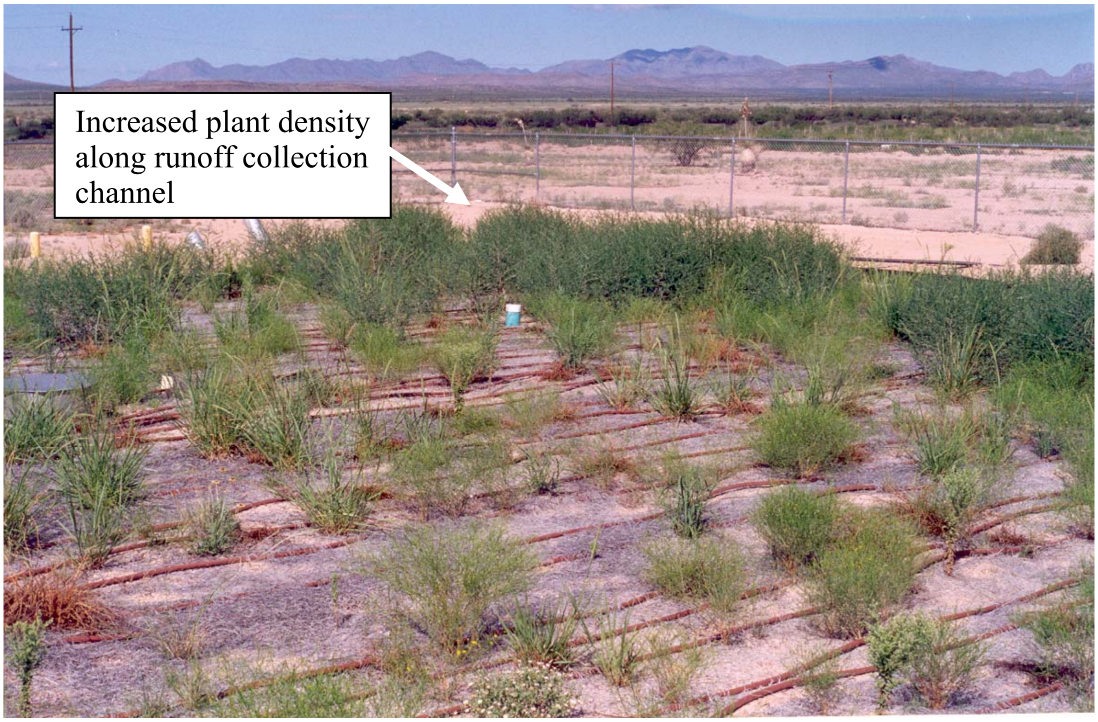

Figure 4.37: Vegetation on Capillary Barrier at Sierra Blanca Site in August 1999.

- The total thickness of cover system soils available for water storage, i.e., the total thickness of a monolithic cover system or the total thickness of soil above the uppermost capillary break in a capillary barrier, ranged from 1.05 to 2.00 m.
- The "water storage" layers were constructed with soils having a USDA texture ranging from loamy sand to sandy clay loam and a Unified Soil Classification of SM to CL.
- At least the lower portion of the water storage layers were heavily compacted to minimum bulk densities of 1.8 to 1.97 Mg/m^3 (17.7 to 19.3 kN/m^3) to limit drainage of water through the soil and to provide slope stability. According to NRCS (2000), soils with such high bulk densities will restrict plant root growth.

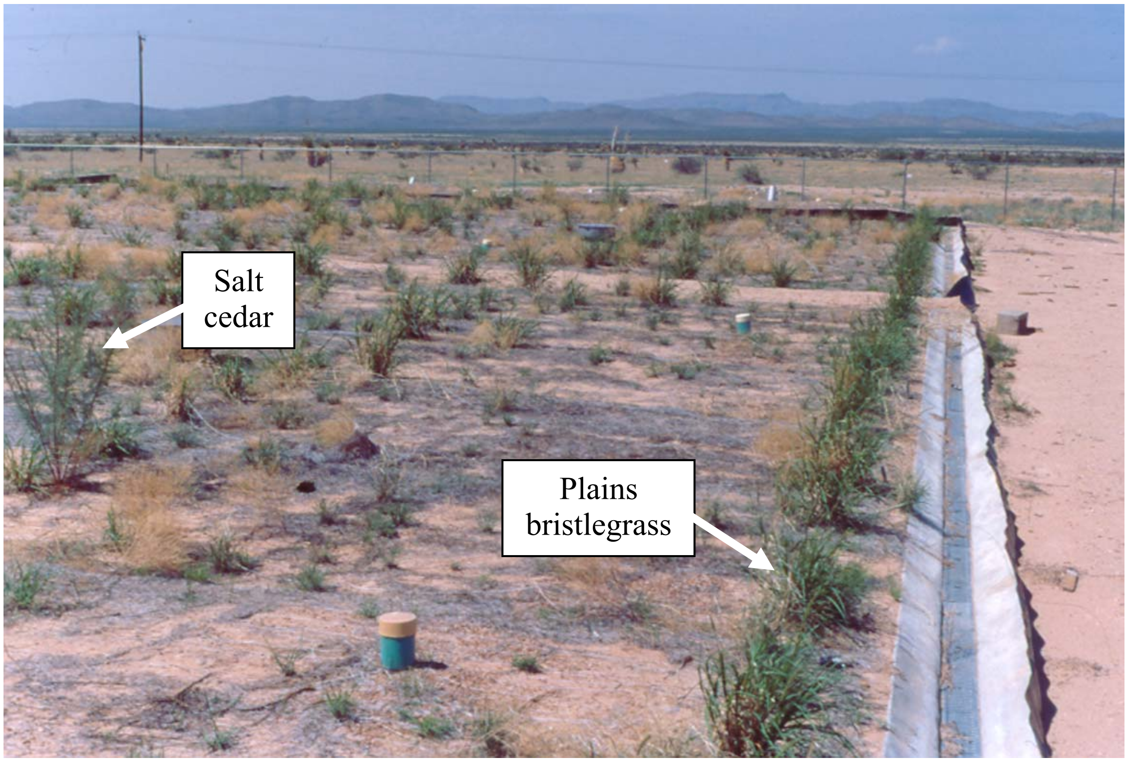

Figure 4.36: Vegetation on Capillary Barrier at Sierra Blanca Site in July 2000.

- The saturated hydraulic conductivities of the cover system soils were evaluated using laboratory and field tests. For the Yucaipa cover system, thin-walled tube samples for laboratory testing could not successively be collected without disturbance due to the gravel content of the cover system soil. For the Albuquerque cover system, laboratory tests on remolded samples and field tests on constructed soil layers yielded similar hydraulic conductivity results (Table 4.4). For the Sierra Blanca site, hydraulic conductivities determined from field tests were up to an order of magnitude greater than those determined from laboratory tests (Table 4.9).
- Only the cover system for the municipal solid waste landfill at the Yucaipa site had to meet a saturated hydraulic conductivity criterion (approximately

1×10^{-7} m/s) during construction. A hydraulic conductivity criterion was not specified for the cover systems for the proposed low-level radioactive waste landfills at the Albuquerque or Sierra Blanca sites.

- The average saturated hydraulic conductivities measured in the field for the uncompacted soil components (surface layers) of the evapotranspirative cover systems ranged from 1.9×10^{-6} to 1.2×10^{-5} m/s. For compacted soils, the values ranged from 2.1×10^{-8} to 4.7×10^{-7} m/s.
- For a given matric potential, the Campbell-Burdine hydraulic conductivity functions indicate higher unsaturated hydraulic conductivities than the van Genuchten-Mualem hydraulic conductivity functions (Figures 4.9, 4.20, and 4.29).
- The Yucaipa and Albuquerque sites both experienced annual rainfall that was higher than the historic average at least one year and lower than the historic average at least one year during their monitoring periods. Annual rainfall at the Sierra Blanca site was below the historic average for the entire monitoring period, and little precipitation occurred during the winter months when infiltration into the cover system was anticipated to be highest.
- During the monitoring periods, average rainfall intensities recorded over a one-hour period at the Yucaipa, Albuquerque, and Sierra Blanca sites were 1.0, 1.6, and 1.5 mm/hr, respectively.
- Localized preferential flow appears to have occurred along the vertical TDR probes in the cover system at the Yucaipa site and near the horizontal TDR probes at the Albuquerque site. Focused flow may also have occurred around the heat dissipation sensors installed during construction at the Sierra Blanca

site. Less compactive effort was applied to the soil when instruments were nearby to avoid damaging the instruments.

- The calibrated TDR probes at the Yucaipa site and the uncalibrated TDR probes (coated) at the Sierra Blanca site overestimated soil water content. The accuracy of the calibrated probes at the Albuquerque site is not known because data, such as water content or matric potential measurements with a different sensor or water content measurements on soil samples collected from the cover system, were not collected during monitoring.
- The TDR probes at the Yucaipa site were affected by the gravel (29% by volume) in the cover system soil. One segment of a probe was apparently damaged by gravel as it was driven into the cover system. In addition, the gravel apparently caused relatively lower water content readings at certain probe segments. The presence of gravel, which was not uniformly dispersed, increased the uncertainty in the measured soil water contents and calculated soil water storage.
- Runoff was monitored at the Albuquerque and Sierra Blanca sites, and both sites exhibited small amounts of runoff associated with precipitation each year.
- Water storage in the cover systems increased during precipitation events and decreased in the summer due to high potential evapotranspiration.
- A rough estimate of the water storage capacity of the three cover systems was calculated using the thicknesses of the cover system soils, the van Genuchten SWCCs (Figures 4.8, 4.19, and 4.28), and assumptions on maximum and minimum water contents of the soils. The effect of a capillary break was ignored. The maximum water content a soil can hold by capillarity without

gravity drainage was assumed to occur at a matric potential of -3.3 m (-33 kPa), i.e., field capacity. The minimum water content of a soil after water is extracted by plants was assumed to occur at a matric potential of -150 m (-1500 kPa), i.e., wilting point. With these assumptions, the calculated storage capacities for the Yucaipa, Albuquerque, and Sierra Blanca cover systems were approximately 110, 110, and 200 mm, respectively.

- The water storage capacities of the cover systems can also be estimated from monitoring data as the difference between the maximum and minimum soil water storage. From Figures 4.14, 4.25, 4.26, and 4.35, the measured storage capacities for the Yucaipa, Albuquerque, and Sierra Blanca cover systems were approximately 80, 110, and 100 mm, respectively. The apparent water storage capacity of the Sierra Blanca cover system is low because annual precipitation was relatively low during the monitoring period and the cover system did not reach its maximum water storage.
- Of the three considered cover systems, the Yucaipa cover system has the highest potential for drainage because it is located at the site with the highest humidity index (0.35 versus 0.10 and 0.11), the site with the highest average annual precipitation (490 mm versus 241 and 303 mm), and the site that receives most of its rainfall (80% versus 28% and 19%) in November through March, when potential evapotranspiration is relatively low.
- Over the five-year monitoring period at the Albuquerque site, a total of 0.4 mm of drainage was measured from the east and west subplots of the monolithic cover system. Drainage was only recorded for one subplot and only during the early part of the monitoring period. Zero drainage was

measured for the capillary barrier at the Sierra Blanca site over a three-year monitoring period.

- Drainage was not monitored at the Yucaipa site. However, drainage, if any, is anticipated to be small. The volumetric moisture contents of soil samples collected on March 10, 1999 at a depth of 1.14 m were 0.13 and 0.14. Using these water contents with the van Genuchten SWCC and the van Genuchten-Mualem hydraulic conductivity function for the soil, the calculated unsaturated hydraulic conductivity near the base of the monolithic cover system is approximately 1×10^{-14} to 3×10^{-14} m/s. Under unit gradient conditions, which are anticipated to exist in deeper reaches of evapotranspirative cover systems of sufficient depth and relatively constant water content, the calculated drainage from the cover system is the product of the unsaturated hydraulic conductivity and the unit gradient, which is 1×10^{-14} to 3×10^{-14} m/s (0.0009 to 0.003 mm/yr).
- Based on the results of the short-term monitoring, the Yucaipa and Sierra Blanca cover systems appear to have achieved their design drainage rates.

Chapter 5: Previous Studies of Evapotranspirative Cover Systems

5.1 OVERVIEW OF PREVIOUS STUDIES

A number of researchers have performed water balance evaluations of landfill cover systems using HELP, LEACHM, or UNSAT-H (Thompson and Tyler, 1984; Peters et al., 1986; Barnes and Rodgers, 1988; Peyton and Schroeder, 1988; Nyhan, 1989b; Nichols, 1991; Fayer et al., 1992; Peyton and Schroeder, 1993; Stephens and Coons, 1994; Martian, 1994; Fleenor and King, 1995; Khire, 1995; Berger et al., 1996; Paige et al. 1996; Fayer and Gee, 1997; Khire et al., 1997; Webb et al., 1997; Khire et al., 1999; Wilson et al., 1999; Andraski and Jacobson, 2000; Berger, 2000; Khire et al., 2000; Scanlon et al., 2001; Berger, 2002; Roesler et al., 2002; Scanlon et al., 2002; Dwyer, 2003; Zornberg et al., 2003; Benson et al., 2005; Scanlon et al., 2005). These studies were used to simulate laboratory or field water balances or in sensitivity studies to investigate the effects of different input parameters on the trends and magnitudes of the different water balance components. The conclusions of these studies are not always in general agreement. For example, some studies found that a certain model over-predicted or under-predicted infiltration or drainage in a certain climate, whereas other studies using the same model concluded just the opposite. In many of the studies, factors exist that preclude making definitive conclusions regarding model accuracy: key input data were not measured, ambiguities exist in the data, or comparisons with field data have not been made (Khire, 1995). In the current state of practice for the design of evapotranspirative cover systems, measurement of site-specific parameters required for the models, such as field water retention or hydraulic conductivity functions or vegetation rooting depth, is often not performed. Thus, the simulations are based on assumed data, which may lead to an inaccurate representation of a site. As a true predictive tool, the value of the models is currently limited unless site-specific calibrations are performed. However, even if the calibrations are performed, the calibrated model may not be much more successful at predicting a water balance than an uncalibrated model (Fayer and Gee, 1997).

The results of selected field studies of evapotranspirative cover systems that included water balance simulations using HELP, UNSAT-H, or LEACHM are summarized below. A number of these studies were conducted using older model versions. Conclusions drawn from studies using these older versions may not be the same as the conclusions that would be made using the most current model versions.

5.2 RICHLAND, WASHINGTON LYSIMETERS

5.2.1 Site Setting

In 1985, a program was started at the DOE Hanford Site to develop, test, and evaluate the effectiveness of various barrier designs for cover systems (Gee et al., 1997a,b). The program objective is to use natural materials to develop an essentially maintenance-free cover system that will isolate wastes and minimize erosion for at least 1,000 years and limit drainage to less than 5 mm/yr. By 1999, over 109 weighing lysimeters (0.3-m diameter by 1.7-m high plastic pipe or 1.5-m wide by 1.5-m long by 1.7-m high cubes) and 14 drainage lysimeters (consisting of 2-m diameter by 3-m high steel cylinders) had been installed at the site (Wilson et al., 1999) to test different cover system options and develop a better understanding of the water balance processes.

Mean annual rainfall at the site is 162 mm, and average potential evapotranspiration is 1,600 mm (Gee et al., 1994). On average, over 70% of precipitation falls during October through April. Average annual (50-year) snowfall is 230 mm, with an average snow accumulation of approximately 25 mm in January (Western Region Climatic Center, 2004).

5.2.2 Fayer et al. (1992) Evaluation of Hanford Lysimeter

Fayer et al. (1992) and Fayer and Gee (1997) used the lysimeter monitoring results to validate the UNSAT-H, Version 2 computer model. In the first study, Fayer et al. (1992) compared simulated water balances and field water balances for eight lysimeters consisting of six 2-m diameter by 3-m high drainage lysimeters and two 1.5-m long by 1.5-m wide by 1.7-m high weighing lysimeters. The soil profile in the lysimeters was intended to simulate a capillary barrier: the uppermost soil was a 1.5-m thick silt loam, and the underlying soils were coarse grained (sand, gravel, and coarser) (Figure 5.1). The soil was unvegetated.

The simulations were performed with daily site weather data from November 1987 to April 1989, measured soil properties for the silt loam, and assumed properties for the coarser-grained materials. The upper boundary condition was determined by meteorological forcing with hourly precipitation and irrigation data. The lower boundary of the 3-m high drainage lysimeters was modeled as a unit gradient. The bottom of the 1.7-m high weighing lysimeters was only 0.2 m below the interface of the silt loam and underlying coarse-grained soil, too close to model as a unit gradient boundary. Consequently, the bottom boundary of these shorter lysimeters was represented as a zero-flux condition. The soil temperature in the lysimeters was maintained constant. Therefore, only isothermal flow of water vapor was considered.

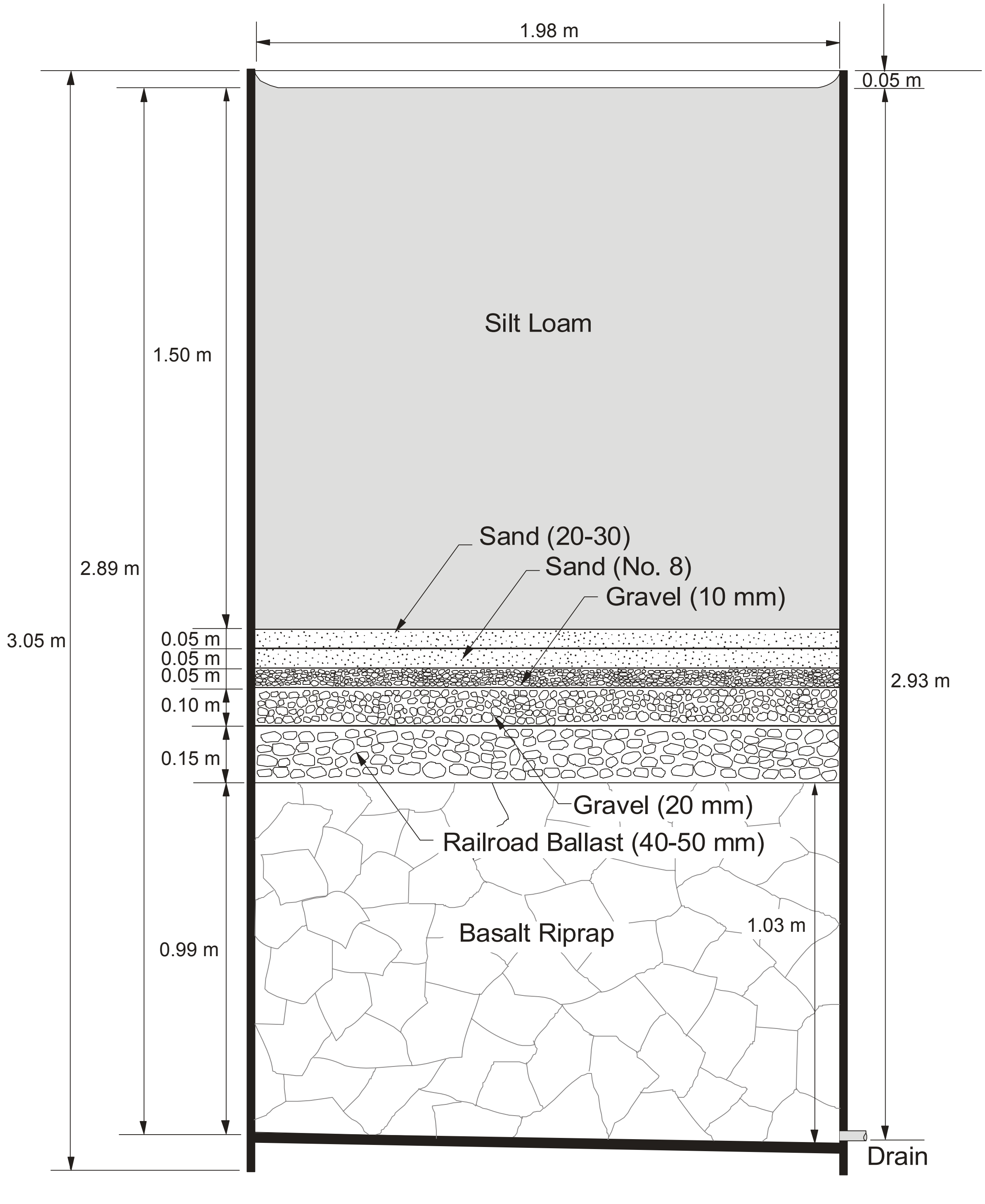

Figure 5.1: Drainage Lysimeter at Richland, Washington Site (from Fayer et al., 1992). [Weighing Lysimeter has Same Profile from Silt Loam to 10-mm Diameter Gravel.]

The simulated water content profiles for the lysimeters showed similar trends as the water contents measured biweekly using a neutron probe. However, predicted changes in storage were less than measured changes during all seasons. In other words, UNSAT-H tended to underestimate the amount of soil water storage during the winter when infiltration is the highest and overestimate the amount of soil water storage during the spring. Fayer et al. (1992) attributed this discrepancy primarily to the overestimation of evaporation in the winter and the underestimation of evaporation in the spring.

Fayer et al. (1992) conducted sensitivity tests on a number of model parameters and identified parameters that appeared to have a significant impact on the simulation results. These parameters are the saturated hydraulic conductivity, the pore interaction term of Mualem (1976) used to develop the hydraulic conductivity function, the presence of snow cover, and potential evaporation. By increasing the saturated hydraulic conductivity measured in the laboratory by a factor of 1.43, i.e., from 1.12×10^{-5} m/s to 1.60×10^{-5} m/s, decreasing the pore interaction term of the silt loam from 0.5 to 0, modeling a snow cover when it was present for more than six days, and decreasing potential evaporation by 30%, simulated soil water storage showed significantly better agreement with measured soil water storage.

In another experiment, the lysimeters were treated with water to cause breakthrough. When simulations were conducted using the desorption SWCC (Figure 3.2), breakthrough did not occur. Simulations performed with the sorption SWCC and with the saturated hydraulic conductivity measured in the field and increased by a factor of 1.56, i.e., from 9.00×10^{-6} m/s to 1.40×10^{-5} m/s, resulted in breakthrough and gave reasonable values for breakthrough time and drainage. Based on these results, Fayer et al. (1992) concluded that hysteresis is important to the successful modeling of drainage.

5.2.3 Fayer and Gee (1997) Evaluation of Hanford Lysimeter

Fayer and Gee (1997) continued the study of Fayer et al. (1992) by testing HELP (Version 2.05) and an updated version of UNSAT-H, Version 2.0, with six years of data from one of the drainage lysimeters. Six different simulations were performed with laboratory-measured soil hydraulic parameters and field meteorological data: (i) HELP in the standard mode; (ii) HELP with the initial soil water content set at the lowest value allowed in the model, i.e., the water content at the soil wilting point; (iii) UNSAT-H in the standard mode; (iv) UNSAT-H with the calibrations described above that were developed by Fayer et al. (1992); (v) UNSAT-H in the standard mode, but with thermal vapor flow; and (vi) UNSAT-H in the standard mode, but with hysteresis in the SWCC.

HELP significantly under-predicted soil water storage and over-predicted drainage for the capillary barrier in the lysimeter. While measured drainage of 29.6 mm occurred during the last year of monitoring, the HELP simulation in the standard mode predicted that drainage would occur every year to yield a total drainage of 537.0 mm. The HELP simulation with a lower initial water content predicted less drainage than the standard simulation until approximately 1.5 years into the simulation, when the water content of the soil had increased to that predicted in the standard simulation. From that point on, both simulation types gave similar results. The overestimation of drainage with the HELP model is not surprising because HELP assumes a unit gradient within vertical drainage layers and at the lower boundary and, thus, cannot model the physics of a capillary barrier.

Consistent with the findings of Fayer et al. (1992), simulations conducted by Fayer and Gee (1997) with UNSAT-H gave reasonable estimates of soil water storage, but under-predicted changes in storage. The simulation performed with calibrated parameters predicted soil water storage the closest. However, the agreement between simulated and measured values was best for the first two years and decreased over time. Simulations that considered thermal vapor flow or hysteresis predicted similar storage as the standard simulation with UNSAT-H. With the exception of the simulation with hysteresis, UNSAT-H predicted matric potential and drainage values that were too low. The simulation with hysteresis predicted matric potentials that were closest to measured potentials and was the only simulation that predicted drainage (15.3 mm versus 29.6 mm measured). As noted by Fayer and Gee (1997), this result demonstrates the sensitivity of drainage to suction values at the capillary break.

Based on their study, Fayer and Gee (1997) concluded that a water balance model that incorporates Richards' equation and hysteresis should be used for capillary barrier simulations. Fayer and Gee (1997) also concluded that thermal evaporation was not that important for the case considered.

Interestingly the simulations with calibrated input parameters did not give better agreement with the monitoring results than the standard simulations. Fayer and Gee (1997) proposed a number of reasons for this, including not considering hysteresis and only calibrating to soil water storage. Another reason may be that the soil hydraulic properties are changing over time. For example, the saturated hydraulic conductivity at six years after lysimeter construction may have been affected by natural processes acting on the cover since the calibration had been performed.

5.3 EAST WENATCHEE, WASHINGTON TEST PLOT

As described by Khire (1995) and Khire et al. (1999), a 30 m × 30 m test plot with a capillary barrier was constructed on the 2.5 horizontal: 1 vertical side slopes of a landfill in East Wenatchee, Washington. The site is located in a cold desert climate that receives an average annual precipitation of 230 mm. Most of the precipitation occurs in the late fall and winter in the form of rain or snow.

The cover system consisted of 0.15 m of sparsely vegetated uncompacted sandy loam (an SM-ML material under the Unified Soil Classification System) over 0.75 m of clean medium sand (an SP material under the Unified Soil Classification System). As noted by Khire et al. (1999), this cover system profile was constructed for research purposes. In practice, the finer-grained soil component of a capillary barrier would be thicker to provide the required soil water storage for design.

Hourly climate, runoff, soil water content, and drainage data were collected for the site. Runoff was collected in a tank and measured, soil water content was measured using two-prong TDR probes (without temperature correction), and drainage was collected using a 12.2 m wide by 18.3 m long pan lysimeter that drained to a tank. The lysimeter was constructed with a geomembrane barrier and overlying geocomposite drainage layer, which served as a capillary break beneath the sand component of the capillary barrier (Khire et al., 1999). Evapotranspiration was calculated from the water balance equation. Construction of the test plots and installation of the instrumentation occurred intermittently from August 1991 to June 1992. From June 1992 to May 1995, the monitored water balance at the site was 559 mm of precipitation, 76 mm of runoff, 48 mm increase in soil water storage, 5 mm of drainage, and 430 mm of evapotranspiration (Khire, 1995).

Khire et al. (1999) simulated the water balance of the ET cover system using UNSAT-H (version 2.0) and compared model predictions for the November 1992 to May 1995 period to monitoring data. The predictions were performed using site climatic data, with precipitation applied at the hourly rate measured at the site, and laboratory-measured soil properties. Input parameters that were not measured were estimated from published information. Simulations were conducted using meteorological forcing at the upper boundary and a unit gradient as the lower boundary condition. The capillary barrier effect of the lysimeter was not included in the simulations. Thus, it would be expected that the simulations would over-predict drainage.

Khire et al. (1999) drew the following conclusions from their study:

- With the exception of runoff, which was significantly underestimated, the water balance trends predicted using UNSAT-H were consistent with field observations.
- Though 76 mm of runoff was measured (Khire, 1995), UNSAT-H predicted no runoff. The primary reason for this is that most runoff occurred in late fall of 1994 and early winter of 1995 when the ground was frozen, and the model does not account for the effects of frozen ground.
- UNSAT-H overestimated the volumetric water content of the sandy loam and underestimated the volumetric water content of the sand. Water contents in the sandy loam were overestimated because runoff was underestimated, allowing more water to infiltrate into the soil. Water contents in the sand were underestimated because the geocomposite drainage layer in the lysimeter beneath the sand created a capillary break below the sand layer. However, the lower boundary of the sand was modeled as a unit gradient condition.
- UNSAT-H underestimated the annual peak soil water storage that occurs in the winter for all three monitoring seasons because the capillary break created by the lysimeter was not modeled. In addition, the algorithm used by Khire et al. (1999) to model snowmelt predicted that snowmelt would occur much earlier than observed in the field. This caused evapotranspiration to be simulated earlier than observed.
- UNSAT-H over-predicted drainage by 90 mm during the simulation period and was much higher than the total measured drainage of 5 mm reported by Khire (1995). Approximately 47 mm of this overestimate was attributed to the

lysimeter effect and the remainder was attributed to the effects of snowmelt and the underestimation of runoff.

5.4 ACAP TEST PLOTS

5.4.1 Description of ACAP Sites, Monitoring Systems, and Monitoring Results

The Alternative Cover Assessment Program (ACAP) was initiated in March 1998 under the EPA Superfund Innovative Technology Evaluation Program to evaluate the field performance of alternative cover systems, including evapotranspirative cover systems, at sites around the U.S. (Bolen et al., 1992). Under this program, twenty-four 10 m × 20 m cover test sections, consisting of fourteen evapotranspirative cover systems and ten conventional cover systems, have been constructed at eleven sites (Figure 2.4) (Albright et al., 2004).

In general, the monitoring system at each site consists of a meteorological station, a runoff collection and measurement system, low-frequency TDR and heat dissipation sensors installed within the cover system soils to measure soil water content and matric potential, respectively, and a pan lysimeter constructed beneath the cover system to measure drainage (Albright et al., 2004). Four to six TDR probes were installed above the lysimeter at each of three monitoring stations. At one of the stations, heat dissipation sensors were co-located with the TDR probes. The lysimeter was constructed with a linear low-density polyethylene geomembrane overlain by a geocomposite drainage layer (hence the capillary barrier effect). Prior to cover system construction, approximately 0.15 to 0.60-m of site soil was placed into the lysimeter. Albright et al. (2004) explained that the purpose of this additional soil is to replicate the intermediate cover soil that is placed over waste at landfills and to isolate the lysimeter from plant roots. Thus, the ACAP lysimeters evaluate flow through a cover system and soil layer underlain by a capillary break. Until the soil layer beneath the cover system becomes almost saturated, drainage from the cover system will not flow through the capillary break and into the lysimeter. After the initial soil was placed, a geotextile impregnated with a root inhibitor was installed on top of the soil to prevent plant roots from removing water from the underlying soil layer. Finally, an evapotranspirative cover system was constructed over the geotextile.

Average annual drainage rates measured for eight of the ten evapotranspirative cover systems in arid, semi-arid, and sub-humid (humidity index of greater than 0.5 to 0.75) climates ranged from 0.0 to 1.5 mm/yr (Albright et al. 2004). The two cover systems with higher drainage rates are the 1.1-m thick monolithic cover system in Sacramento, with an average annual drainage rate of 26.8 mm/yr, and the 1.5-m thick capillary barrier in Marina, California, with an average annual drainage rate of 52.0 mm/yr. For the humid sites, the measured drainage ranged from 33.3 to 159.6 mm/yr.

5.4.2 Roesler et al. (2002) Evaluation of ACAP Sites with Evapotranspirative Covers

Roesler et al. (2002) presented an evaluation of the measured and predicted water balances for the ACAP sites, including eight sites with eleven evapotranspirative cover systems. Simulations of the water balance over a two to three-year period were conducted using HELP (version 3.07) and UNSAT-H (version 2.0) with most climatic, soil, and vegetation inputs measured in the laboratory or the field. Meteorological forcing was used as the upper boundary condition, and the lower boundary condition was specified as unit gradient. Daily meteorological data were used. For UNSAT-H, daily precipitation was applied at the default application rate of 10 mm/hr.

In the initial simulations conducted by Roesler et al., both HELP and UNSAT-H over-predicted runoff at most sites by up to 86% of precipitation. Consequently, there was less water to infiltrate the cover systems, and the other simulated water balance components were not in agreement with monitoring results. This discrepancy was attributed to the hydraulic conductivities of the surface layers being too low. The hydraulic conductivities of the surface layers were subsequently increased by up to three orders of magnitude and the runoff curve number in HELP was adjusted to get better agreement between simulated and field results. This magnitude of increase was believed to be reasonable based on all the stressors, such as desiccation cracks, cracks from freeze and thaw cycles, and wormholes, that may affect a surface layer in the field over time. The site water balances were then re-simulated.

The water balances predicted using the calibrated models better matched the measured water balance components, but still did not agree very well or consistently over time, i.e., to get better agreement between monitored and modeled runoff, the hydraulic conductivities input for the surface layers would need to change over time, as they do in nature. With the calibrations, UNSAT-H generally underestimated runoff, sometimes overestimated or underestimated storage, and never over-predicted drainage. HELP generally predicted runoff values that agreed better with measured values. However, storage was consistently under-predicted with HELP, and predicted drainage was always higher than that simulated with UNSAT-H and occasionally higher than measured drainage.

Roesler et al. (2002) also tried to get better agreement between measured and predicted water balance components by modifying the van Genuchten water retention parameters, runoff curve number, wilting point, or leaf area index. While these parameters could be optimized for a specific site, not all of the sites monitored required the same types of parameter adjustments and no general conclusions were drawn regarding how to better simulate the water balance of evapotranspirative cover systems.

5.4.3 Benson et al. (2005) Evaluation of Evapotranspirative Cover System in Altamont, California

Benson et al. (2005) presented an evaluation of the measured and predicted water balances for the monolithic cover system at the Altamont, California site. The average annual rainfall for this semi-arid site is 358 mm. The 1.2-m cover system consists of three layers of crushed claystone (a CL material under the Unified Soil Classification System): an upper 0.15-m thick uncompacted surface layer, a 0.9-m thick water storage layer, and an underlying 0.3-m thick interim cover layer. During construction, undisturbed soil samples were collected from the cover system and tested in the laboratory for water retention characteristics and saturated hydraulic conductivity. The mean hydraulic conductivities of the surface layer and upper 0.3 m of the storage layer, lower 0.6 m of the storage layer, and interim cover were measured as 5.3×10^{-9} m/s, 4.5×10^{-9} m/s, and 3.0×10^{-8} m/s, respectively. After construction, soil samples were collected annually from the surface layer to evaluate how weathering and vegetation has affected its SWCC and saturated hydraulic conductivity over time. At two years after construction, no change had been observed in the SWCC determined in the laboratory; however, the saturated hydraulic conductivity of the surface soil and upper 0.3 m of the storage layer had increased from 5.3×10^{-9} m/s to 1.1×10^{-6} m/s.

Water balance simulations of the Altamont cover system over an approximately three-year period were performed using UNSAT-H (versions 2.04 and 3.01) with most climatic, soil, and vegetation inputs measured in the laboratory or the field. Soils data included in-situ SWCCs developed for each soil layer using the water contents and matric potentials measured in the field and the geometric means of the saturated hydraulic conductivities measured for the different layers. Meteorological forcing with daily precipitation applied at a rate of 10 mm/hr was used as the upper boundary condition, and the lower boundary condition was specified as unit gradient. The effect of the lysimeter underlying the interim cover layer on the lower boundary condition was not considered. The results of the simulations are shown graphically in Benson et al. (2005).

UNSAT-H significantly over-predicted runoff. Less than 100 mm of cumulative runoff had been measured, but more than 250 mm was simulated. With runoff overestimated, evapotranspiration, storage, and drainage were underestimated. Because the hydraulic properties of the site soil had been carefully measured, Benson et al. (2005) concluded that the over-prediction of runoff might be due to not testing a representative sample size of the surface layer, which would lead to underestimation of saturated hydraulic conductivity, or to factors besides saturated hydraulic conductivity.

Additional simulations were conducted to evaluate the effects of precipitation intensity and hydraulic properties on the simulated water balance. For the considered site conditions, decreasing precipitation intensity to the average measured value of 0.68 mm/hr decreases runoff, but not by enough to make the measured and simulated water balances agree. In addition, decreasing precipitation intensity had almost no effect on simulated drainage. Approximately 0.2 mm of cumulative drainage were simulated with UNSAT-H, but about 4 mm were measured. When the saturated hydraulic conductivities of all layers were increased by a factor of 10, calculated runoff agreed better with simulated runoff, and approximately 2 mm of cumulative drainage was calculated. Increasing the saturated hydraulic conductivity by a factor of 20 resulted in even better agreement between measured and simulated runoff; however, cumulative drainage was over-predicted by 100%. The effect of these increases in hydraulic conductivity on simulated storage was not discussed.

The above simulations were conducted using a unit gradient lower boundary. This boundary condition does not simulate the capillary break between the interim cover layer and the lysimeter. It is anticipated that the calculated drainage would have been even lower if the effect of the lysimeter lower boundary had been incorporated into the simulations.

5.5 Idaho Falls, Idaho Test Plots

There have been a number of field studies conducted at the Idaho National Engineering and Environmental Laboratory, located near Idaho Falls, Idaho, to evaluate the performance of evapotranspirative cover systems. The objective of the studies is to develop a cover system that will function for at least 500 years and limit drainage to less than 10 mm/yr (Wilson et al., 1999). Scanlon et al. (2002) compared monitoring and modeling results for one of the test plots constructed in the Engineered Barriers Test Facility at the site. This study is summarized below.

The Idaho Falls site is located in a cold desert climate and receives an average annual (40-year) rainfall of 221 mm (Scanlon et al., 2002). Winters are cold, with several months of snow cover; topsoils usually remain frozen from mid- to late November through February or early March (Anderson et al., 1993). Similar to other cold desert sites in the U.S., such as the DOE Hanford Site, much of the annual precipitation is received during the late fall to early spring when plants are dormant or just initiating growth. In comparison to the Hanford Site, the Idaho Falls site is wetter and colder.

The Engineered Barriers Test Facility is a concrete structure with ten 3 m × 3 m × 3 m isolated cells confined by four sidewalls and a floor and open to the atmosphere on top. Because the structure is enclosed on its sides, runoff cannot occur. Evapotranspirative cover systems with monolithic and capillary barriers have been constructed at the facility and are being monitored for soil water content using TDR probes, matric potential using tensiometers, sidewall drainage using a perimeter drain, and floor drainage using a lysimeter. Meteorological data were not collected at the site, but are available from a National Oceanic and Atmospheric Administration (NOAA) weather station located 11 km northeast of the test plots. Some details on the test facility are presented in Porro and Keck (1997) and Porro (2001).

Scanlon et al. (2002) evaluated the performance of one of the four replicate monolithic cover systems referred to as S2. This cover system consists of a 3-m thick silt loam layer with 25% gravel by volume mixed unto the upper 0.15 m of soil to control wind erosion.

Water balance monitoring results for test plot S2 over 27 months (21 July 1997 to 31 October 1999) were compared to the results of simulations using seven different models, including HELP (version 3.07) and UNSAT-H (version 3.0). Test plot S2 was bare (unvegetated) during the considered monitoring period

Previous simulations conducted at the site using measured soil hydraulic properties did not adequately predict the field water balance (Scanlon et al., 2002). The Scanlon et al. (2002) study used van Genuchten SWCCs and hydraulic conductivities for the soils that were developed by others from UNSAT-H calibrations with field data. Because UNSAT-H was used to calibrate the hydraulic properties of the soils, it "predicts" the field water balance reasonably well. The calibrated saturated hydraulic conductivity of the upper 0.15 m of soil was approximately 16 times greater than the saturated hydraulic conductivity measured in the laboratory, i.e., 1.1×10^{-5} m/s versus 6.8×10^{-7} m/s. The calibrated saturated hydraulic conductivity of the lower soil layer was about 5 times greater than the laboratory value, i.e., 5.0×10^{-6} m/s versus 1.0×10^{-6} m/s.

Meteorological forcing was used as the upper boundary condition. Daily precipitation data were input, and precipitation was applied at a rate of 10 mm/hr. The capillary break effect of the lysimeter was modeled by including a gravel layer beneath the cover system in the UNSAT-H simulations. The lower boundary condition was specified as unit gradient for UNSAT-H and is the default boundary condition for HELP.

Precipitation data were manipulated to account for snow accumulation and melt, and potential evaporation was adjusted to account for frozen ground. The adjusted climate data were used in the HELP and UNSAT-H simulations. It is noted that the HELP incorporates routines that account for snow accumulation and melt and frozen ground. However, these processes were not tested in the evaluations conducted by Scanlon et al. (2002).

Except for water balance prediction with HELP during the first simulation period (July to September 1997), when the site was irrigated, Scanlon et al. (2002) found the simulation results from both models to be similar and to reasonably approximate measured water balance parameters. Of the 759 mm of water that was applied during the first simulation period, 52 mm was lost to evaporation, 227 mm was lost to drainage, and the remaining 480 mm of water was stored in the soil. HELP predicted that 100 mm would be lost to evaporation, 73 mm would be stored in the soil, and 587 mm would be drainage. Thus, HELP significantly underestimated soil water storage and overestimated drainage for the first simulation year. During the subsequent two simulation years, 83 and 89 mm of drainage was measured. HELP predicted 70 and 88 mm of drainage during this time, and UNSAT-H predicted 103 and 123 mm of drainage.

Additional simulations with UNSAT-H were conducted by Scanlon et al. (2002) to evaluate the effects of water retention function, hydraulic conductivity function, precipitation intensity, isothermal vapor flow, and hysteresis on the simulated water balance. They found that a simulation with the Campbell-Burdine hydraulic conductivity function resulted in higher evaporation and lower drainage than a simulation with the van Genuchten-Mualem hydraulic conductivity function. These differences were attributed to the higher unsaturated hydraulic conductivities predicted by the Campbell-Burdine hydraulic conductivity function.

When daily precipitation was applied over 24-hours rather than at a rate of 10 mm/hr, evaporation was underestimated and drainage was overestimated. These differences were attributed to the upper boundary condition of UNSAT-H: when precipitation is applied, evaporation cannot occur. When net precipitation (precipitation minus potential evaporation) was applied as the upper boundary condition, evaporation was overestimated and drainage was underestimated the first simulation year. For the second and third simulation years, the water balance simulations using net precipitation approximated the field water balances.

Including isothermal vapor flow had a negligible effect on the simulated water balance.

Hysteresis was modeled assuming that the van Genuchten α parameter for sorption is two times that for desorption and that air is entrapped in 10% of soil pores during desorption. Simulated storage decreased and simulated annual drainage increased by 32 to 48% when hysteresis was considered.

5.6 ALBUQUERQUE, NEW MEXICO TEST PLOTS

5.6.1 Description of Albuquerque Test Plots and Monitoring Results

Three evapotranspirative cover systems (Figure 5.2) were constructed at the Albuquerque site. The cover systems consisted of a capillary barrier, an anisotropic barrier (a specialized capillary barrier that incorporates permeable layers, in this case a sand wicking layer, above the capillary break to encourage lateral flow), and a monolithic cover system. The capillary barrier consisted of the following components, from top to bottom:

- 0.3-m thick loosely placed loamy sand;
- 0.15-m thick clean sand (1 mm);
- 0.22-m thick clean pea gravel (10 mm);
- 0.45-m thick compacted loamy sand; and
- 0.3-m thick clean sand (1mm).

The anisotropic barrier consisted of the following components, from top to bottom:

- 0.15-m thick loosely placed gravelly loam sand (25% pea gravel and 75% loamy sand);
- 0.60-m thick compacted loamy sand;
- 0.15-m thick clean sand (1 mm); and
- 0.15-m thick clean pea gravel (10 mm).

The monolithic cover system consisted of the following components, from top to bottom:

- 20 to 40-mm thick gravel mulch;
- 0.15-m thick loosely placed loamy sand; and
- 0.90-m thick compacted loamy sand.

Details on the design, construction, and installation of the monolithic cover system were presented in Section 4.4.

The cover systems were monitored from May 1997 until September 2002 with the same instrument schemes. Therefore, details on the monitoring system for the monolithic cover system presented in Section 4.4.3 are also applicable to the capillary barrier and anisotropic barrier.

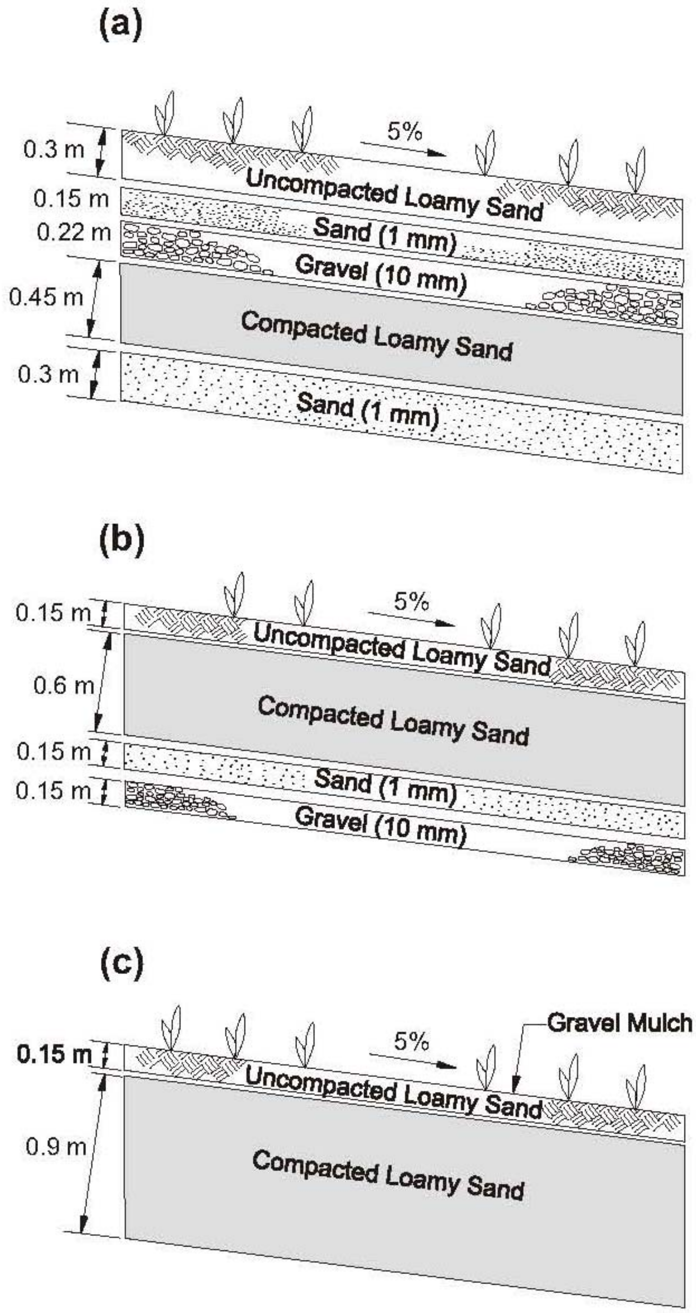

Figure 5.2: Profiles of Evapotranspirative Cover Systems at the Albuquerque, New Mexico Site: (a) Capillary Barrier; (b) Anisotropic Barrier; and (c) Monolithic Cover System.

The annualized measured water balances from 1998 to 2001 for the three cover systems are summarized in Table 5.1. Dwyer (2003) concluded that the primary difference in runoff values between cover systems was due to the inadequacies of the runoff monitoring system. The instruments occasionally malfunctioned during rainstorms because of the high flow and the frequently occurring high sediment load in the water. According to Dwyer (2003), visual observation coupled with manual backup measurements indicated that runoff was approximately equal for each cover system type.

Table 5.1: Annualized Water Balance Components (in mm/yr) Measured from 1998 through 2001 for Test Plots with Evapotranspirative Cover Systems at the Albuquerque Site. (Average Annual Precipitation = 268 mm).

Cover Type	Runoff (mm)	Drainage (mm)	Change in Storage (mm)	Evapotranspiration (mm)
Capillary Barrier	4	0.1	-8	271
Anisotropic Barrier	5	0.05	-5	268
Monolithic Cover System	3	0.06	-15	279

All of the cover system configurations exhibited small amounts of drainage that generally occurred in the spring or summer as the finer-grained soils in the cover systems became wetted after rainfall. The highest drainage rates were observed during the summer of 1997, spring of 1998, and summer of 1999. During the summer of 1997, the cover system soils were still relatively wet from construction water and vegetation was just beginning to become established. The higher drainage rates occurring in the spring of 1998 were related to a snowstorm that resulted in a snow accumulation.

In 1999, the anisotropic barrier and monolithic cover system exhibited small amounts of drainage, 0.14 and 0.01 mm, respectively, when the cover system soils became wetter after a series of precipitation events. Zero drainage was recorded from the capillary barrier.

Over time, the cover system soils became drier and, therefore, had more available storage capacity for infiltrating water. Plants also became better established. Due, at least in part, to the drying of the soils, the development of vegetation, and below average rainfall in 2000 and 2002, zero drainage was recorded for the evapotranspirative cover systems from 2000 to 2002.

For the capillary barrier, Dwyer (2003) found that the water content in the upper uncompacted soil layer fluctuated with precipitation. He also found peaks in the water content of the lower compacted soil and sand layers to lag about two to three months behind the water content peaks in the upper soil layer. Interestingly, the trend for the sand does not follow the expected trend for a capillary break. As previously discussed, if there is sufficient textural contrast at a capillary break, the upper finer-grained soil should approach saturation before water flows into the underlying coarser-grained soil. However, this does not appear to be occurring for the capillary barrier at the Albuquerque site. In other words, the water contents of the compacted soil layer and the underlying sand layer of the capillary barrier should not follow the same time trend unless the compacted soil layer is saturated (which it is not, based on the measured water contents) or there is some other mechanism that increases the water contents of these layers at the same time, such as preferential flow or the lack of textural contrast at the interface between the soil layers.

The upper uncompacted soil layer for the anisotropic barrier was thinner than the layer for the capillary barrier and experienced more extreme fluctuations in volumetric water content (ranging from 0.07 to 0.24 versus 0.13 to 0.20). The underlying compacted soil also experienced greater water content fluctuations than the uncompacted soil for the capillary barrier (approximately 0.08 to 0.22 versus 0.12 to 0.18), except at the end of the monitoring period in 2002 when the finer-grained soil component of the capillary barrier began to wet up significantly more than any other soil layer of the three evapotranspirative cover systems.

The monolithic cover system has a 0.15-m thick uncompacted soil layer at its surface, like the anisotropic barrier, and exhibited similar trends in wetting and drying as the anisotropic barrier. The volumetric water content of the uncompacted soil layer ranged from 0.14 to 0.25. Like the capillary barrier, the peaks in the water content of the compacted soil layer trailed the peaks in the measured water contents of the uncompacted soil layer by several months.

Dwyer (2003) noted that drainage from the cover systems occurred when the volumetric water content of the compacted soil layers approached 0.20. At this water content, the soil matric potential is estimated to be approximately -1 m (-10 kPa) (Figure 4.19). Interestingly, the relative storage capacity of the compacted soil layer in the capillary barrier did not appear to be enhanced by its capillary break any more than the monolithic cover system: both appeared to drain at the same volumetric water content of about 0.20. The reason for this may be that the monolithic cover system has a capillary break too, provided by the lysimeter beneath it. Further, the soil matric potential at which breakthrough occurs (-1 m (-10 kPa)) is consistent with the estimated breakthrough potential for the sand layer in the capillary barrier. As described in Section 2.2.3, the breakthrough potential at a capillary break is controlled by the coarser-grained layer and occurs approximately at the inflection point in the SWCC, where the curve is steeply sloping and the water content is tending towards zero.

The lysimeters constructed beneath each cover system essentially cause all of the evapotranspirative cover systems to have an underlying capillary break at their base. Thus, the performance of an evapotranspirative cover system with and without a capillary barrier cannot be directly compared when both cover systems are constructed directly over a drainage lysimeter with a capillary break.

Dwyer (2003) compared the measured drainage from the cover systems to the drainage calculated under unit gradient conditions using the unsaturated hydraulic conductivity corresponding to the measured soil water content. The measured drainage was two to three orders of magnitude greater than the calculated drainage during 1998. These results were interpreted by Dwyer (2003) as indicating that preferential flow was occurring. The preferential flow corresponded with ongoing ecological changes observed on the cover profiles (desiccation cracking, root intrusion, earthworm tunnels, and animal intrusion) as well as soil pedogenic processes that led to changed soil properties, e.g., increased saturated hydraulic conductivity, as demonstrated with field tension infiltrometer measurements conducted seven years after the cover systems were constructed.

5.6.2 Dwyer (2003) Evaluation of Evapotranspirative Cover Systems at Albuquerque Site

Dwyer (2003) assessed the applicability of HELP (version 3.07) and UNSAT-H (version 3.01) as design tools for cover systems and for their accurate prediction of the cover system balance at the Albuquerque site. Three types of simulations were conducted: (i) as designed, using parameters that would typically be available for design, e.g., SWCC and saturated hydraulic conductivity for site soils compacted to densities specified in the test cover design documents, expert opinion, and historical weather data (forward simulations); (ii) as constructed, using soil hydraulic properties measured in the initial or as-built condition and on-site vegetation and meteorological data collected during the monitoring period (simulations with initial soil parameters); and (iii) the same as (ii), except using soil hydraulic parameters measured at the end of the monitoring period (seven years after construction was completed) using a tension infiltrometer (simulations with final soil parameters).

For the first type of simulation (forward simulation), Dwyer (2003) compared the field water balance from 1998 to 2001 to the water balance calculated using HELP and UNSAT-H and reported the average annual values simulated for the water balance components. Weather data from the Albuquerque, New Mexico weather station for 1997 were used in a three-year simulation to calculate the antecedent water content of the cover system soils. A five-year simulation was then conducted with weather data from 1998, a relatively wet year (355 mm of precipitation versus an average of 268 mm) and soils at their calculated antecedent water content. The results of these simulations are summarized in Table 5.2. It is noted that in all simulations conducted by Dwyer (2003) the maximum rooting depth of vegetation was assumed to be 1.0 m. However, this would mean that the vegetation would extend into the highly compacted soil. In reality, plant roots would likely have been limited primarily to the 0.15 m to 0.30 m of uncompacted soil at the top of the cover system for at least a large part of the monitoring period.

Table 5.2: Annualized Results (in mm/yr) of Forward Simulations Conducted by Dwyer (2003) for Test Plots with Evapotranspirative Cover Systems at the Albuquerque Site. (Measured Average Annual Precipitation = 268 mm, Simulated Average Annual Precipitation = 355 mm).

Cover Type	Evaluation Method	Runoff (mm)	Drainage (mm)	Change in Storage (mm)	Evapotranspiration (mm)
Capillary Barrier	Measured	4	0.1	-8	271
	HELP	0.3	11	3	341
	UNSAT-H	2	0.02	6	347
Anisotropic Barrier	Measured	5	0.05	-5	268
	HELP	0.3	68	3	284
	UNSAT-H	0.02	0.0	13	342
Monolithic Cover System	Measured	3	0.06	-15	279
	HELP	0.3	70	0.7	284
	UNSAT-H	7	30	16	301

The average annual drainage measured for the capillary barrier, anisotropic barrier, and monolithic cover system was 0.1, 0.05, and 0.06 mm, respectively. The average annual drainage simulated with HELP for these cover systems was 11, 68, and 70 mm, respectively, and the average annual drainage simulated with UNSAT-H was 0.02, 0.0, and 30 mm, respectively.

Dwyer (2003) noted that the HELP and UNSAT-H simulations gave significantly different water balance results; however, this is expected as the simulations for the two models were conducted with different input data. For example, the HELP simulations were performed with HELP default material properties, and the UNSAT-H simulations were conducted with SWCCs and saturated hydraulic conductivities from laboratory testing of soils collected near the test site prior to installation of the test plots. In addition, the UNSAT-H simulations were conducted with a unit gradient lower boundary, while the cover systems have a lysimeter lower boundary in the field. All other things being equal, water balance simulations with a unit gradient lower boundary have a higher potential to exhibit drainage than simulations with a seepage face (lysimeter) lower boundary.

For the second type of simulations, Dwyer incorporated weather data from the on-site meteorological station, soil hydraulic properties measured in the laboratory during construction, and on-site vegetation observations. To better represent field conditions, a gravel layer was modeled below the evapotranspirative barrier to simulate a lysimeter boundary. This layer was not required below the capillary barrier or anisotropic barrier because their bottom layers already consisted of a coarse-grained layer. The results of these simulations are summarized in Table 5.3.

The average annual drainage simulated with HELP for the capillary barrier, anisotropic barrier, and monolithic cover system was 43, 9, and 7 mm, respectively. The average annual drainage simulated with UNSAT-H for these cover systems was 38, 23, and 0.2 mm, respectively. For all cover systems, the simulations generally underestimated runoff, (HELP to a greater degree than UNSAT-H), underestimated the decrease in storage, and overestimated drainage.

Table 5.3: Annualized Results (in mm/yr) of Simulations with As-Built Parameters Conducted by Dwyer (2003) for Test Plots with Evapotranspirative Cover Systems at the Albuquerque Site. (Measured and Simulated Average Annual Precipitation = 268 mm).

Cover Type	Evaluation Method	Runoff (mm)	Drainage (mm)	Change in Storage (mm)	Evapotranspiration (mm)
Capillary Barrier	Measured	4	0.1	-8	271
	HELP	0.07	43	-3	242
	UNSAT-H	0.5	38	1	269
Anisotropic Barrier	Measured	5	0.05	-5	268
	HELP	0.07	9	-2	294
	UNSAT-H	3	23	23	261
Monolithic Cover System	Measured	3	0.06	-15	279
	HELP	0.07	7	-0.3	287
	UNSAT-H	4	0.2	16	274

In the third type of simulations conducted by Dwyer (2003), field hydraulic properties of the loamy sand used to construct the cover systems were measured using a tension infiltrometer. The tests were conducted in the summer of 2002 at the end of the monitoring period. The results of the infiltrometer tests were used to calculate the field water retention functions and saturated hydraulic conductivities. The retention functions were used, in turn, with the initial water contents at the start of the monitoring period to recalculate the initial matric potentials at the start of monitoring. The results of these simulations are summarized in Table 5.4.

For the capillary barrier and monolithic cover system, the field measured hydraulic properties at the end of the monitoring period were generally similar to the properties measured in the laboratory at the start of construction. For the anisotropic barrier, the saturated hydraulic conductivity of the uncompacted soil layer was approximately ten times lower than that measured in the laboratory. In addition, the recalculated initial matric potentials were lower for the anisotropic barrier and monolithic cover system and higher for the compacted soil component of the capillary barrier.

Table 5.4: Annualized Results (in mm/yr) of Simulations with Final Soil Parameters Conducted by Dwyer (2003) for Test Plots with Evapotranspirative Cover Systems at the Albuquerque Site. (Measured and Simulated Average Annual Precipitation = 268 mm).

Cover Type	Evaluation Method	Runoff (mm)	Drainage (mm)	Change in Storage (mm)	Evapotranspiration (mm)
Capillary Barrier	Measured	4	0.1	-8	271
	HELP	0.07	27	30	253
	UNSAT-H	0.5	80	-11	240
Anisotropic Barrier	Measured	5	0.05	-5	268
	HELP	0.1	13	36	261
	UNSAT-H	87	0.07	16	210
Monolithic Cover System	Measured	3	0.06	-15	279
	HELP	0.07	0.0	73	237
	UNSAT-H	5	1	19	269

As expected, the simulation conducted with HELP and UNSAT-H for the anisotrophic barrier with a less permeable surface layer resulted in greater runoff. The effect of modifying the initial matric potentials was mixed. When the initial matric potentials of the compacted soil component of the capillary barrier were increased, UNSAT-H predicted a significant increase in drainage, while HELP predicted a significant decrease in drainage. When the initial matric potentials of the monolithic cover system were decreased, UNSAT-H predicted an increase in drainage, while HELP predicted zero drainage. The point is that water balances conducted over a short-time period can be strongly dependent on initial conditions.

5.6.3 Scanlon et al. (2005) Evaluation of Monolithic Cover System at Albuquerque Site

Scanlon et al. (2005) simulated the water balance of the monolithic cover system during its five-year monitoring period using UNSAT-H (version 3.01). They used the as-constructed soil hydraulic parameters reported by Dwyer (2003), an ecosystem leaf area index of 0.3 based on the vegetation data presented by Dwyer (2003), and a rooting depth of 0.75 m. Meteorological forcing was used as the upper boundary condition. Daily precipitation data were input, and precipitation was applied at a rate of 10 mm/hr. The capillary break effect of the lysimeter was modeled by including a gravel layer beneath the cover system. The lower boundary condition was specified as unit gradient.

They found good agreement between the modeling and the monitoring results. For the east subplot, 2.8 mm of runoff was measured and zero was simulated, zero drainage was measured and simulated, and measured and simulated evapotranspiration were 1354 mm and 1376 mm, respectively. Simulated changes in storage also matched measured trends, except for water year 2000 (the 12-month period from October 1, 1999 to September 30, 2000), when storage was predicted to increase, but field measurements indicated storage decreased.

5.7 SIERRA BLANCA, TEXAS TEST PLOTS

Scanlon et al. (2001, 2002, and 2005) simulated the water balance of the capillary barrier test plots at the Sierra Blanca site. Details on the design, construction, and monitoring of the test plots were presented in Section 4.5.

5.7.1 Scanlon et al. (2001) Evaluation

Scanlon et al. (2001) simulated the water balance of the capillary barrier for the 1998 water year (a 12-month period from October 1997 through September 1998) and compared the simulation results to monitoring results. Of the 427 mm of precipitation (including irrigation) that were measured, 60 mm were attributed to runoff, 41 mm were attributed to an increase in soil water storage, and the remainder was considered evaporation. Zero drainage was measured.

Seven models, including HELP (version 3.07) and UNSAT-H (version 3.0), were used in the study. The cover system profile was divided into six layers representing the different materials (Figure 4.5). Soil hydraulic properties were assumed and were based on published values for soils of similar texture.

Meteorological forcing determined the upper boundary condition, and the lower boundary condition was specified as unit gradient. Precipitation was applied with the measured hourly duration and intensity in the UNSAT-H simulations. HELP only allows input of daily precipitation and applies it over 24 hours. Scanlon et al. (2001) recognized that a seepage face lower boundary would have been more appropriate than a unit gradient boundary because the cover system was underlain by a lysimeter. However, most of the considered computer models did not explicitly allow a seepage face lower boundary. Initial conditions were based on field measurements of matric potential made with heat dissipation sensors.

Scanlon et al. (2001) found that UNSAT-H under-predicted runoff when the specified precipitation intensity was set at 10 mm/hr. When daily precipitation was applied uniformly over a 24-hour period, HELP predicted 15 mm of runoff, while UNSAT-H did not predict runoff. When precipitation is not appropriately discretized, e.g., daily precipitation is spread out uniformly over 24 hours rather than applied at the actual intensity and duration at which it occurred, runoff and evaporation will be underestimated.

Because runoff was underestimated and infiltration was, thus, overestimated for all simulations, evaporation, storage, and drainage should also be overestimated. Scanlon et al. (2001) found that evaporation predicted with UNSAT-H (335 mm) was similar to measured values. HELP, however, under-predicted evaporation (273 mm). UNSAT-H and HELP both overestimated storage (88 and 130 mm, respectively) and drainage (3 and

9 mm, respectively). Scanlon et al. (2001) attributed the simulated drainage to the unit gradient lower boundary condition used in the simulations. This boundary condition is not representative of the boundary condition of the lysimeter beneath the cover system.

5.7.2 Scanlon et al. (2002) Evaluation

Scanlon et al. (2002) compared the results of water balance simulations with seven models, including HELP (Version 3.07) and UNSAT-H (Version 3.0), to each other and to monitoring data for the Sierra Blanca cover system from the 1998 water year. This work was an expansion of the Scanlon et al. (2001) study.

In earlier simulations of the water balance at the Sierra Blanca site, Scanlon et al. (2001) used assumed hydraulic properties for the capillary barrier soils. In the 2002 publication, SWCCs determined from laboratory tests were used for all soils. The saturated hydraulic conductivity of the uncompacted soil was determined from field tests with a Guelph permeameter. The saturated hydraulic conductivity of the sand was evaluated in the laboratory. Although the saturated hydraulic conductivity of the compacted soil was measured in the laboratory and field (Table 4.8), water balance simulations conducted using the mean measured hydraulic conductivities (2.1×10^{-9} to 2.2×10^{-8} m/s) for the compacted soil did not adequately predict the measured water balance. Therefore the saturated hydraulic conductivity of the compacted soil presumed for the Scanlon et al. (2001) study was also used in the Scanlon et al. (2002) study. The presumed hydraulic conductivity of 1.1×10^{-6} m/s is 50 times greater than the mean hydraulic conductivity of 2.2×10^{-8} m/s measured in the field. Scanlon et al. (2002) indicated that the difference between the saturated hydraulic conductivity of the compacted soil measured in the field and the apparent saturated hydraulic conductivity of the soil based on model calibrations might be related to scaling issues, i.e., a representative sample size of the soil for saturated hydraulic conductivity was not tested.

Meteorological forcing was used as the upper boundary condition. Precipitation was applied in UNSAT-H at its measured hourly duration and intensity. The lower boundary condition was specified as unit gradient.

Both HELP and UNSAT-H underestimated runoff. HELP predicted 15 mm and UNSAT-H predicted zero. To correct for under-prediction of runoff and to assess how well the models partition the different water balance components when runoff is adequately estimated, simulations were performed using net precipitation, defined as precipitation minus runoff. The results of the simulations with net precipitation are summarized in Table 5.5.

Table 5.5: Measured and Simulated Water Balance Components for the Sierra Blanca Site Presented by Scanlon et al. (2002) (Net Precipitation = 367 mm, Calculated Potential Evaporation = 1,640 mm).

Evaluation Method	Precipitation Duration and Intensity	Runoff (mm)	Evapotrans. (mm)	Change in Storage (mm)	Drainage (mm)
Measured		0	326	41	0
UNSAT-H	Hourly Precipitation at Measured Intensity	0	299	66	3
	Daily Precipitation at 10 mm/hr	0	297	67	3
	Daily Precipitation over 24 hours	0	180	184	3
	Net Precipitation over 24 hours	0	344	20	3
HELP	Daily Precipitation over 24 hours	0	215	142	9
UNSAT-H with isothermal vapor flow	Hourly Precipitation at Measured Intensity	0	301	64	3
UNSAT-H with hysteresis	Hourly Precipitation at Measured Intensity	0	307	58	3

HELP and UNSAT-H both predicted small amounts of drainage (9 mm and 3 mm, respectively) even though none was measured. UNSAT-H slightly underestimated evaporation and, therefore, overestimated storage. HELP significantly underestimated evaporation and significantly overestimated storage. Scanlon et al. (2002) suggested that the differences between the measured and simulated water balances may be the result of the wet initial conditions, the idealized initial conditions, i.e., the assumed matric potential profiles, and other factors.

Additional simulations with UNSAT-H were conducted by Scanlon et al. (2002) to evaluate the effects of precipitation intensity, isothermal vapor flow, and hysteresis on the simulated water balance. When daily precipitation was applied at a rate of 10 mm/hr rather than at its measured hourly intensity, there was essentially no change in the simulated water balance. This result suggests that using daily precipitation data and a precipitation intensity of 10 mm/hr is appropriate when there is no runoff (Scanlon et al., 2002). When daily precipitation was applied over 24 hours, evaporation was underestimated and drainage was overestimated. When net precipitation (precipitation minus potential evaporation) was applied as the upper boundary condition, evaporation was overestimated and drainage was underestimated.

Including isothermal vapor flow or hysteresis had a negligible effect on the simulated water balance.

5.7.3 Scanlon et al. (2005) Evaluation

Scanlon et al. (2005) used UNSAT-H (version 3.01) to simulate the water balance of the capillary barrier during water year 2000 (defined as the 12-month period from October 1, 1999 to September 30, 2000) when the cover system was vegetated. Only the first three layers of the capillary barrier were modeled to reduce computation time and because zero drainage was recorded.

Hydraulic parameters for the soils were the same as those used in the Scanlon et al. (2002) study. The rooting depth was assumed to be 0.75 m, and the vegetation was assumed to have an ecosystem leaf area index of 0.1. Meteorological forcing was used as the upper boundary condition. Daily precipitation was input at the measured hourly intensity. The capillary break beneath the upper sand was modeled by adding a gravel layer beneath the sand layer. The lower boundary condition was specified as unit gradient.

Only 130 mm of precipitation were recorded for the site in 2000. Even so, a small amount of runoff (8.2 mm) was measured. Storage decreased (-13 mm), and zero drainage was recorded.

In the initial simulations of the water balance, runoff was underestimated. To better simulate runoff, the uncompacted soil was assumed to have a 50-mm thick surface crust with a 44% lower hydraulic conductivity than the un-crusted uncompacted soil. By incorporating a surface crust, Scanlon et al. (2005) found good agreement between the modeling and the monitoring results for this calibrated simulation: 8.2 mm of runoff were measured and 8.1 mm were simulated, zero drainage was measured and simulated, and 131 mm of evapotranspiration was measured and 130 mm was simulated.

5.8 SUMMARY AND SYNTHESIS

The results of selected field studies of evapotranspirative cover systems that included water balance simulations using HELP or UNSAT-H were summarized in this chapter. Conclusions drawn from these studies are as follows:

- Modeling, together with monitoring, is being used to demonstrate that drainage through evapotranspirative cover systems is small. For the cover systems described in this chapter, average annual drainage must be limited to values in the range of 5 to 10 mm/yr.
- Even with simplified and carefully controlled experimental conditions, such as exist with the weighing and drainage lysimeters at the DOE Hanford Site, it is difficult to accurately simulate the field water balance of evapotranspirative

cover systems. Part of the inaccuracy may be attributed to the methods used by the computer models to analyze the different water balance processes, e.g., the unit gradient assumption for vertical drainage layers coded in HELP. The inaccuracy may also be related to the difficulty in estimating key design parameters, such as unsaturated hydraulic conductivity as it varies with water contents measured in the field or even the saturated hydraulic conductivity existing in the field. These parameters are expected to change with time. As demonstrated by Benson et al. (2005), the saturated hydraulic conductivity of soils in an evapotranspirative cover system may increase by several orders of magnitude within a few years after construction.

- Runoff was not accurately predicted by HELP or UNSAT-H in any of the studies. If runoff is significantly overestimated or underestimated, infiltration into the cover system will not be accurately predicted and the remaining water balance components will not be accurately estimated.
- Frozen ground, snow pack, and snow melt can have a significant impact on runoff and needs to be carefully considered in simulations (Fayer et al., 1992; Khire et al., 1995).
- Some studies found that UNSAT-H generally underestimated runoff (Scanlon et al., 2002), and other studies found the opposite (Roesler et al., 2002; Benson et al., 2005). Part of the differences between measured and simulated runoff have been attributed to not being able to accurately assess the hydraulic conductivity of the surface layer and to not using the true precipitation intensity in the model.
- Model calibrations are typically performed by increasing saturated hydraulic conductivity until the simulated water balance approximately equals the

measured water balance. Because it is difficult to calibrate a model to simultaneously fit multiple water balance components, e.g., runoff and storage, calibrations often focus on one component, e.g., storage. For the cover system evaluations described in this chapter, calibrations with UNSAT-H required that saturated hydraulic conductivities be increased by factors of up to approximately 50 (Fayer et al., 1992; Gee and Fayer, 1997; Scanlon et al., 2002; Benson et al., 2005).

- Based on the studies by Scanlon et al. (2002) and Benson et al. (2005), at sites where significant runoff is anticipated, it is important to appropriately discretize precipitation, e.g., apply precipitation at its measured hourly intensity and duration. However, for cover systems with shallow slopes and relatively permeable surface layers that exhibit negligible runoff in relation to the amount of water infiltrating the cover system, applying daily precipitation at an intensity of 10 mm/hr may be sufficient, i.e., applying precipitation at a lower intensity has negligible effect on the simulated water balance.
- As demonstrated by Dwyer (2003), the assumed initial matric potential profile for a cover system can have a significant effect on the short-term water balance of a cover system. The exact matric potential profile in a cover system at a specific time is not known because matric potentials are only measured at limited intervals within the cover system. In addition, matric potential profiles are sometimes developed from water content profiles using the SWCC, which leads to more uncertainty in the profiles.
- Fayer et al. (1992) and Fayer and Gee (1997) found that hysteresis should be considered when simulating the water balance of capillary barriers. The layering sequence of capillary barriers promotes increased water storage in the

soil above a capillary break and the manifestation of hysteresis. If hysteresis is not considered, drainage may be under-predicted in simulations with UNSAT-H.

- Scanlon et al. (2002) did not find hysteresis to significantly influence the water balance of the Sierra Blanca cover system simulated with UNSAT-H. Hysteresis did, however, decrease the predicted storage and increase the predicted drainage for the Idaho cover system. Hysteresis may not have been important for the Sierra Blanca cover system because, based on water content and matric potential measurements, water was not moving deeply enough into the soil profile to be affected by the sand capillary break. In contrast, the Idaho cover system had exhibited drainage. Hysteresis was important for the Idaho cover system apparently because water movement through this cover system had been affected by the capillary break of the underlying lysimeter.
- If a capillary break is present, even in the form of a lysimeter beneath the cover system, the effect of the capillary break should be considered. If water is moving deep enough into the cover system profile to be affected by the capillary break, the capillary break should be incorporated into water balance modeling.
- HELP usually under-predicted storage and over-predicted drainage for the sites considered. The discrepancy between simulated and measured drainage is generally greater for capillary barriers and cover systems underlain by lysimeters because water movement through these systems is greatly affected by matric potential gradients and HELP only considers unit gradient conditions (Fayer and Gee, 1997; Scanlon et al., 2001; Roesler et al., 2002; Dwyer, 2003).

- UNSAT-H sometimes over-predicts and sometimes under-predicts drainage. The model performs especially well when soil hydraulic properties are calibrated to measured soil water storage.
- Drainage is the key parameter for cover system performance. For the studies considered, drainage was sometimes under-predicted and even predicted to be zero with UNSAT-H, except when model calibrations were performed (Fayer et al., 1992; Fayer and Gee, 1997; Scanlon et al., 2001; Roesler et al., 2002; Scanlon et al., 2002; Benson et al., 2005).

Chapter 6: Short-Term Performance Assessment -- Comparison of Numerical Modeling Results and Monitoring Results for Study Sites

6.1 OVERVIEW

6.1.1 Scope of Short-Term Performance Assessment

The water balances of the evapotranspirative cover systems at the Yucaipa, Albuquerque, and Sierra Blanca sites were simulated during their 30 to 60-month monitoring periods using HELP, LEACHM, and UNSAT-H. The purpose of the simulations was to evaluate the short-term (2 to 5-year) performances of the cover systems and perform a process validation of the models when used for design with measured input parameters, to the extent available, and without calibration. The input data used for the numerical simulations and the results of the simulations, including a comparison of the simulated and measured water balances, are described in this chapter.

The water balance simulations for the Albuquerque site differ primarily from those presented by Dwyer (2003) and Scanlon et al. (2005) in that a simulation with LEACHM was also conducted. The water balance simulations for the Sierra Blanca site primarily differs from those presented by Scanlon et al. (2001, 2002, and 2005) in that the saturated hydraulic conductivity of the compacted soil measured in the field (2.2×10^{-8} m/s), rather than the saturated hydraulic conductivity calibrated to measured soil water storage (2.3×10^{-6} m/s), was used. In addition, the Sierra Blanca simulations were conducted with three years of weather data and included simulations with HELP and LEACHM. The Scanlon et al. (2001, 2002) studies also used the HELP model, but only considered a one-year simulation period.

6.1.2 The Need for Model Calibration

While calibrations are typically performed for groundwater modeling because of heterogeneities and uncertainties in the stratigraphy and hydraulic properties of naturally placed subsurface materials and because of uncertainties in recharge, there is a desire in the engineering community to be able to model the water balance of engineered covers without model calibration and obtain reasonable solutions. With engineered covers, thicknesses of the different materials are well defined and the hydraulic properties presumably can be characterized.

There have been attempts to calibrate water balance models with field data and use these calibrated models to predict the future water balance, i.e., forward modeling. Fayer and Gee (1997) presented this approach for small-scale lysimeter experiments. The lysimeters were bare, without vegetation, and the conditions were much better defined than for the three monitored cover systems evaluated herein. Nonetheless, they found a calibrated model no more successful at predicting a water balance than an uncalibrated model.

The real benefit of calibrating a model to field data is to better understand the important processes at a given time (Fayer and Gee, 1997). However, there is generally not a unique solution to this calibration, and when there are few data for the calibration, there is a greater likelihood that the solution may not be correct. For example, the only water balance parameter collected for the evapotranspirative cover system at the Yucaipa site was soil water storage (Figure 4.14), which is based on water content measurements made with segmented TDR probes (Figures 4.12 and 4.13). As described in Section 4.3.3, the differences between laboratory and field measured water contents for different segments of the TDR probes make it difficult to assess the absolute water content of the cover system at the Yucaipa site (Figures 4.14, 4.15, and 4.17) or even absolute changes in water content. There are at least several ways model input parameters could be modified to simulate the storage profiles shown in Figure 4.16.

Although more of the major water balance components were measured at the Albuquerque site than at the Yucaipa site, there is also significant uncertainty with calibrating water balance models to field data, primarily storage, from the former site. For example, there are only three depths within the cover system profile where water contents were measured. The lack of data and the need to relate initial water content to initial matric potentials using a SWCC make it difficult to develop a reasonably accurate profile of initial matric potentials. Besides the spatial variability of the measured soil water contents along the slope of the Albuquerque subplots (Figures 4.23 and 4.24), which make it difficult to determine the appropriate measured water content to use for calibration, the Albuquerque cover system is underlain by a pan lysimeter. The capillary break caused by the lysimeter boundary may make hysteresis more important in the water balance. If hysteresis is important, then it should be considered in the model calibration. However, most water balance models do not consider hysteresis or only consider a simple hysteresis model. In addition, unless field matric potential and water content measurements are made and desorption, sorption, and scanning curves are defined, it is not known which retention curve a soil is tracking.

The Sierra Blanca site had more extensive instrumentation than the Yucaipa and Albuquerque sites. All of the major water balance components were measured, and the matric potential of the soil was monitored. Scanlon et al. (2002) conducted numerical modeling of the water balance for the site and found that hysteresis had a negligible effect on the water balance. In addition, neutron probe measurements indicated water was not moving deep enough into the soil profile to be affected by the sand capillary break. Of the three study sites, this site is most appropriate for model calibration, i.e., there are fewer uncertainties in input parameters. The studies by Scanlon et al. (2001, 2002, and 2005) were all conducted with a calibrated model.

With the exception of cover system monitoring at DOE sites, the field monitoring programs that have been implemented at a number of sites with evapotranspirative cover systems do not have sufficient data to allow for unique model calibrations. In addition, the calibration parameters will change over time. Therefore, the water balance simulations presented herein for the three study sites were all conducted with uncalibrated models.

6.2 MODEL INPUT

6.2.1 Overview of Input Parameters

The information required as input for the HELP, LEACHM, and UNSAT-H models includes soils, vegetation, hydrologic, climatologic, and modeling data. The input data used to simulate the water balances for the cover systems at the Yucaipa, Albuquerque, and Sierra Blanca sites are summarized in Tables 6.1 to 6.3, respectively, and briefly described below. Also included in these tables is the range of values that may be reasonably expected in the long term, for example 1,000 years, for key parameters. The cover system profiles for the three sites are shown in Figure 4.5.

Input data measured in the laboratory or in the field were used to the greatest extent possible. When site-specific measured data were not available, input parameters were obtained from the literature.

Table 6.1: Input Data for Yucaipa Test Plot.

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Soils Data			
Number of Layers, Layer Thickness (m)	1, 1.20	Specified	All
Saturated Water Content (-)	0.25 (0.387 ± 0.085)	Representative: pressure plate test Range (mean ± σ): Schaap and Leij (1998) combined database for sandy loam with bulk density (mean ± σ) = 1.46 ± 0.26 Mg/m^3	All
Residual Water Content (-)	0.0	Assumed to develop SWCCs	UNSAT-H
van Genuchten Parameters for SWCC and Hydraulic Conductivity Function with Mualem (ℓ = 0.5), α (mm^{-1}), n (-)	α (log(|α|)) = -0.00159 (-2.57 ± 0.56) n (log (n)) = 1.21 (log(0.16 ± 0.11))	Representative: pressure plate test and SOLVER Range (mean ± σ): same as above	UNSAT-H
Campbell Parameters for SWCC and Hydraulic Conductivity Function with Burdine (p=1), h_b (mm), λ (-)	h_b = -393 λ = 0.189	van Genuchten function and SOLVER	LEACHM
Water Content at Field Capacity (-) and Wilting Point (-)	0.172 0.079	Calculated from van Genuchten SWCC	HELP
Matric Potential at Wilting Point (m)	-150	Assumed for annual grasses	LEACHM, UNSAT-H
Initial Water Content (-)	0.10 to 0.21 (0.163 profile average used in HELP)	Based on TDR measurements at Station A on 12/31/1997 (simulation day 0)	HELP
Initial Matric Potential (m)	-39 to -0.8	Calculated from initial water contents and van Genuchten SWCC	LEACHM, UNSAT-H
Depletion Matric Potential (m)	-15	Based on Allen et al. (1998) with depletion fraction of 0.5	UNSAT-H
Anaerobiosis Matric Potential (m)	-0.5	Calculated at 90% saturation with van Genuchten SWCC	UNSAT-H

Table 6.1: Input Data for Yucaipa Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Soils Data (cont.)			
Saturated Hydraulic Conductivity (m/s)	k_s ($\log(k_s)$) = 8.7 x 10^{-8} (-5.39 ± 0.18)	Representative: 10 x BAT geometric mean Range (mean ± σ): Schaap and Leij (1998) combined database for sandy loam with bulk density (mean ± σ) = 1.55 ± 0.18 Mg/m^3	All
Vegetation Data			
Evaporative Zone Depth (m)	0.45	Based on field water content measurements, root depth, and HELP guidance on evaporative depths for sand and silt	HELP
Vegetation Quality	Fair grass	Site observations	HELP
Root Depth (m)	0.13	Site observations	LEACHM, UNSAT-H
Root Length Density Function Parameters (-)	f = 0.91, g = 0.011 mm^{-1}, i = 0.07 (Equation A.5)	Winkler (1999) for ripgut brome (*Bromus* sp.) in Sacramento, CA	UNSAT-H
Root Resistance (-)	1.05	Hutson (2003)	LEACHM
Minimum Root Potential (m)	-300	Hutson (2003)	LEACHM
Maximum Leaf Area Index (-) (Ecosystem, with Bare Area Fraction = 0)	1.35	Site observations (HELP default maximum value for Los Angeles, CA = 2.0)	HELP, UNSAT-H
Crop Cover Fraction (-)	0.90	Site observations	LEACHM
Growing Season, 0 °C Limit (Julian Day)	85-346 (start: 20-128, end: 282-361)	Rep: Site temperature data Range: Historical weather data for Beaumont, CA (7/1/1948-2/28/2004)	HELP, UNSAT-H
Germination, Emergence, Maturity, and Harvest Dates (Julian Day)	85, 95, 115, 346	Based on growing season	LEACHM
LAI Versus Julian Day Function	0 at day 85, 1.35 at days 115 to 316, 0 at day 346	Assumed for annual vegetation	UNSAT-H
Maximum Actual Transpiration: Potential Transpiration (-)	1.1	Hutson (2003)	LEACHM

Table 6.1: Input Data for Yucaipa Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Hydrologic Data			
SCS Runoff Curve Number (-)	76.3	Based on slope inclination (50%), length (6 m from slope crest to monitoring station), HELP soil texture (#6), and fair vegetation	HELP
	74.6	HELP value without slope correction	LEACHM
Climatological Data			
Precipitation, Air Temperature, Solar Radiation	Measured	On-site meteorological station, daily values	HELP, UNSAT-H
Precipitation Intensity (mm/hr)	Hourly intensity	On-site meteorological station, average hourly for LEACHM and hourly for UNSAT-H	LEACHM UNSAT-H
Wind Speed	Measured	On-site meteorological station, daily values	UNSAT-H
Dew Point Temperature	Calculated	On-site meteorological station, daily values	UNSAT-H
Average Quarterly Relative Humidity (%)	60.0, 59.8, 42.9, 35.4	On-site meteorological station	HELP
Average Wind Speed (km /hr)	6.4	On-site meteorological station	HELP
Potential Evapotranspiration	Calculated with UNSAT-H	On-site meteorological station	LEACHM
Latitude (degrees)	34.05	Topographic map	HELP
Altitude (m)	800	Topographic map	UNSAT-H
Soil Surface Albedo (-)	0.3 (HELP uses 0.23 internally)	Hillel (1998)	UNSAT-H
Modeling Data			
Boundary Conditions			
Upper	Meteorological forcing		All
Lower	Unit gradient		All
Number of Nodes	22 77		LEACHM UNSAT-H

Table 6.2: Input Data for Albuquerque Test Plot.

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Soils Data			
Number of Layers, Layer Thickness (m)	2, 0.15, 0.90	Specified	All
Saturated Water Content (-)	0.39 (0.390 ± 0.070) 0.32 (0.390 ± 0.070)	Representative: tension infiltrometer test Range (mean ± σ): Schaap and Leij (1998) combined database for loamy sand with bulk density (mean ± σ) = 1.52 ± 0.19 Mg/m^3	All
Residual Water Content (-)	0.0	Assumed to develop SWCCs	UNSAT-H
van Genuchten Parameters for SWCC and Hydraulic Conductivity Function with Mualem (ℓ = 0.5), α (mm^{-1}), n (-)	α (log(|α|)) = -0.00723 (-2.46 ± 0.47) n (log (n)) = 1.371 (log(0.24 ± 0.16)) α (log(|α|)) = -0.00269 (-2.46 ± 0.47) n (log (n)) = 1.264 (log(0.24 ± 0.16))	Representative: pressure plate test and SOLVER Range (mean ± σ): same as above	UNSAT-H
Campbell Parameters for SWCC and Hydraulic Conductivity Function with Burdine (p=1), h_b (mm), λ (-)	h_b = -70.7, -226 λ = 0.302, 0.236	van Genuchten function and SOLVER	LEACHM
Water Content at Field Capacity (-) and Wilting Point (-)	0.118, 0.174 0.029, 0.065	Calculated from van Genuchten SWCC	HELP
Matric Potential at Wilting Point (m)	-200	Assumed for perennial grasses	LEACHM, UNSAT-H
Initial Water Content (-)	0.20, 0.16-0.17 (0.176 profile average used in HELP)	Based on TDR probe measurements for east subplot on 9/30/97 (simulation day 0)	HELP
Initial Matric Potential (m)	-0.8, -4 to -2	Calculated from initial water contents and van Genuchten SWCC	LEACHM, UNSAT-H
Depletion Matric Potential (m)	-12, -15	Based on Allen et al. (1998) with depletion fraction of 0.5	UNSAT-H

Table 6.2: Input Data for Albuquerque Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Soils Data (cont.)			
Anaerobiosis Matric Potential (m)	-0.08, -0.25	Calculated at 90% saturation with van Genuchten SWCC	UNSAT-H
Saturated Hydraulic Conductivity (m/s)	k_s ($\log(k_s)$) = 1.2×10^{-5}, 4.7×10^{-7} (-6.89 ± 0.64)	Representative: tension infiltrometer test Range (mean ± σ): Schaap and Leij (1998) combined database for loamy sand with bulk density (mean ± σ) = 1.53 ± 0.19 Mg/m^3	All
Vegetation Data			
Evaporative Zone Depth (m)	0.45	Based on field water content measurements, root depth, and HELP guidance on evaporative depths for sand and silt	HELP
Vegetation Quality	Poor grass	Site observations	HELP
Root Depth (m)	0.15	Assumed to penetrate depth of uncompacted soil	LEACHM, UNSAT-H
Root Length Density Function Parameters (-)	f = 0.54, g = 0.008 mm^{-1}, i = 0.14 (Equation A.5)	Winkler (1999) for black grama (*Bouteloua eriopoda*) in Jornada, NM	UNSAT-H
Relative Root Length Density (-)	0.43 (0 to 50 mm), 0.32 (50 to 100 mm), 0.25 (100 to 150 mm)	Based on above root length density function	LEACHM
Root Resistance (-)	1.05	Hutson (2003)	LEACHM
Minimum Root Potential (m)	-300	Hutson (2003)	LEACHM
Maximum Leaf Area Index (-) (Ecosystem, with Bare Area Fraction = 0)	0.32	Site measurements (HELP default maximum value for Albuquerque, NM = 1.2)	HELP, UNSAT-H
Crop Cover Fraction (-)	0.18	Site measurements	LEACHM
Growing Season, 0 °C Limit (Julian Day)	105-290 (start: 147-272, end: 75-298)	Rep: Site temperature data Range: Historical weather data for Albuquerque, NM (1931-1990)	HELP, LEACHM, UNSAT-H
LAI Versus Julian Day Function	0 at day 105, 0.32 at days 165 to 260, 0 at day 290	Assumed for perennial vegetation	UNSAT-H
Maximum Actual Transpiration: Potential Transpiration (-)	1.1	Hutson (2003)	LEACHM

Table 6.2: Input Data for Albuquerque Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Hydrologic Data			
SCS Runoff Curve Number (-)	88.0	Based on slope inclination (5%), length (46 m from slope crest to collection point), HELP soil texture (#9), and poor vegetation	HELP, LEACHM
Climatological Data			
Precipitation, Air Temperature, Solar Radiation	Measured	On-site meteorological station, daily values	HELP, UNSAT-H
Precipitation Intensity (mm/hr)	1 mm/hr (average) (10 mm/hr gives approx. same results)	On-site meteorological station, 1-hour recording interval	LEACHM UNSAT-H
Wind Speed	Measured	On-site meteorological station, daily values	UNSAT-H
Dew Point Temperature	Calculated	On-site meteorological station, daily values	UNSAT-H
Average Quarterly Relative Humidity (%)	50.6, 31.5, 47.4, 52.8	On-site meteorological station	HELP
Average Wind Speed (km /hr)	10.8	On-site meteorological station	HELP
Potential Evapotranspiration	Calculated with UNSAT-H	On-site meteorological station	LEACHM
Latitude (degrees)	35.0	Topographic map	HELP
Altitude (m)	1,620	Topographic map	UNSAT-H
Soil Surface Albedo (-)	0.3 (HELP uses 0.23 internally)	Hillel (1998)	UNSAT-H
Modeling Data			
Boundary Conditions Upper Lower	 Meteorological forcing Unit gradient Seepage face		 All HELP, UNSAT-H LEACHM
Number of Nodes	97 (28 for 0.1 m gravel at base to model lysimeter boundary) 23		UNSAT-H LEACHM

Table 6.3: Input Data for Sierra Blanca Test Plot.

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Soils Data			
Number of Layers, Layer Thickness (m)	3, 0.3, 1.7, 0.3	Specified	All
Saturated Water Content (-)	0.45 (0.384 ± 0.061) 0.35 (0.384 ± 0.061) 0.40 (0.375 ± 0.055)	Representative: pressure plate test Range (mean ± σ): Schaap and Leij (1998) combined database for sandy clay loam with bulk density (mean ± σ) = 1.57 ± 0.18 Mg/m^3 and for sand with bulk density = 1.53 ± 0.12 Mg/m^3	All
Residual Water Content (-)	0.0	Assumed to develop SWCCs	UNSAT-H
van Genuchten Parameters for SWCC and Hydraulic Conductivity Function with Mualem (ℓ = 0.5), α (mm^{-1}), n (-)	α (log(|α|)) = -0.0026 (-2.68 ± 0.71) n (log (n)) = 1.276 (log(0.12 ± 0.12)) α (log(|α|)) = -0.0020 (-2.68 ± 0.71) n (log (n)) = 1.166 (log(0.12 ± 0.12)) α (log(|α|)) = -0.0020 (-2.45 ± 0.25) n (log (n)) = 1.464 (log(0.50 ± 0.18))	Representative: pressure plate test and SOLVER Range: same as above	UNSAT-H
Campbell Parameters for SWCC and Hydraulic Conductivity Function with Burdine (p=1), h_b (mm), λ (-)	h_b = -237, -294, -265 λ = 0.243, 0.149, 0.373	van Genuchten function and SOLVER	LEACHM
Water Content at Field Capacity (-) and Wilting Point (-)	0.244, 0.251, 0.161 0.087, 0.135, 0.028	Calculated from van Genuchten SWCC	HELP
Matric Potential at Wilting Point (m)	-200	Assumed for perennial grasses	LEACHM, UNSAT-H
Initial Water Content (-)	0.096, 0.17-0.26, 0.18 (0.181 profile average used in HELP)	Calculated from initial matric potential and van Genuchten SWCC	HELP
Initial Matric Potential (m)	-107, -107 to -3, -3	Based on heat dissipation sensor measurements on 10/1/97 (simulation day 1)	LEACHM, UNSAT-H
Depletion Matric Potential (m)	-14, -17, -11	Based on Allen et al. (1998) with depletion fraction of 0.5	UNSAT-H

Table 6.3: Input Data for Sierra Blanca Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Soils Data (cont.)			
Anaerobiosis Matric Potential (m)	-0.25, -0.50, -0.25	Calculated at 90% saturation with van Genuchten SWCC	UNSAT-H
Saturated Hydraulic Conductivity (m/s)	k_s ($\log(k_s)$) = 1.9 x 10^{-6}, 2.2 x 10^{-8}, 7.4 x 10^{-5} (-5.82 ± 0.59, -4.12 ± 0.59)	Representative: geometric mean from Guelph permeameter, sealed double ring infiltrometer, and rigid wall permeameter respectively Range (mean ± σ): Schaap and Leij (1998) combined database with bulk density (mean ± σ) = 1.59 ± 0.18 Mg/m^3 for sandy clay loam and 1.53 ± 0.13 Mg/m^3 for sand	All
Vegetation Data			
Evaporative Zone Depth (m)	0.60	Based on field water content measurements, root depth, and HELP guidance on evaporative depths for sand and silt	HELP
Vegetation Quality	Poor grass	Site observations	HELP
Root Depth (m)	0.3	Assumed to penetrate depth of uncompacted soil	LEACHM, UNSAT-H
Root Length Density Function Parameters (-)	f = 0.54, g = 0.008 mm^{-1}, i = 0.14 (Equation A.5)	Winkler (1999) for black grama (*Bouteloua eriopoda*) in Jornada, NM	UNSAT-H
Relative Root Length Density (-)	0.49 (0 to 100 mm), 0.30 (100 to 200 mm), 0.21 (200 to 300 mm)	Based on above root length density function	LEACHM
Root Resistance (-)	1.05	Hutson (2003)	LEACHM
Minimum Root Potential (m)	-300	Hutson (2003)	LEACHM
Maximum Leaf Area Index (-) (Ecosystem, with Bare Area Fraction = 0)	0.09	Site observations (HELP default maximum value for El Paso, Texas = 1.2)	HELP, UNSAT-H
Crop Cover Fraction (-)	0.40	Site observations	LEACHM
Growing Season, 0 °C Limit (Julian Day)	80 - 321 (91-303, 58-337)	Rep: Site temperature data Range: Historical weather data for El Paso, TX (1961-1990)	HELP, LEACHM, UNSAT-H

Table 6.3: Input Data for Sierra Blanca Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Vegetation			
LAI Versus Julian Day Function	0 at day 80, 0.09 at days 140 to 291, 0 at day 321	Based on growing season	UNSAT-H
Maximum Actual Transpiration: Potential Transpiration (-)	1.1	Hutson (2003)	LEACHM
Hydrologic Data			
SCS Runoff Curve Number (-)	94.3, 86.9	Based on slope inclination (2%), length (17 m from slope crest to monitoring station), HELP soil texture (#10), and bare ground/fair grass	HELP, LEACHM
Climatological Data			
Precipitation, Air Temperature, Solar Radiation	Measured	On-site meteorological station, daily values	HELP, UNSAT-H
Precipitation Intensity (mm/hr)	Measured (1 mm/hr gives approx. same results as 10 mm/hr)	On-site meteorological station, 1-hour recording interval	LEACHM, UNSAT-H
Wind Speed	Measured	On-site meteorological station, daily values	UNSAT-H
Dew Point Temperature	Calculated	On-site meteorological station, daily values	UNSAT-H
Average Quarterly Relative Humidity (%)	67.3, 58.3, 31.6, 67.4,	On-site meteorological station	HELP
Average Wind Speed (km /hr)	6.7	On-site meteorological station	HELP
Potential Evapotranspiration	Calculated with UNSAT-H	On-site meteorological station	LEACHM
Latitude (degrees)	31.15	Topographic map	HELP
Altitude (m)	1,340	Topographic map	UNSAT-H
Soil Surface Albedo (-)	0.3 (Note that HELP uses 0.23 internally)	Hillel (1998)	UNSAT-H

Table 6.3: Input Data for Sierra Blanca Test Plot (cont.).

Parameter	Representative Value (Representative Long-Term Range)	Reference	Model
Modeling Data			
Boundary Conditions Upper Lower	 Meteorological forcing Unit gradient Seepage face		 ALL HELP, UNSAT-H LEACHM
Number of Nodes	137 (23 for 0.1 m gravel at base to model lysimeter boundary) 25		UNSAT-H LEACHM

6.2.2 Soils Data

Soils data required for the simulations primarily consist of the parameters for water retention and hydraulic conductivity functions, the water content at certain matric potentials, i.e., standard field capacity [-3.3 m (-33 kPa)] and standard wilting point [-150 m (-1500 kPa)], and the matric potentials corresponding to the vegetative conditions, i.e., depletion and anaerobiosis. The depletion matric potential is the matric potential below which transpiration starts to decrease due to water stress. The anaerobiosis matric potential is the matric potential above which transpiration ceases because water has displaced air in the soil voids and anaerobic conditions prevail.

For all sites, desorption SWCCs (Figures 4.8, 4.19, and 4.28) were developed from laboratory or field data. Hydraulic conductivity functions (Figures 4.9, 4.20, and 4.29) were estimated using the water retention function parameters and the saturated hydraulic conductivities measured in the laboratory or field. The van Genuchten SWCCs were used for the UNSAT-H simulations. The van Genuchten SWCCs were also used to calculate soil water contents at standard field capacity and standard wilting point, which are required for HELP, and to calculate matric potentials corresponding to depletion and anaerobiosis.

Saturated hydraulic conductivities used to develop the hydraulic conductivity functions were representative of field test results, if available, otherwise laboratory test results were used. Hydraulic conductivities determined from field tests were considered more likely to be representative of in-situ soil structure than hydraulic conductivities determined in the laboratory for samples compacted in the laboratory or for small, i.e., 76-mm diameter, thin-walled tube samples collected from the field.

The Campbell (1974) hydraulic conductivity function with the Burdine (1953) pore-size distribution model was used for the HELP and LEACHM simulations, and the van Genuchten hydraulic conductivity function with the Mualem (1976) pore-size distribution model was selected for the UNSAT-H simulations.

The initial conditions of soil required for the simulations, i.e., initial water content for HELP and initial matric potential for LEACHM and UNSAT-H, were developed from monitoring data on the day prior to the simulation start date or the simulation start date. Initial water contents for the Yucaipa and Albuquerque cover systems were determined from field measurements with TDR probes. Initial matric potentials for these cover systems were calculated from initial water contents using the van Genuchten SWCCs. For the Sierra Blanca cover system, initial matric potentials were determined from measurements by heat dissipation sensors. Initial water contents for the Sierra Blanca cover system were calculated from initial matric potentials using the van Genuchten SWCCs.

Initial water content and matric potential profiles required for the simulations were developed assuming that measured water contents and matric potentials varied essentially step-wise with depth. As previously discussed, the actual distribution of water contents and matric potentials with depth is uncertain. The matric potential profiles used for the UNSAT-H simulations are shown in Figures 6.1 to 6.3. The matric potential profiles used for the LEACHM simulations were similar, except that matric potentials could only be defined at equally spaced depths in the soil profile. The average water content in the soil profile was used as the initial water content condition for the HELP simulations.

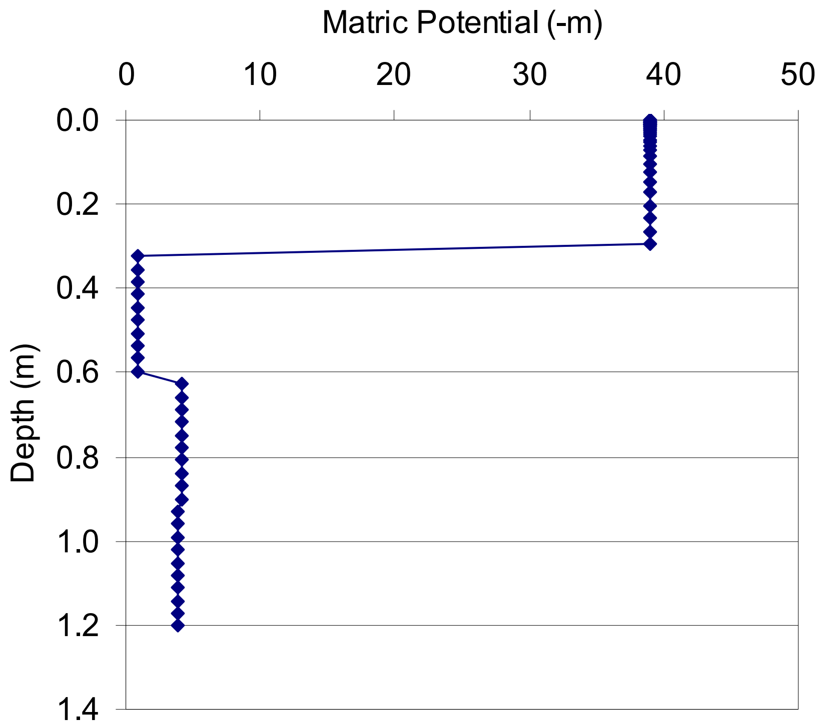

Figure 6.1: Profile of Matric Potentials Used in UNSAT-H as Initial Conditions for the Yucaipa Monolithic Cover System.

From a comparison of these figures, the Albuquerque cover system had the highest initial matric potentials and the Sierra Blanca cover system exhibited the lowest initial matric potentials. The matric potential profiles for all cover systems included relatively wet intervals with matric potentials greater than field capacity. For all cover systems, initial matric potentials were greater than wilting point.

The representative range of long-term values listed in Tables 6.1 to 6.3 for the SWCCs and hydraulic conductivity functions were taken from Schaap and Leij (1998), who combined information from the three soils databases and presented average data on hydraulic properties for different soil textural classes. The textural classes of the soils used to construct the cover systems at the Yucaipa, Albuquerque, and Sierra Blanca sites include sandy loam (with gravel), loamy sand, and sandy clay loam (with and without gravel). The Schaap and Leij (1998) database is for natural, uncompacted soils rather than compacted soils.

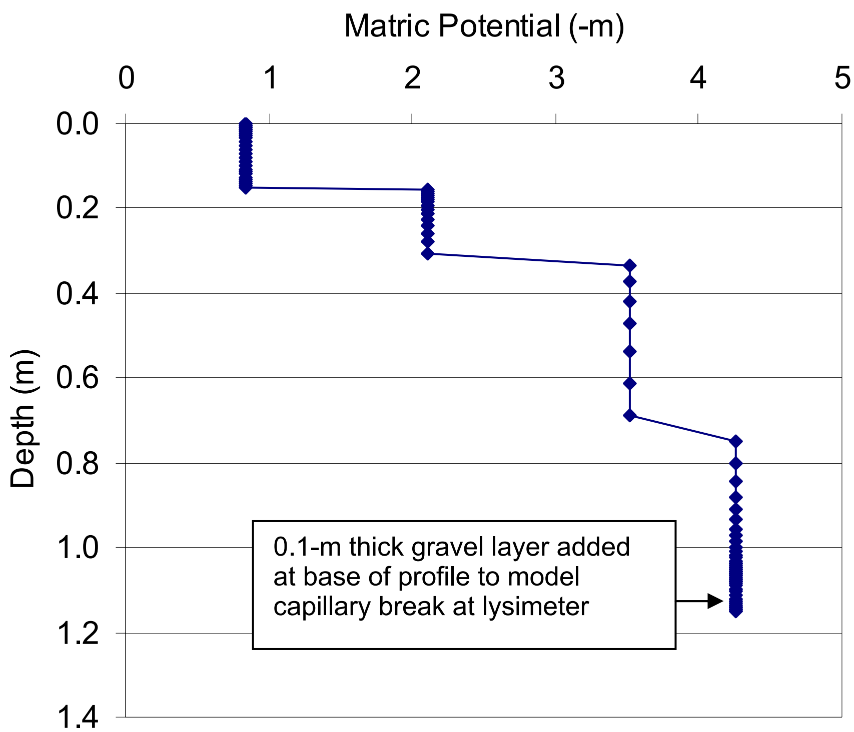

Figure 6.2: Profile of Matric Potentials Used in UNSAT-H as Initial Conditions for the Albuquerque Monolithic Cover System.

Except for the saturated hydraulic conductivity of the compacted soil component of the capillary barrier at the Sierra Blanca site, the parameters calculated for the van Genuchten (1980) water retention function and the measured saturated hydraulic conductivities of the cover system soils fell within one standard deviation of the average values reported by Schaap and Leij (1998). The saturated hydraulic conductivity of the compacted soil component of the capillary barrier at the Sierra Blanca site was measured in the laboratory and the field by different parties. The geometric mean hydraulic conductivities of the soil determined by three different types of field tests were approximately the same (2.1×10^{-8} to 2.9×10^{-8} m/s). Native soils of the same texture in the Schaap and Leij database have higher hydraulic conductivities than these values, i.e., 1.2×10^{-6} to 1.4×10^{-5} m/s, within three standard deviations of the mean.

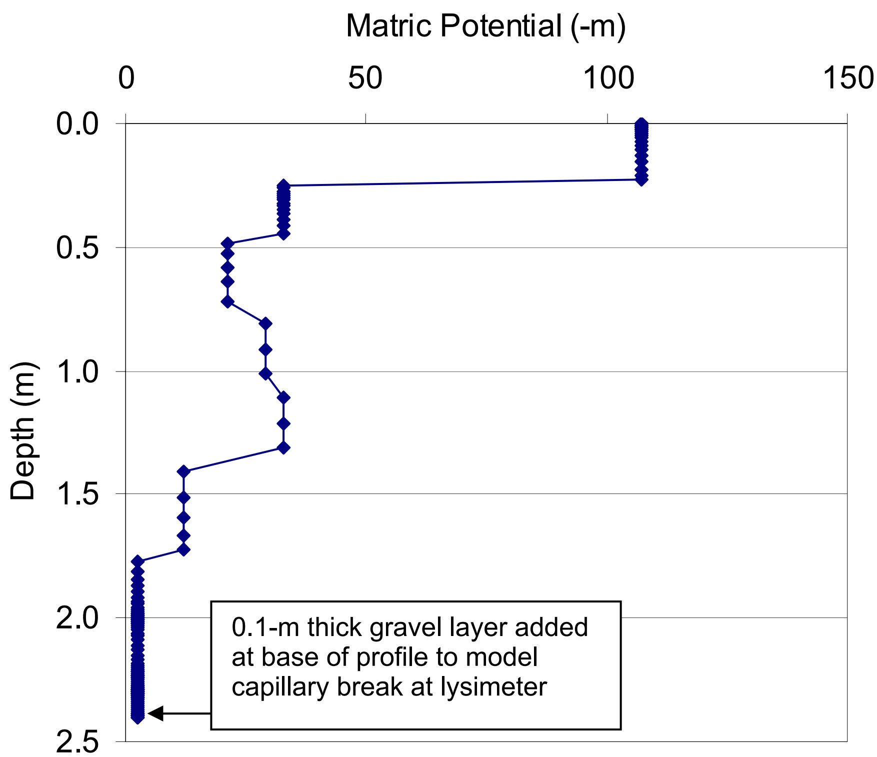

Figure 6.3: Profile of Matric Potentials Used in UNSAT-H as Initial Conditions for the Sierra Blanca Capillary Barrier.

Simulations were conducted with UNSAT-H to evaluate the effect of hysteresis on the water balance of the three cover systems. Similar to the procedures used by Scanlon et al. (2002), the van Genuchten α parameter for wetting was assumed to be two times the α parameter for drying. The maximum entrapped air content was assumed to be 10% of the porosity. This assumption of entrapped air was made for all sites even though entrapped air should have been at least partially accounted for in the field measurements of saturated hydraulic conductivity made for the sites. At the start of the simulations, the matric potentials and water contents of the cover system soils were assumed to be tracking the desorption SWCC.

6.2.3 Vegetation Data

The vegetation data needed for the models include root depth, root length density, ecosystem leaf area index, crop cover fraction, and growing season. Most site-specific plant data were not measured at the study sites or were only measured infrequently. For example, rooting depth was only evaluated for the Yucaipa cover system, which had the least sophisticated monitoring system. The observed root depth at the site was at least 0.13 m. For the Albuquerque and Sierra Blanca cover systems, plant roots were assumed to extend through the upper uncompacted soil layers to depths of 0.15 and 0.3 m, respectively, and be impeded by the underlying compacted soil layer due to its high bulk density. The assumption that roots are impeded is reasonable for this short-term evaluation of cover system water balance. The author has observed this root impedance at landfills in Texas with cover systems constructed with compacted clay barriers overlain by 0.15 to 0.3 m of uncompacted soil. Roots were still impeded by the compacted soil layers of the cover systems even after the cover systems had been in place for up to five years.

The parameters for root length density function, a function that relates root length density to depth, were taken from Winkler (1999), who derived root length density functions for a variety of plants in different settings using published root length density data. A function typical of an annual grass in California was specified for the Yucaipa cover system, because the cover system was vegetated with non-native annual grasses during the first year of monitoring, when the majority of the measured precipitation occurred. For the Albuquerque and Sierra Blanca cover systems, a root length density function representative of perennial grass was used. However, as reported by Khire (1995) and demonstrated for the Albuquerque and Sierra Blanca cover systems by Scanlon et al. (2005), water balance predictions made using UNSAT-H are not particularly sensitive to the shape of the root length density function.

Ecosystem leaf area index and crop cover fraction were estimated for the Yucaipa site and measured at the Albuquerque and Sierra Blanca sites. The ecosystem leaf area index is the basis of the relationship between potential transpiration and potential evapotranspiration developed by Ritchie and Burnett (1971) from observations of the growth of a corn crop and incorporated into the transpiration routine in UNSAT-H. Though UNSAT-H includes an option to specify a localized leaf area index and a bare area fraction to represent an ecosystem leaf area index, this option was not used because: (i) the ecosystem leaf area index was used by Ritchie and Burnett (1971); and (ii) if there are extensive bare areas or extensive localized areas with different leaf area indices, the correct way to model these areas would be to use the ecosystem leaf area indices for these sub-areas, e.g., a leaf area index of zero for bare areas. Further, the bare area fraction in UNSAT-H is an artifact of the UNSAT code developed by Gupta et al. (1978) that was carried along into the UNSAT-H code (personal communication with Mike Fayer, author of UNSAT-H, July 2005). Scanlon et al. (2005) recently used ecosystem leaf area index in their simulations of water balances of the Albuquerque and Sierra Blanca cover systems with UNSAT-H.

HELP, LEACHM, and UNSAT-H all use empirical equations based on corn crop data to partition potential evaporation and potential transpiration from potential evapotranspiration. The differences in the partitioning of potential evapotranspiration for a corn crop and for the grasses and shrubs on the three cover systems were not investigated for this dissertation.

For the Yucaipa cover system, the grass quality was assumed fair for the HELP simulations. For the Albuquerque and Sierra Blanca cover systems, grass quality was assumed poor.

The growing season for each site was developed from historical weather data from nearby weather stations. The growing season was assumed to start on the day after the last spring freeze and end the day before the first fall freeze. As shown in Tables 6.1 to 6.3, there can be a significant amount of variation in the annual growing season for a site. For LEACHM and UNSAT-H simulations, annual plants were assumed to reach maturity 30 days into the growing season and perennial plants were assumed to reach maturity 60 days into the growing season. For simulations with LEACHM, annual and perennial plants were assumed to cease transpiration at the end of the growing season. For simulations with UNSAT-H, plants were assumed to have an ecosystem leaf area index that decreased linearly from its maximum at 30 days from the end of the growing season to zero at the end of the growing season.

6.2.4 Hydrologic Data

The SCS runoff curve number is required as input for HELP and LEACHM. HELP optionally calculates the runoff curve number internally and allows the number to be adjusted for surface slope, slope length, soil type, and vegetation quality. LEACHM requires the input of a runoff curve number that has not been adjusted for surface slope, as it makes it own adjustments to the runoff curve number for slopes greater than 5%.

In this chapter, the runoff curve number used in computer simulations with HELP was calculated by HELP. For the Albuquerque and Sierra Blanca cover systems, which are constructed on slopes of 5% or less, the runoff curve number determined by HELP was used in the LEACHM simulations. Because the Yucaipa cover system is constructed on 50% slopes, a baseline slope of 5% was used in HELP to calculate a runoff curve number for input to LEACHM. The runoff curve number was then adjusted internally by LEACHM to account for the steep surface slope.

6.2.5 Climatologic Data

Meteorological data needed for the models include precipitation, precipitation intensity, and potential evapotranspiration or meteorological parameters to calculate potential evapotranspiration. Meteorological data for the sites were obtained from on-site meteorological stations. In some cases, the data were required to be processed to obtain the required parameters for the models. For example, dew point temperature is required for UNSAT-H to calculate potential evapotranspiration. Dew point temperature was not measured for the Yucaipa site; therefore, it was calculated from relative humidity and temperature data.

LEACHM and UNSAT-H require precipitation intensity to be specified. HELP applies daily precipitation over 24 hours. For the Yucaipa and Albuquerque sites, measured hourly precipitation was used as input for LEACHM and UNSAT-H. For all sites, simulations were conducted with a uniform precipitation intensity equal to 10 mm/hr, often used as a default value for UNSAT-H, and with a uniform precipitation intensity of 1 mm/hr, which is approximately equal to the average measured hourly precipitation intensity at the sites during the monitoring period, i.e., 1.0 to 1.6 mm/hr.

For the Yucaipa and Albuquerque sites, daily potential evapotranspiration was calculated internally by HELP and UNSAT-H using meteorological data. Weekly potential evapotranspiration calculated with UNSAT-H was used as input for LEACHM. For the Sierra Blanca site, daily potential evapotranspiration was calculated internally by HELP using meteorological data. Similar to the procedures followed by Scanlon et al.

(2001, 2002, 2005) in their numerical modeling of the water balance of the Sierra Blanca cover system, potential evapotranspiration calculated using the Penman-Monteith equation (Monteith, 1965) was used as input for LEACHM and UNSAT-H. The calculated potential evapotranspiration values, rather than the meteorological data for the Sierra Blanca site, were used as input for the UNSAT-H simulations to better compare the results of these simulations to the results presented by Scanlon et al.

6.2.6 Modeling Data

Modeling data needed for the simulations include the number of nodes and node spacings used to represent the cover systems, conditions assumed for the upper and lower boundaries of the cover systems, specified minimum and maximum time steps for the simulations, and allowable mass balance errors.

The Yucaipa cover system consists of one 1.2-m thick soil layer. The cover system was represented as one 1.2-m thick soil layer for simulations with HELP and as 20 soil layers of equal thickness (a model requirement) for simulations with LEACHM. For simulations with UNSAT-H, 77 nodes were used to represent the cover system profile. The node spacing ranged from 0.5 mm near the soil surface to a maximum of 30 mm within the cover system. The node spacings used for the Yucaipa cover system were required to be smaller than the spacings used for the other two cover systems to keep annual mass balance errors low, i.e., less than simulated annual drainage and less than 0.5% of annual precipitation when simulations were conducted with hourly measured precipitation.

The Albuquerque and Sierra Blanca cover systems are both multi-layered. For simulations with HELP, the Albuquerque cover system was represented by two soil layers: a 0.15-m thick uncompacted soil layer and a 0.9-m thick compacted soil layer. This cover system was represented by 21 soil layers of equal thickness for simulations with LEACHM. For simulations with UNSAT-H, the Albuquerque cover system was represented by 69 nodes with spacing ranging from 2 mm near the soil surface to a maximum of 77 mm within the cover system.

Only the upper three layers of the Sierra Blanca cover system were used in the water balance simulations. This simplification is considered reasonable as drainage was not measured during the modeling period, soil water content and matric potential measurements indicated that water was not moving deep into the soil profile, the water balance results do not change significantly when these lower layers are neglected, and this approach saved computation time. This simplification was also made by Scanlon et al. (2005) in their simulations of the water balance of the Sierra Blanca cover system. For simulations with HELP, the Sierra Blanca cover system was represented by three soil layers: a 0.3-m thick uncompacted soil layer; a 1.7-m thick compacted soil layer; and a 0.3-m thick sand layer. The cover system was represented by 23 soil layers of equal thickness for simulations with LEACHM. For simulations with UNSAT-H, the cover system was represented by 114 nodes with spacing ranging from 2 mm near the soil surface to a maximum of 100 mm within the cover system.

For all cover systems, nodes were spaced closer near material interfaces and upper and lower boundaries and became exponentially larger to a certain maximum away from interfaces and boundaries (Figures 6.1 to 6.3). This node spacing scheme resulted in placement of more nodes in areas where gradients were anticipated to be the highest.

The boundary at the top of the cover systems (upper boundary condition) was controlled by meteorological forcing based on the climatic data and the specified minimum matric potential that could exist at the soil surface. The value specified for the minimum matric potential at the soil surface was -10,000 m (-100 MPa).

The boundary at the bottom of the Yucaipa cover system (bottom boundary condition) was specified as unit gradient. This condition was considered appropriate because the cover system is underlain by a soil layer of the same texture (intermediate cover soil) and not a capillary break. In addition, monitored water contents at the bottom of the Yucaipa cover system exhibited little change. For the Sierra Blanca and Albuquerque cover systems, the lower boundary was specified as seepage face in LEACHM. When UNSAT-H was used, a 0.1-m thick gravel layer was added to the bottom of the cover systems to model a capillary break, and a unit gradient boundary was applied at the bottom of the gravel layer. A seepage face or gravel layer with a unit gradient lower boundary approximates the capillary barrier effect of the pan lysimeter at the base of the Albuquerque cover and gravel capillary break of the Sierra Blanca cover. The properties assumed for the gravel layer are a saturated water content of 0.42, residual water content of zero, van Genuchten α parameter of -0.493 mm^{-1}, van Genuchten n parameter of 2.19, and saturated hydraulic conductivity of 3.5×10^{-3} m/s. This procedure for representing the bottom boundary condition of the Albuquerque and Sierra Blanca cover systems was previously used by Scanlon et al. (2005).

The maximum time step for LEACHM simulations was specified as 1.2 hours. The minimum and maximum time steps specified for UNSAT-H simulations were 1×10^{-15} hours and 1 hour, respectively.

The mass balance errors of the numerical solution of the water balance equation are included as output for UNSAT-H. The node spacings and simulation time steps were selected to provide acceptable mass balance errors. The highest, though acceptable, mass balance errors were obtained for UNSAT-H simulations of the water balance of the Yucaipa cover system. The annual mass balance error was less than simulated annual drainage and less than 0.5% of annual precipitation when simulations were conducted with hourly measured precipitation. Much lower and acceptable mass balance errors of less than 0.01 mm/yr were obtained for UNSAT-H simulations of the water balance of the Albuquerque and Sierra Blanca cover systems.

6.3 MODELING AND MONITORING COMPARISON FOR YUCAIPA SITE

The water balance of the monolithic cover system at the Yucaipa site was simulated using HELP, LEACHM, and UNSAT-H with the input parameters presented in Table 6.1. The measured and simulated water balances for the cover system at the Yucaipa site are summarized in Table 6.4. The cumulative water balances determined from the simulations are shown in Figures 6.4 to 6.6. Also shown on these figures is the measured storage at Stations A and B.

Runoff was predicted with all of the models, and most of the predicted runoff occurred during February 1998, when the site received a significant amount of precipitation (278 mm) during the 1997 to 1998 El Niño. Although runoff was not monitored at the Yucaipa site, it likely occurred. The Yucaipa cover system was constructed on steep slopes with a relatively low permeability (8.7×10^{-8} m/s or 0.3 mm/hr) soil. Higher runoff rates are anticipated for a given cover system on a relatively steep slope than on a relatively flat slope. In addition, when the surface soil of a cover system has a relatively low saturated hydraulic conductivity relative to the applied precipitation intensity, i.e., 0.3 mm/hr versus approximately 1 to 10 mm/hr, infiltration will be limited, and runoff is expected.

Table 6.4: Measured and Simulated Water Balances for Yucaipa Monolithic Cover System.

	Year[1]	Precip. (mm)	Potential Evapotrans.[2] (mm)	Runoff (mm)	Evapotrans. (mm)	Storage (mm)	Change in Storage (mm)	Drainage (mm)
Measured (Sta. A)	1997					195[3]		-
	1998	658	-	-	-	187	-8	
	1999	187	-	-	-	171	-16	-
	2000	230	-	-	-	195	24	-
Measured (Sta. B)	1997					180[3]		
	1998	658	-	-	-	192	12	-
	1999	187	-	-	-	170	-22	-
	2000	230	-	-	-	206	36	-
HELP (Sta. A)	1998	658	-	106	365	167	-28	215
	1999	187	-	0.0	187	166	-0.8	0.4
	2000	230	-	17	149	164	-2	66
Precipitation Intensity = measured hourly intensity								
LEACHM (Sta. A)	1998	658	1418	234	316	167	-28	136
	1999	187	1630	0.9	192	157	-10	3
	2000	230	773	48	154	175	18	10
UNSAT-H (Sta. A)	1998	658	1418	467	175	207	12	2
	1999	187	1630	85	112	193	-13	2
	2000	230	773	143	85	193	-0.1	0.9
Precipitation Intensity = 0.5 mm/hr (median value during monitoring period)								
LEACHM (Sta. A)	1998	658	1418	207	324	167	-28	155
	1999	187	1630	0.0	192	158	-9	4
	2000	230	773	39	154	178	20	17
UNSAT-H (Sta. A)	1998	658	1418	374	201	226	31	34
	1999	187	1630	48	146	208	-18	7
	2000	230	773	106	108	216	8	3
Precipitation Intensity = 1 mm/hr (average value during monitoring period)								
LEACHM (Sta. A)	1998	658	1418	219	330	167	-28	136
	1999	187	1630	0.1	193	157	-10	4
	2000	230	773	46	154	176	19	11
UNSAT-H (Sta. A)	1998	658	1418	414	196	221	26	12
	1999	187	1630	75	127	201	-20	5
	2000	230	773	129	95	203	2	2
Precipitation Intensity = 10 mm/hr (previously used by others as UNSAT-H default value)								
LEACHM (Sta. A)	1998	658	1418	324	339	167	-28	23
	1999	187	1630	17	180	156	-11	1
	2000	230	773	79	146	160	4	1
UNSAT-H (Sta. A)	1998	658	1418	537	126	191	-4	0.9
	1999	187	1630	121	74	182	-9	1
	2000	230	773	179	54	178	-4	0.4
Hysteresis with Precipitation Intensity = measured hourly intensity								
UNSAT-H (Sta. A)	1998	658	1418	517	139	195	-0.6	1
	1999	187	1630	112	82	186	-9	1
	2000	230	773	165	65	183	-0.3	0.5

[1] 2000 = Jan - Jun
[2] Not included in HELP output
[3] Measured storage at beginning of monitoring and simulation periods

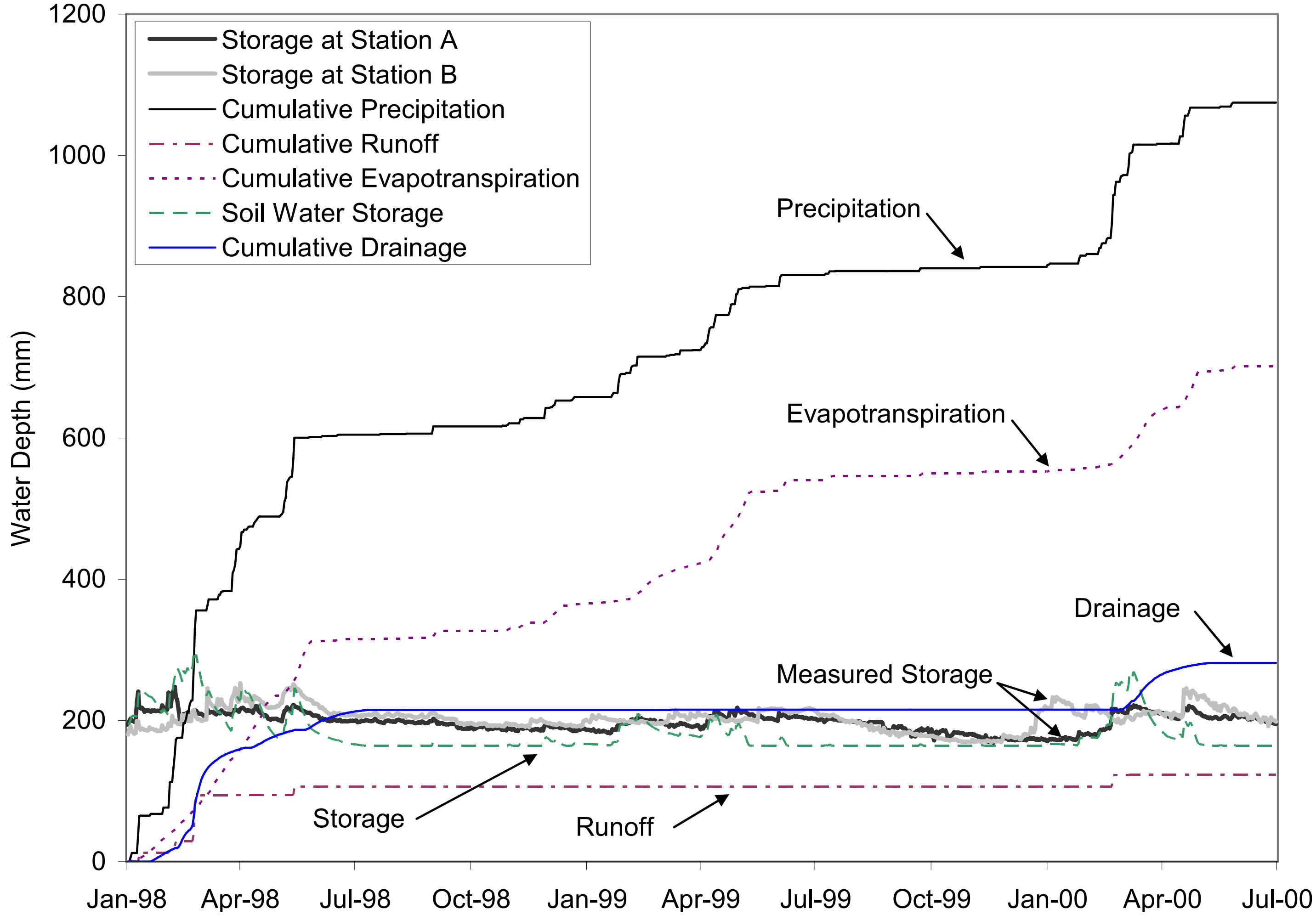

Figure 6.4: Water Balance of the Yucaipa Monolithic Cover System Predicted by HELP.

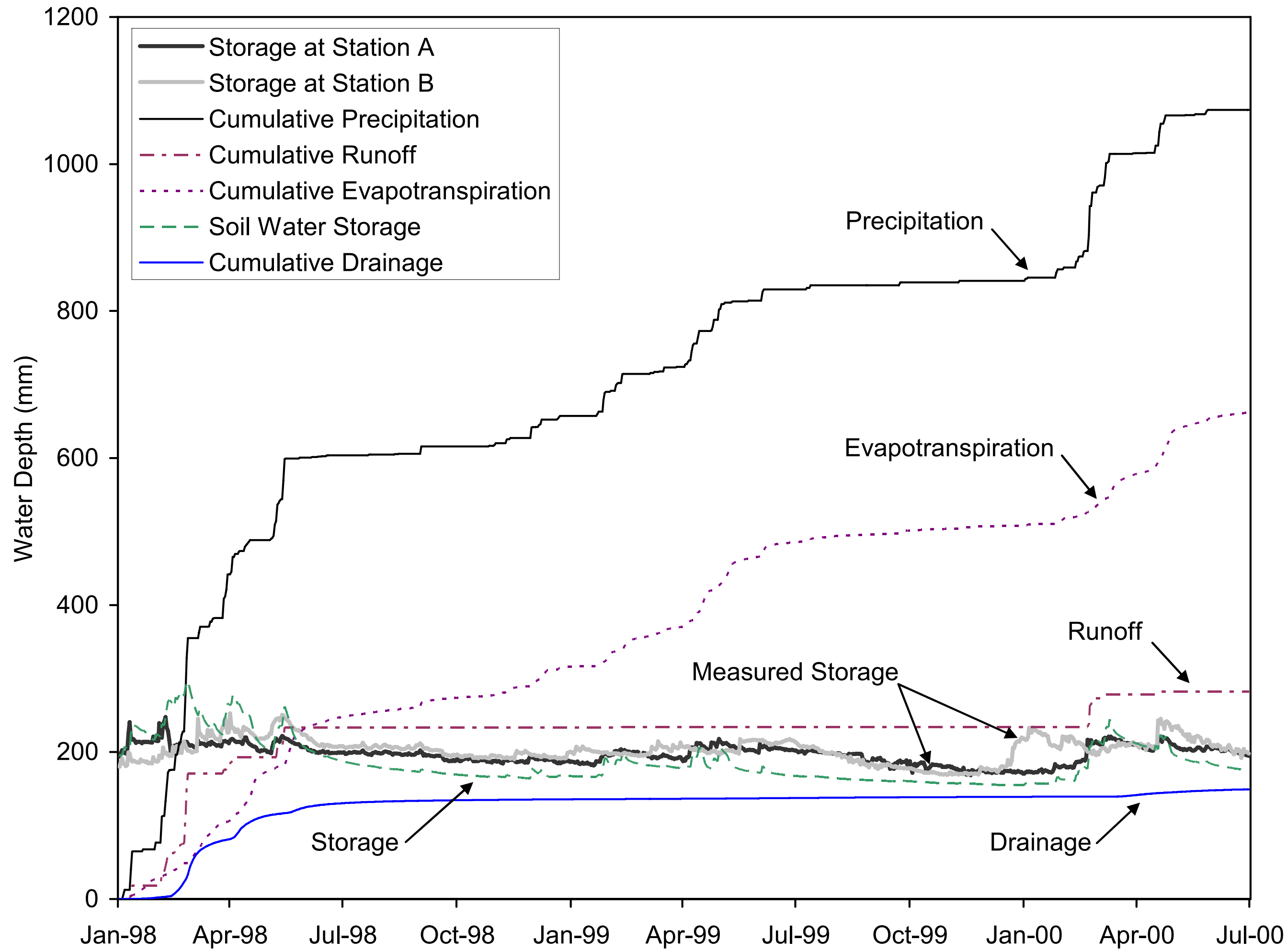

Figure 6.5: Water Balance of the Yucaipa Monolithic Cover System Predicted by LEACHM with Measured Hourly Precipitation.

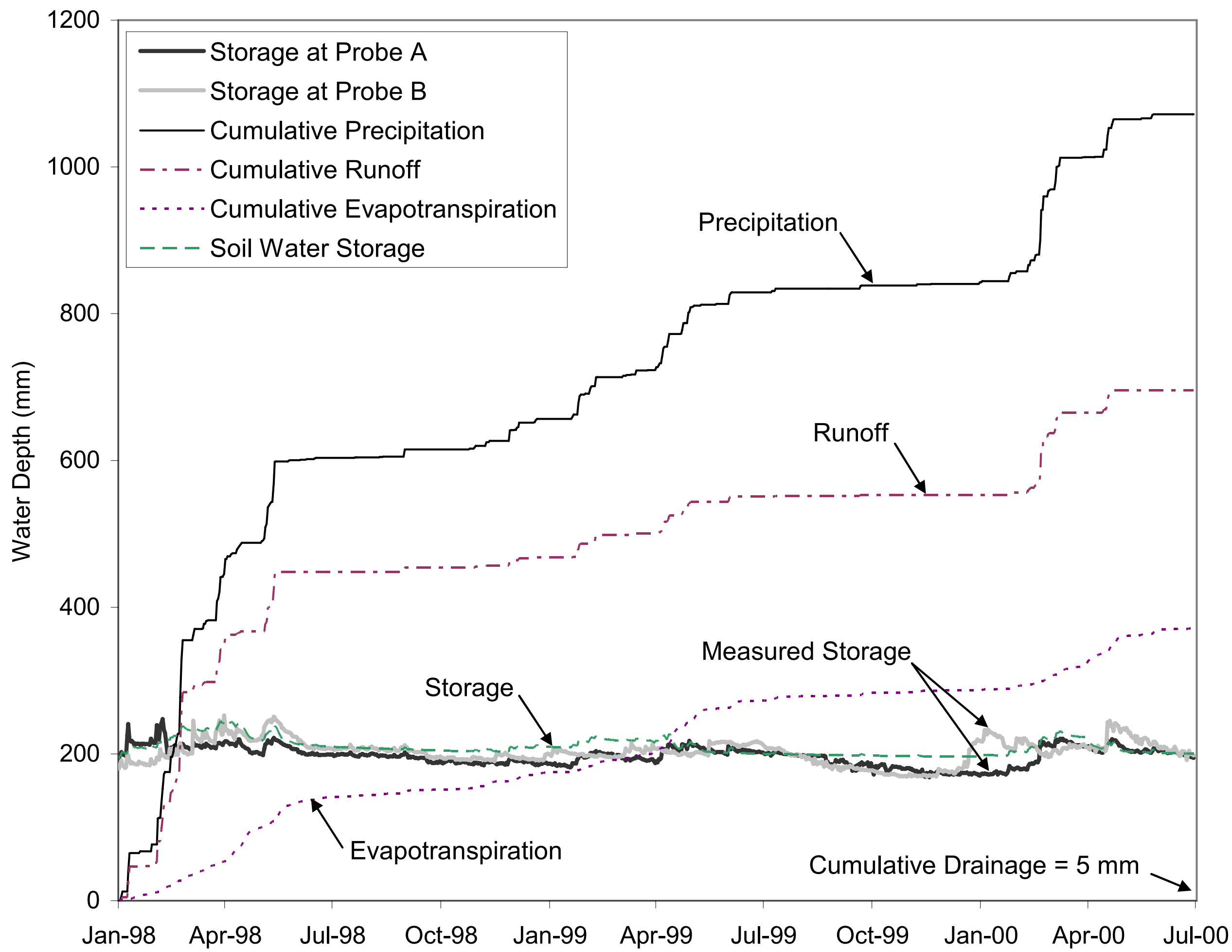

Figure 6.6: Water Balance of the Yucaipa Monolithic Cover System Predicted by UNSAT-H with Measured Hourly Precipitation and no Hysteresis.

The highest cumulative runoff was predicted with UNSAT-H, while the lowest was predicted with HELP. The primary reasons for this may be the difference between the rates at which rainfall was applied by the models and the difference in the hydraulic conductivity functions used by the models. Daily rainfall was uniformly applied to the Yucaipa cover system over a 24-hour period with HELP. In contrast, daily rainfall was applied at its measured hourly intensity with LEACHM and UNSAT-H. When a given amount of precipitation is applied at a low intensity, runoff rates are relatively low. When the precipitation intensity is increased, i.e., the given amount of precipitation is applied in a shorter time, the potential for runoff increases. If precipitation is applied at a rate less than its actual intensity, runoff may be under-predicted.

The effect of precipitation intensity on the water balance for the Yucaipa cover system predicted using the LEACHM and UNSAT-H models is shown in Table 6.4. The highest rates of runoff were simulated when precipitation was applied at 10 mm/hr, a precipitation rate that was formerly coded into UNSAT-H as a default rate. The lowest rates of runoff were predicted when precipitation was applied at the measured median hourly rate of 0.5 mm/hr. Runoff calculated using measured hourly precipitation intensities was somewhat greater than runoff calculated using the measured average hourly precipitation intensity of 1 mm/hr, but less than runoff calculated using a precipitation intensity of 10 mm/hr.

Both the HELP and LEACHM models incorporate the Campbell-Burdine hydraulic conductivity function. The van Genuchten hydraulic conductivity function was specified for simulations with the UNSAT-H model. For a given matric potential, the Campbell-Burdine hydraulic conductivity function predicts higher unsaturated hydraulic conductivities than the van Genuchten hydraulic conductivity function. All else being equal, lower runoff rates, higher infiltration rates, and higher evaporation rates are predicted when the Campbell-Burdine hydraulic conductivity function, rather than the van Genuchten-Mualem function, is used.

Because significantly higher rates of runoff and thus lower rates of infiltration were predicted with UNSAT-H than with HELP and LEACHM, lower evapotranspiration rates were also predicted with UNSAT-H than with HELP and LEACHM. Conversely, the lowest rates of runoff and the highest evapotranspiration rates were predicted with HELP. It is important to simulate the surface water balance (Equation 3.2) as accurately as possible because it controls the amount of water infiltrating into the subsurface, and thus, the subsurface water balance (Equation 3.3). Because runoff was not monitored at the Yucaipa site, the ability of the models to accurately simulate runoff from the cover system cannot be evaluated.

Soil water storage (Figures 6.4 to 6.6) was the only water balance parameter measured. Storage was under-predicted with HELP and LEACHM and somewhat over-predicted with UNSAT-H. Change in storage over time was best predicted with UNSAT-H (Figure 6.6). Zero change in storage was often predicted with HELP (Figure 6.4) because the Yucaipa cover system was relatively dry and at the lower limit of storage allowed by HELP (164 mm) during much of the simulation period.

Drainage each year of the simulation was predicted by all of the models. As expected, the highest cumulative drainage of 281 mm for the 2.5-year simulation period was predicted with HELP. One reason why drainage tends to be over-predicted and storage tends to be under-predicted with HELP is that the model allows water within a user-specified evaporative zone to drain by gravity to the water content corresponding to wilting point. Conceptually, water should only drain by gravity to the water content corresponding to field capacity. If the field capacity concept for drainage was used for the evaporative zone, drainage would only be predicted with HELP when soil water storage was greater than 206 mm.

Cumulative drainage of 149 mm was predicted with LEACHM. The highest predicted drainage rates generally coincided with the 1997 to 1998 El Niño. Significantly more runoff was predicted during that time with UNSAT-H than with LEACHM. As a result, only 5 mm of cumulative drainage was predicted with UNSAT-H. Small amounts of drainage ranging from 0.002 to 0.008 mm were simulated each day with UNSAT-H. The highest drainage rates were predicted in November 1998 as water that infiltrated into the cover system earlier in the year reached the lower boundary of the cover system. For the remainder of the simulation period, drainage rates decreased.

The effect of hysteresis on the water balance of the Yucaipa cover system was evaluated with UNSAT-H. More runoff and less infiltration were simulated. As a result, less water was available for evapotranspiration, storage, or drainage. Less infiltration was simulated because air was assumed to be entrapped in 10% of the soil voids. Thus, the maximum hydraulic conductivity of the surface soil was effectively reduced from 8.7×10^{-8} m/s to 1.4×10^{-9} m/s given the SWCC and hydraulic conductivity function in Figures 4.8 and 4.9, respectively.

6.4 MODELING AND MONITORING COMPARISON FOR ALBUQUERQUE SITE

The water balance of the monolithic cover system at the Albuquerque site was simulated using HELP, LEACHM, and UNSAT-H with the input parameters presented in Table 6.2. The measured and simulated water balances for the cover system at the Albuquerque site are summarized in Table 6.5. The cumulative water balances determined from the simulations are shown in Figures 6.7 to 6.9. Also shown on these figures is the measured storage for the east and west subplots.

Table 6.5: Measured and Simulated Water Balances for Albuquerque Monolithic Cover System.

	Year[1]	Precip. (mm)	Potential Evapotrans.[2] (mm)	Runoff (mm)	Evapotrans. (mm)	Storage	Change in Storage (mm)	Drainage (mm)
						184[3]		
Measured (East Subplot)	1998	299	-	0.8	373	110	-75	0.0
	1999	280	-	0.6	286	102	-7	0.0
	2000	189	-	0.2	170	121	19	0.0
	2001	341	-	0.8	349	113	-8	0.0
	2002[4]	181	-	0.4	166	127	14	0.0
						166[3]		
Measured (West Subplot)	1998	299	-	22	347	96	-71	0.4
	1999	280	-	0.8	279	96	-0.1	0.0
	2000	189	-	0.2	150	134	38	0.0
	2001	341	-	0.6	387	88	-46	0.0
	2002	291[5]	-	0.6	262	116	28	0.0
HELP (East)	1998	299	-	5	331	106	-79	42
	1999	280	-	1	295	89	-17	0.3
	2000	189	-	0.7	179	98	9	0.1
	2001	341	-	1	347	92	-6	0.3
	2002	181	-	1	161	112	20	0.1
Precipitation Intensity = 1 mm/hr (average value during monitoring period)								
LEACHM (East)	1998	299	1755	0.0	323	160	-24	0.0
	1999	280	1834	0.0	295	146	-15	0.0
	2000	189	1890	0.0	198	137	-9	0.0
	2001	341	1770	0.0	336	141	5	0.0
	2002	181	1993	0.0	180	142	0.4	0.0
UNSAT-H (East)	1998	299	1755	0.0	295	188	4	0.0
	1999	280	1834	0.0	289	179	-9	0.0
	2000	189	1890	0.0	202	165	-14	0.0
	2001	341	1770	0.0	325	181	16	0.0
	2002	181	1993	0.0	177	185	4	0.0
Precipitation Intensity = 10 mm/hr (previously used by others as UNSAT-H default value)								
LEACHM (East)	1998	299	1755	0.0	323	160	-25	0.0
	1999	280	1834	0.0	296	144	-16	0.0
	2000	189	1890	0.0	197	135	-8	0.0
	2001	341	1770	0.0	336	140	5	0.0
	2002	181	1993	0.0	182	139	-1	0.0
UNSAT-H (East)	1998	299	1755	0.0	297	186	2	0.0
	1999	280	1834	0.0	290	176	-10	0.0
	2000	189	1890	0.0	201	163	-13	0.0
	2001	341	1770	0.0	326	179	15	0.0
	2002	181	1993	0.0	177	183	4	0.0

Table 6.5: Measured and Simulated Water Balances for Albuquerque Monolithic Cover System (cont).

	Water Year[1]	Precip. (mm)	Potential Evapotrans.[2] (mm)	Runoff (mm)	Evapotrans. (mm)	Storage	Change in Storage (mm)	Drainage (mm)
Hysteresis with Precipitation Intensity = 10 mm/hr								
UNSAT-H (Sta. A)	1998	299	1755	0.1	301	183	-2	0.0
	1999	280	1834	0.0	293	170	-13	0.0
	2000	189	1890	0.0	201	158	-12	0.0
	2001	341	1770	0.0	330	169	11	0.0
	2002	181	1993	0.0	176	173	4	0.0
Plant Root Depth = 0.75 m with Precipitation Intensity = 10 mm/hr								
UNSAT-H (Sta. A)	1998	299	1755	0.0	386	97	-84	0.0
	1999	280	1834	0.0	294	83	-14	0.0
	2000	189	1890	0.0	200	71	-11	0.0
	2001	341	1770	0.0	343	70	-1	0.0
	2002	181	1993	0.0	162	88	17	0.0

[1] Water Year = 12-month period from October to September
[2] Not included in HELP output
[3] Measured storage at beginning of monitoring and simulation periods
[4] Water Year 2002 ends on September 24, 2002
[5] Includes 100 mm of irrigation

Small amounts of runoff from the east and west subplots of the Albuquerque cover system were measured. However, runoff was essentially only predicted with HELP. Runoff was simulated with HELP when daily precipitation was greater than 18 mm or when daily precipitation was greater than 16 mm after two days with lesser precipitation amounts. Zero runoff was predicted by LEACHM and UNSAT-H when hourly precipitation was applied at an intensity of 1 mm/hr, approximately the average measured precipitation intensity during the monitoring period, or when hourly precipitation was applied at an intensity of 10 mm/hr. The uncompacted soil layer at the surface of the Albuquerque cover system had a relatively high saturated hydraulic conductivity relative to the applied precipitation intensity, i.e. 36 mm/hr versus 1 to 10 mm/hr, and, in the simulations with LEACHM and UNSAT-H, this soil layer could accommodate the precipitation without runoff.

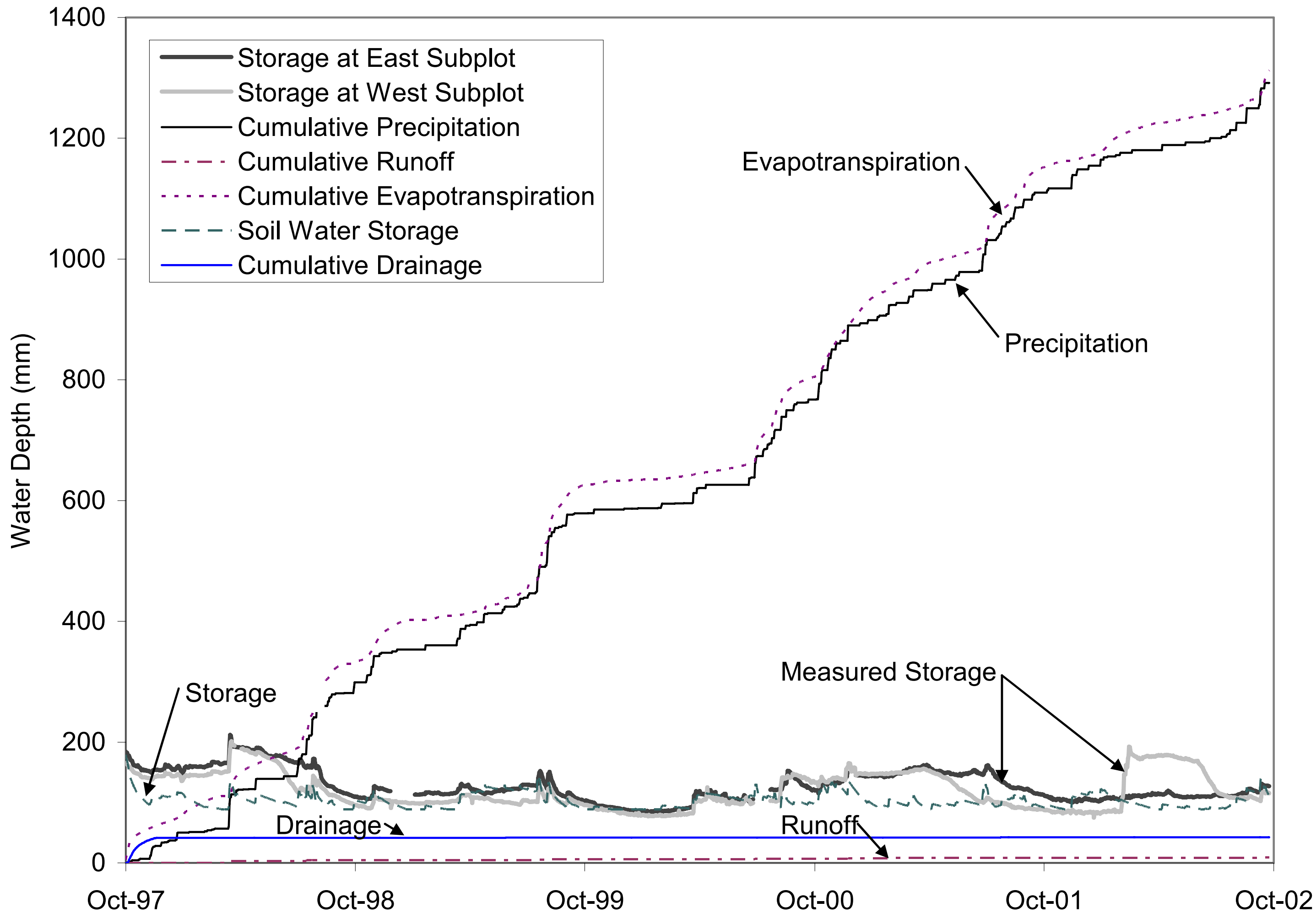

Figure 6.7: Water Balance of the Albuquerque Monolithic Cover System Predicted by HELP.

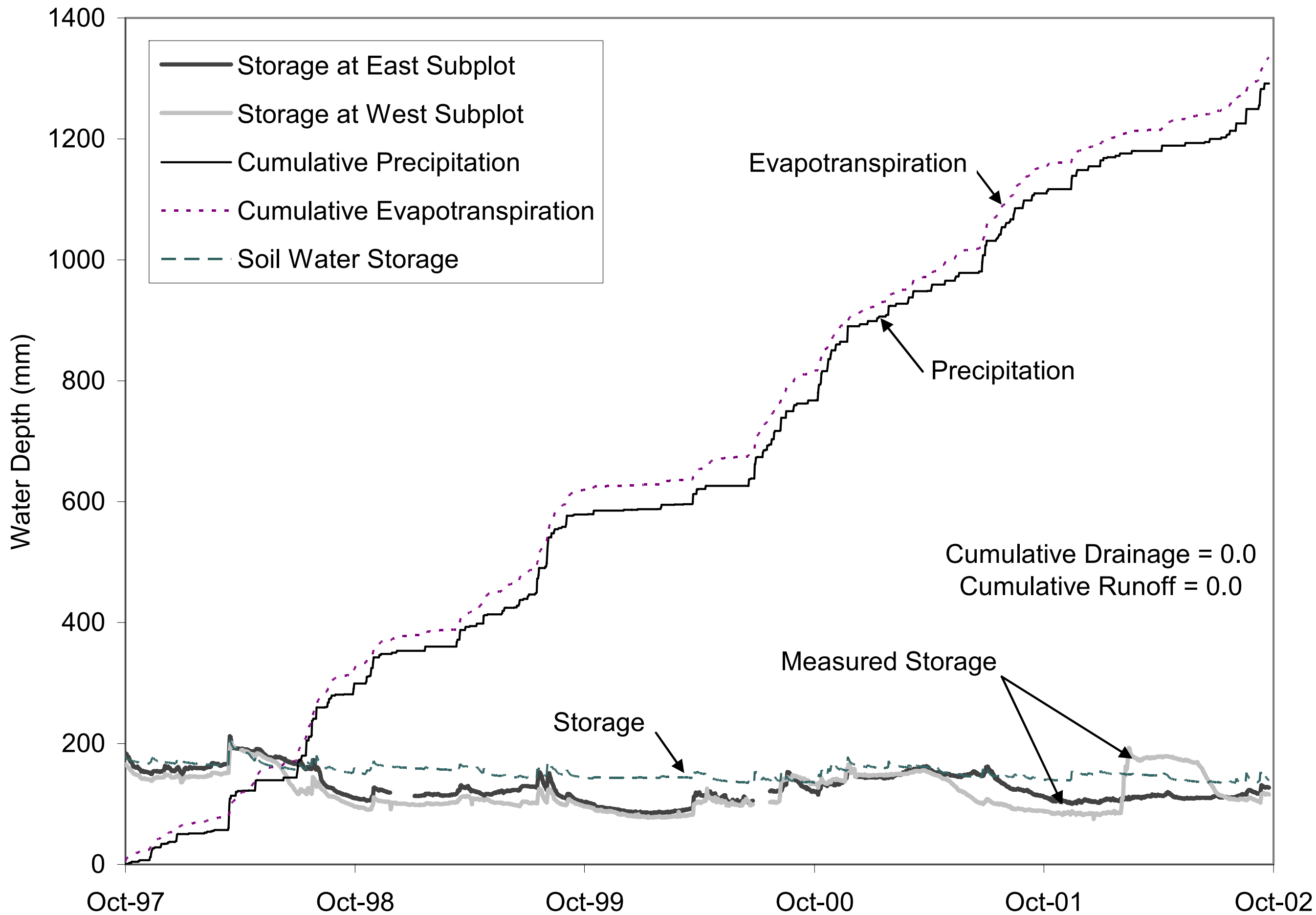

Figure 6.8: Water Balance of the Albuquerque Monolithic Cover System Predicted by LEACHM with Daily Precipitation Applied at Intensity of 10 mm/hr.

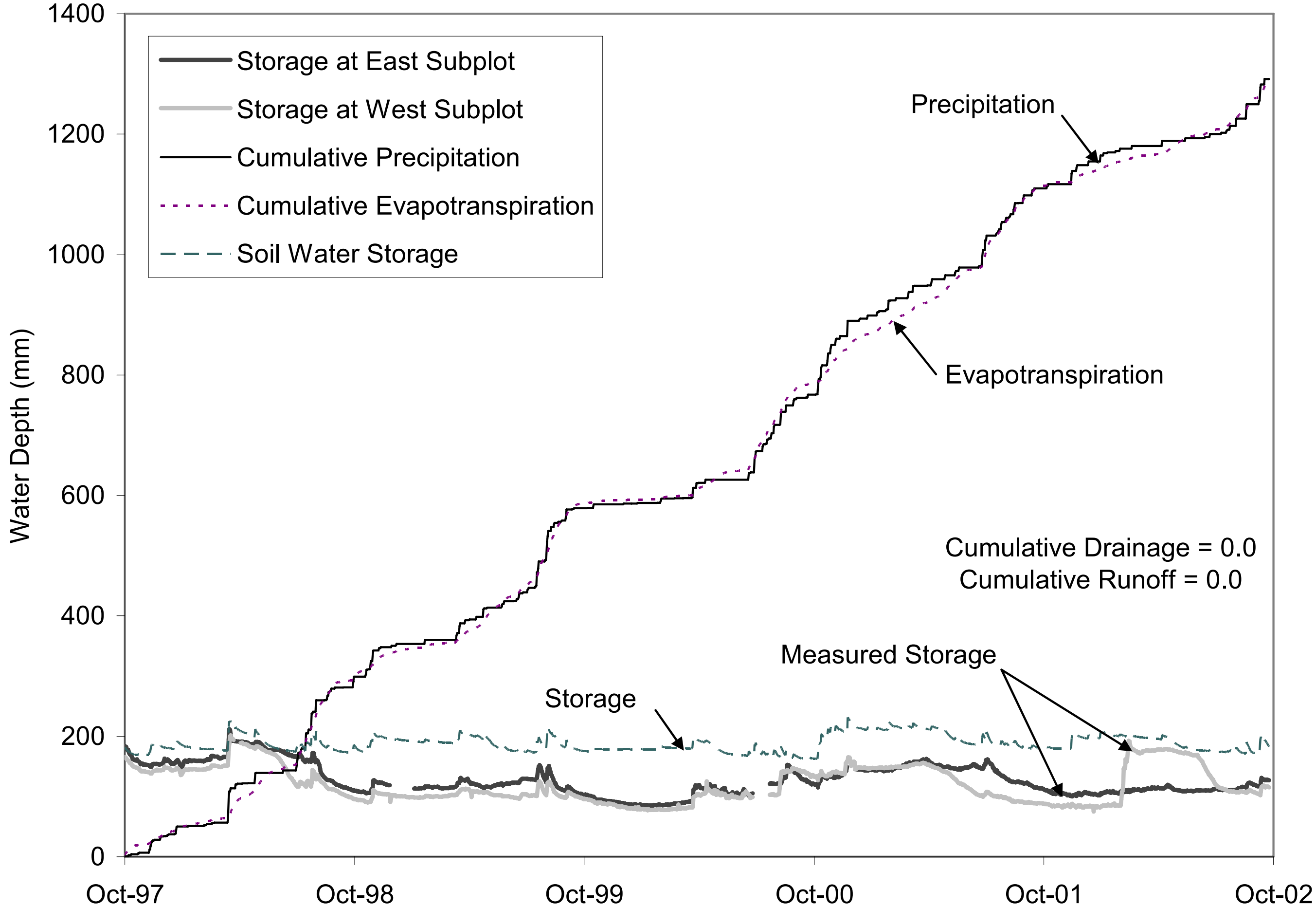

Figure 6.9: Water Balance of the Albuquerque Monolithic Cover System Predicted by UNSAT-H with Daily Precipitation Applied at Intensity of 10 mm/hr and no Hysteresis.

Because there was little to no simulated runoff or drainage for the Albuquerque cover system, the difference in the evapotranspiration predictions between models led to similar, but opposite, differences in predictions of change in soil water storage. Overall, more evapotranspiration and a drier cover system profile during the simulation period were predicted with HELP than with LEACHM and UNSAT-H. Storage predicted with HELP better matched measured storage (Figure 4.7) than storage predicted with LEACHM and UNSAT-H (Figures 4.7 and 4.8). The latter two models significantly over-predicted storage.

Part of the reason for the apparent over-prediction of storage for the Albuquerque cover system may be related to the vegetation rooting depth assumed for the simulations. Roots were assumed to be confined to the upper 0.15 m of the cover system. Because, the depth of roots was not measured, the actual root depth is uncertain.

To evaluate the potential impact of deeper roots on simulated evapotranspiration and soil water storage, an additional simulation was conducted with UNSAT-H assuming that the root depth was 0.75 m. This root depth was assumed by Scanlon et al. (2005) in their evaluation of the water balance of the Albuquerque cover system. The results of this simulation (Table 6.5) suggest that the plant root depth may be greater than 0.15 m, but less than 0.75 m. While evapotranspiration appears to be under-predicted and storage appears to be over-predicted by water balance simulations with a root depth of 0.15 m, evapotranspiration appears to be over-predicted and storage appears to be under-predicted by water balance simulations with a root depth of 0.75 m.

Drainage of 0.1 to 42 mm/yr was predicted with HELP, and zero drainage was predicted with LEACHM and UNSAT-H. Drainage was only measured during one year and for the west subplot. As previously discussed in Section 4.3.3, this small amount of measured drainage may be attributable to preferential flow. A primary reason why drainage was overestimated with HELP may be that the model only considers unit gradient conditions within and at the lower boundary of evapotranspirative cover systems. It cannot model the hydraulic gradients that exist at the capillary break induced by the lysimeter that underlies the Albuquerque cover system. A capillary break can significantly increase the storage capacity of cover system soils: the soils become much wetter before drainage occurs. The capillary break can, however, be modeled with LEACHM and UNSAT-H.

The effect of hysteresis on the water balance of the Albuquerque cover system was evaluated with UNSAT-H and found to be minimal. When hourly precipitation was applied at an intensity of 10 mm/yr, 0.1 mm of runoff was predicted by UNSAT-H during water year 1998 and zero runoff was predicted during the remaining four years. Evapotranspiration was slightly higher (by up to 4 mm/yr) and storage was slightly lower (by up to 4 mm/yr). Zero drainage was predicted.

6.5 MODELING AND MONITORING COMPARISON FOR SIERRA BLANCA SITE

The water balance of the capillary barrier at the Sierra Blanca site was simulated using HELP, LEACHM, and UNSAT-H with the input parameters presented in Table 6.3. The measured and simulated water balances for the cover system at the Yucaipa site are summarized in Table 6.6. The cumulative water balances determined from the simulations are shown in Figures 6.10 to 6.12. Also shown on these figures is the average measured storage.

Table 6.6: Measured and Simulated Water Balances for Sierra Blanca Capillary Barrier.

	Water Year[1]	Precip. (mm)	Potential Evapotrans.[2] (mm)	Runoff (mm)	Evapotrans. (mm)	Storage[3]	Change in Storage (mm)	Drainage (mm)
						390[4]		
Measured	1998	427[5]	-	60	308	449	59	0.0
	1999	246	-	6	311	378	-71	0.0
	2000	130	-	8	135	365	-13	0.0
HELP	1998	427	-	19	346	451	61	0.0
	1999	246	-	22	224	452	1	0.0
	2000	130	-	7	136	441	-12	0.0
Precipitation Intensity = measured hourly intensity								
LEACHM	1998	427	1644	0.0	398	417	27	2
	1999	246	1588	0.0	273	391	-27	0.0
	2000	130	1484	0.0	133	388	-3	0.0
UNSAT-H	1998	427	1644	8	347	462	72	0.0
	1999	246	1588	36	270	402	-60	0.0
	2000	130	1484	10	132	390	-12	0.0
Precipitation Intensity = 1 mm/hr (average value during monitoring period)								
LEACHM	1998	427	1644	0.0	396	420	30	2
	1999	246	1588	0.0	297	392	-28	0.0
	2000	130	1484	0.0	134	388	-4	0.0
Precipitation Intensity = 10 mm/hr (previously used by others as UNSAT-H default value)								
LEACHM	1998	427	1644	0.0	397	418	28	2
	1999	246	1588	0.0	273	391	-27	0.0
	2000	130	1484	0.0	134	387	-4	0.0
Hysteresis with Precipitation Intensity = measured hourly intensity								
UNSAT-H	1998	427	1644	55	314	449	59	0.0
	1999	246	1588	73	225	397	-52	0.0
	2000	130	1484	26	111	359	-38	0.0

[1] Water Year = 12-month period from October to September
[2] Not included in HELP output
[3] Storage in upper 2-m of cover system
[4] Measured storage in upper 2-m of cover system at beginning of monitoring and simulation periods
[5] Includes 225 mm of irrigation

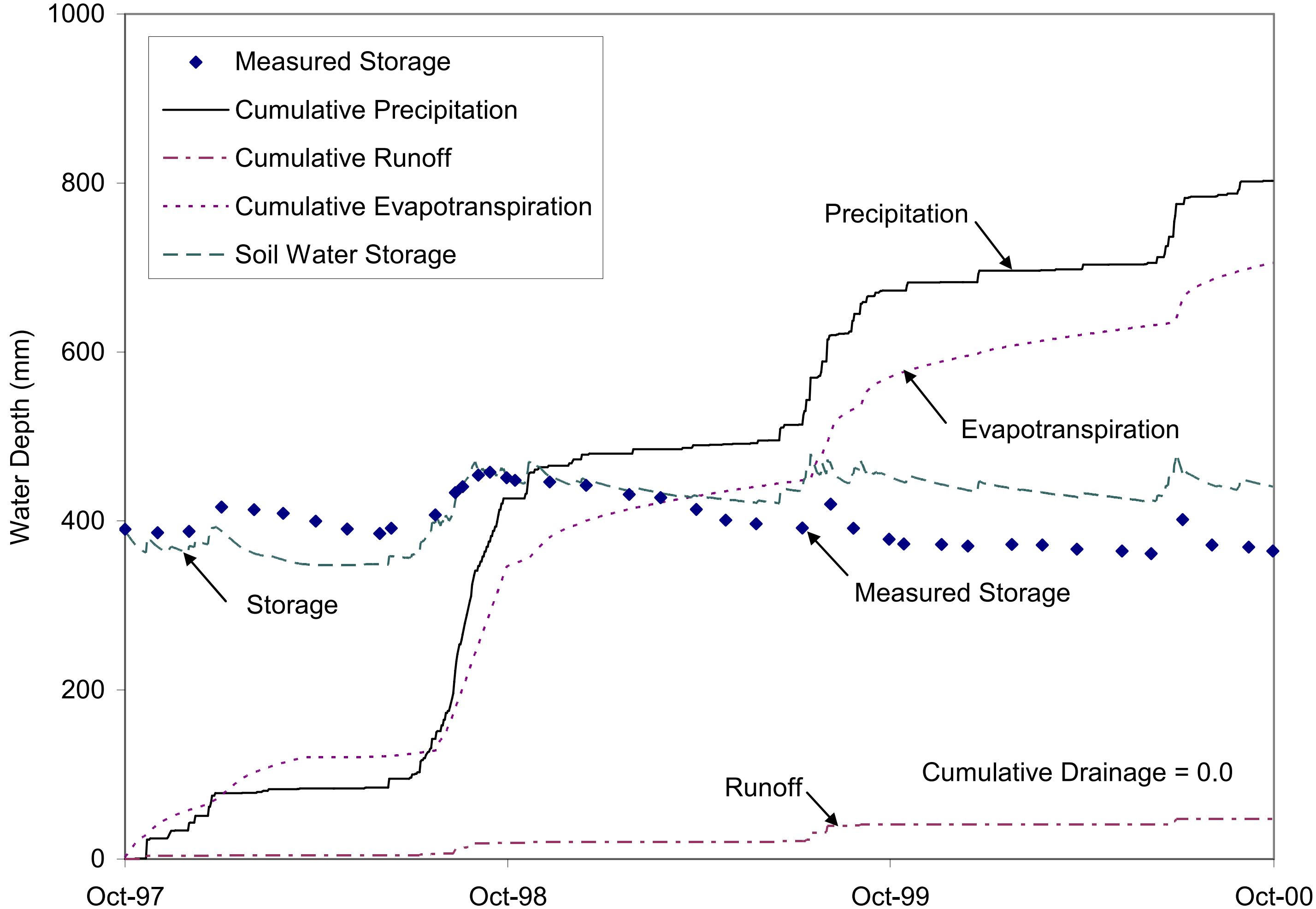

Figure 6.10: Water Balance of the Sierra Blanca Capillary Barrier Predicted by HELP.

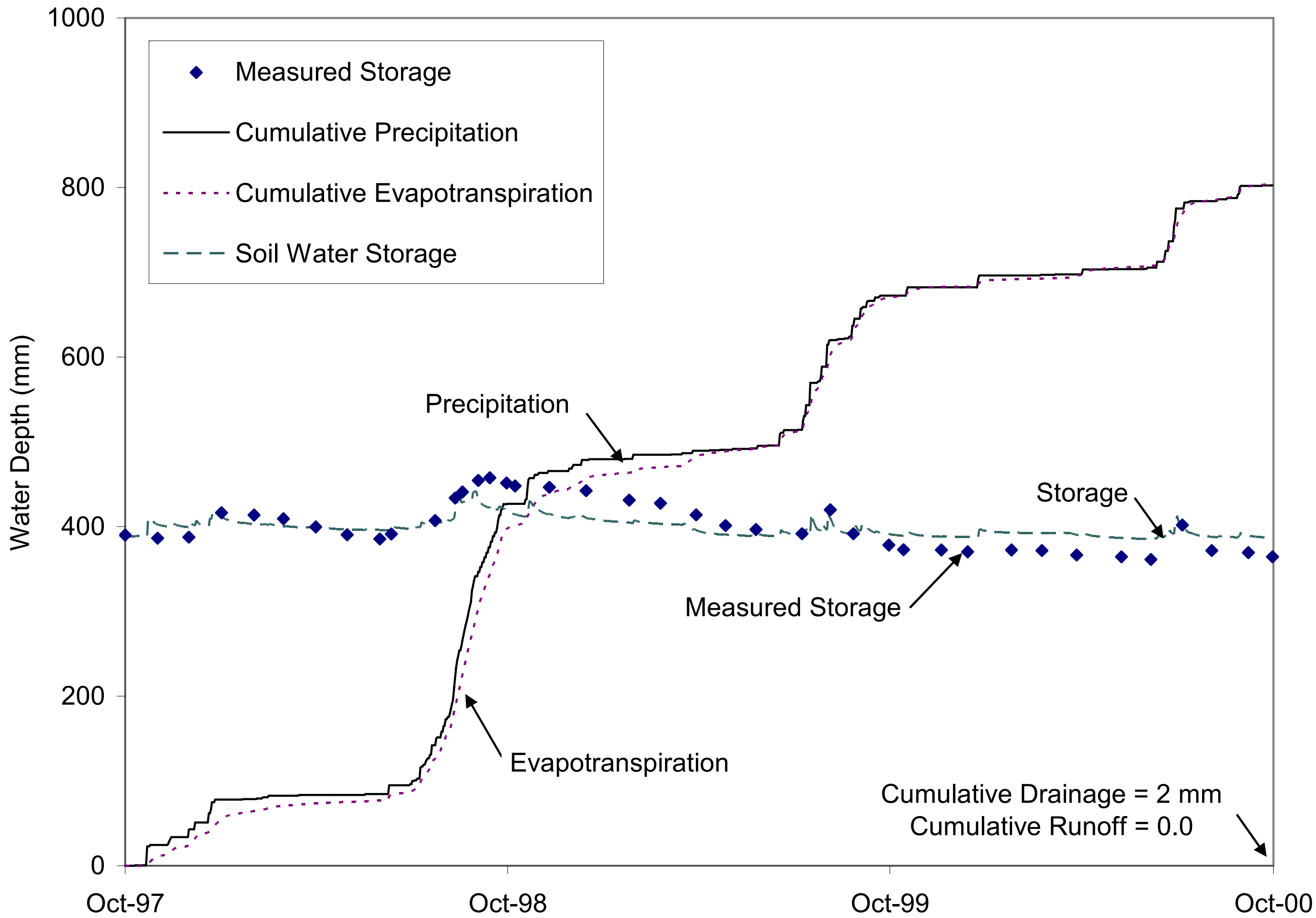

Figure 6.11: Water Balance of the Sierra Blanca Capillary Barrier Predicted by LEACHM with Measured Hourly Precipitation.

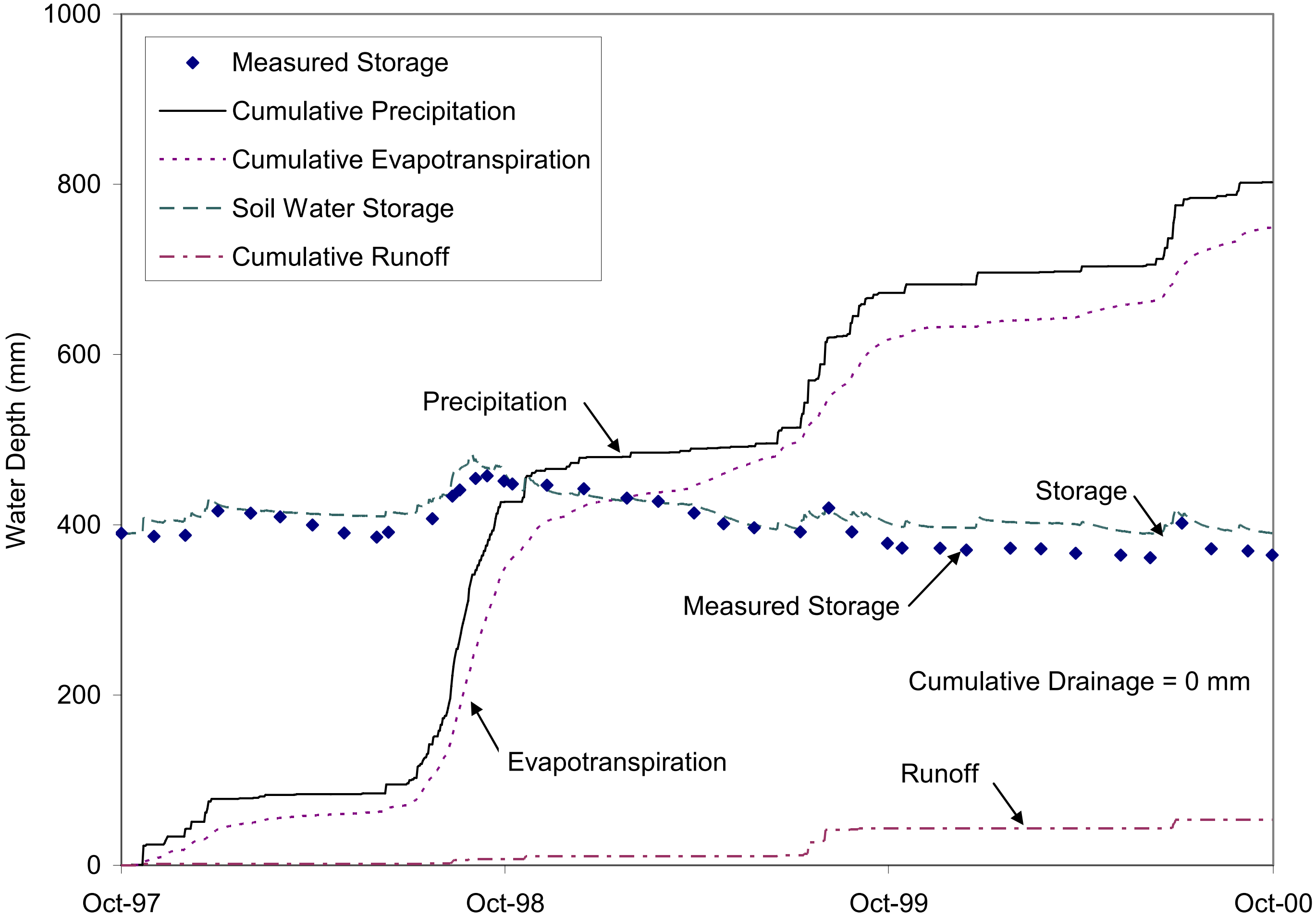

Figure 6.12: Water Balance of the Sierra Blanca Capillary Barrier Predicted by UNSAT-H with Measured Hourly Precipitation and no Hysteresis.

Although 6 to 60 mm/yr of runoff was measured for the Sierra Blanca cover system, runoff was only predicted with HELP and UNSAT-H. Both of the models predicted that runoff would occur during the summer rains, but did not accurately predict the trends in runoff values. The highest runoff was measured in the 1998 water year, when the cover system vegetation was irrigated. However, the highest runoff values were predicted to occur during the 1999 water year. Similar to the simulations for the Yucaipa and Sierra Blanca cover systems, the highest runoff values were predicted when hysteresis was considered.

Changing the precipitation intensity from 1 mm/hr to 10 mm/hr had no effect on the water balance of the Sierra Blanca cover system simulated with LEACHM. A similar effect was observed for LEACHM simulations of the water balance of the Albuquerque cover system. The saturated hydraulic conductivity of the uncompacted soil layer of the Sierra Blanca cover system was relatively high (1.9×10^{-6} m/s (6.8 mm/hr)). Thus, the Sierra Blanca cover system was predicted to provide little impedance to infiltration.

Unlike the water balance simulations conducted for the Yucaipa and Albuquerque cover systems, the effect of precipitation intensity on UNSAT-H simulations was not evaluated for the Sierra Blanca cover system. Because potential evapotranspiration and hourly precipitation data, rather than meteorological data, were used as input data for this cover system, the option to specify a uniform precipitation intensity was not available. To do this, each precipitation event would have to manually be spread out over a shorter or longer time.

Less evapotranspiration and greater soil water storage was predicted with HELP than with LEACHM and UNSAT-H. Storage was under-predicted by HELP due to the water content limits set by HELP: the minimum soil water content within the user-specified evaporative zone corresponds to wilting point and the minimum soil water content below the evaporative zone corresponds to field capacity. Thus, the minimum storage under steady-state conditions was limited to 417 mm for the Sierra Blanca cover system. Measured matric potentials for the cover system were lower than wilting point. The initial soil water storage at the start of the HELP simulations was 390 mm, which is less than the minimum storage allowed by HELP. Thus, infiltration applied to the cover system during the first year of the simulation was used to fulfill the storage deficit.

Storage predicted by LEACHM and UNSAT-H reasonably matched the trends in measured storage (Figures 6.11 and 6.12). The best agreement between measured and simulated storage was obtained when hysteresis was considered. The effect of hysteresis on the UNSAT-H simulations was increased runoff, decreased evapotranspiration, and decreased soil water storage.

Drainage was not observed for the Sierra Blanca capillary barrier or predicted by any of the three models.

6.6 SUMMARY AND SYNTHESIS

The short-term performance of the monolithic cover systems at the Yucaipa and Albuquerque sites and the capillary barrier at the Sierra Blanca site were evaluated in Chapter 4 using data from field monitoring programs and in this chapter using the HELP, LEACHM, and UNSAT-H computer programs for water balance. Conclusions drawn from the water balance simulations are as follows:

- Based on the results of the simulations, the primary water balance components for the Albuquerque and Sierra Blanca cover systems were precipitation, evapotranspiration, and change in storage. These components as well as runoff and drainage were significant elements of the water balance for the Yucaipa cover system.

- The highest runoff values (up to 537 mm/yr) were predicted for the Yucaipa cover system and the lowest (up to 0.1 mm/yr) were predicted for the Albuquerque cover system. The primary reason for this is that the Yucaipa cover system was constructed with a relatively low permeability (8.7×10^{-8} m/s or 0.3 mm/hr) soil that impeded infiltration. The uncompacted soil layers at the surface of the Albuquerque and Sierra Blanca cover systems had saturated hydraulic conductivities that were up to one to two orders of magnitude greater than the saturated hydraulic conductivity of the Yucaipa cover system.
- The default precipitation intensity of 10 mm/hr formerly coded in UNSAT-H may not be appropriate for simulating the water balance of relatively low permeability cover systems, such as the Yucaipa cover system, that have surface layers with saturated hydraulic conductivities that are less than precipitation intensity. Using a precipitation intensity that is higher than the actual intensity would tend to result in the over-prediction of runoff and the under-prediction of drainage for these cover systems (Table 6.4). Conversely, assuming a precipitation intensity that is lower than the actual intensity would tend to result in the under-prediction of runoff and the over-prediction of drainage.
- Varying precipitation intensity from 1 mm/hr to 10 mm/hr had no significant effect on the simulated water balance for the Albuquerque and Sierra Blanca cover systems.
- Less runoff was predicted with LEACHM than with UNSAT-H. The primary reason for this may be the hydraulic conductivity functions used by the models. The Campbell-Burdine hydraulic conductivity function is

incorporated into the LEACHM model, and the van Genuchten-Mualem hydraulic conductivity function was specified for simulations with the UNSAT-H model. All else being equal, lower runoff rate, higher infiltration rates, and higher evaporation rates are predicted when the Campbell-Burdine hydraulic conductivity function, rather than the van Genuchten-Mualem function, is used.

- When hysteresis was considered, more runoff and less infiltration were predicted with UNSAT-H. Less infiltration was simulated because air was assumed to be entrapped in 10% of the soil voids. Due to these air voids, the maximum hydraulic conductivity of the surface of the cover systems was effectively reduced. It is noted that in contrast to the water balance simulations for the Sierra Blanca cover system presented in this chapter, Scanlon et al. (2002) did not find hysteresis to significantly influence the water balance of the Sierra Blanca cover system. The reason for this difference is unclear, but may be related to the way that precipitation was applied. In the Scanlon et al. (2002) study, net precipitation, i.e., measured precipitation minus measured runoff, was used as input.
- Consistent with the monitoring results, water storage in the cover systems increased during precipitation events and decreased in the summer due to high potential evapotranspiration.
- Trends in soil water storage were best predicted with UNSAT-H, though predictions with LEACHM were also reasonable.
- The highest drainage rates for the Yucaipa and Albuquerque cover systems were predicted with HELP.

- Drainage for the Yucaipa cover system was predicted by all models. Because drainage was not monitored at the site, the accuracy of the predictions cannot be accessed.
- Zero drainage was measured for the Albuquerque and Sierra Blanca cover systems, and zero drainage was predicted with UNSAT-H. Both of these cover systems are underlain by lysimeters, which tend to increase soil water storage and decrease drainage. Zero drainage for the Albuquerque cover system was also predicted with LEACHM, and zero drainage for the Sierra Blanca cover system was also predicted with HELP.
- Drainage for the Sierra Blanca cover system was only predicted with LEACHM and only predicted during one precipitation event during the first simulation year.
- The comparison of simulated and measured drainage for the considered sites was not ideal because drainage was not monitored at the Yucaipa site and zero drainage was measured at the Albuquerque and Sierra Blanca sites.
- The uncalibrated simulations predict the water balance of the cover systems reasonably well. The measured water balances were generally bounded by the water balances predicted using the three models.

Chapter 7: Intermediate-Term and Long-Term Performance Assessment -- Numerical Modeling Results for Study Sites

7.1 INTRODUCTION

When an evapotranspirative cover system is used in a containment application, the performance of the cover system has to be demonstrated to a regulatory agency through monitoring, typically combined with modeling, or by modeling alone. If the soils in a cover system have not equilibrated with the natural environment and "permanent" vegetation has not been established during a short-term (2 to 5-year) monitoring period, the performance observed during the monitoring period may bear no resemblance to the intermediate-term or long-term performance of the cover system (Figure 7.1). This has been demonstrated for conventional cover systems with compacted clay barriers that tend to desiccate and crack over time. Thus, the results of a short-term field water balance, such as those presented for the Yucaipa, Albuquerque, and Sierra Blanca cover systems in Chapter 4, provide just a snapshot of cover system performance in time. As suggested by Fayer and Gee (1997), when trying to predict the performance of a cover system over hundreds or even thousands of years, monitoring periods of 30 years or more may be needed to capture significant hydrologic events.

Modeling of cover system performance has often been performed using input parameters, e.g., saturated hydraulic conductivities and initial water contents, that are based on construction specifications or that are representative of cover system conditions after construction. However, this may not be the most critical condition. A more critical condition might be at sometime in the future when the cover system soil is closer to equilibrium conditions with the natural environment.

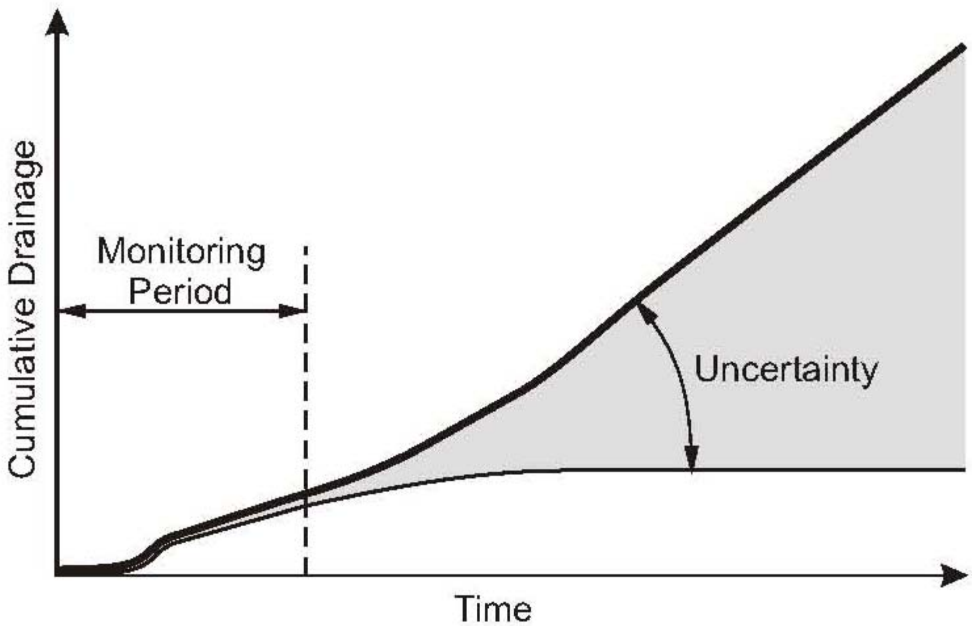

Figure 7.1: Uncertainty in the Water Balance of a Cover System.

A number of factors that affect the reliability of short-term performance assessments of evapotranspirative cover systems were discussed in this dissertation and are listed in Table 7.1. This list is it not intended to be all inclusive, i.e., there are other factors not discussed herein that could affect the reliability of performance assessments.

The reliability of short-term water balance monitoring is primarily affected by instrumentation limitations. The instruments often either monitor such a small area that they do not capture the overall water balance parameter they are intended to measure or the presence of the instruments affects the water balance. In addition, instruments may be affected by their environment, i.e., temperature, instruments may not provide measurements with sufficient accuracy to assess the water balance parameter they are intended to measure, and data may be lost due to power outages.

Table 7.1: Factors that May Affect the Reliability of Short-Term Performance Assessments of Evapotranspirative Cover Systems.

Factors that May Affect Water Balance Monitoring
Preferential flow, both vertical and interlayer (parallel to slope), that occurs and is not captured by sensors placed at discrete locations in the cover system Effect of pan lysimeter on hydraulic gradients at lower boundary of cover system Effect of pan lysimeter on vapor flow at lower boundary of cover system Effect of supplemental storage of lysimeter, e.g., wrinkles along geomembrane lower boundary and soil between cover system and geosynthetics, on measured drainage Effect of looser soil around sensors and sensor cables installed during construction on soil hydraulic properties and water redistribution Preferential flow along sensors that are installed after construction and extend above the ground surface, e.g., TDR and vertical access tubes for neutron probes Effect of temperature on soil dielectric content and, thus, TDR readings Effect of soil salinity and high clay content on TDR readings Effect of adjacent gravel particles on TDR readings Effect of air gaps between sensors and soil, i.e., non-intimate contact, on sensor readings Sensor damage during installation Effect of sediment load on instruments used to monitor runoff Biased readings of water contents and matric potentials that occur when monitoring is only conducted at a few discrete locations that are not representative of average cover system conditions Pioneer plant species that become temporarily established and alter the field water balance Data loss due to animals/mowers severing power cables or lightning strikes
Processes and Parameters that May Affect the Results of Water Balance Simulations
Processes that May Not Be Considered in a Water Balance Model Precipitation intensity Evaporation during precipitation Interception Effect of surface slope on runoff Freeze and thaw of cover system surface Snow accumulation and melt Formation of a surface crust Lateral flow in a sloping cover system Preferential flow Hysteresis in SWCC and hydraulic conductivity function Change in soil hydraulic conductivity over time Temperature effect on hydraulic conductivity Effect of applying empirical methods used to evaluate transpiration of corn to cover system plants Multiple plant species Plant growth dynamics Isothermal and thermal vapor flow Thermal water flow
Processes and Parameters that Are Difficult to Assess or Are Infrequently Measured Precipitation intensity Field SWCC and hydraulic conductivity function SWCC and hydraulic conductivity function at high matric potentials Plant parameters (leaf area index, root depth) Initial conditions (representative matric potential or water content)

The reliability of short-term water balance modeling is primarily affected by uncertainty in values of input parameters that are frequently assumed and not measured and by processes that are not included in a model.

To better understand the effects of different processes and stressors on cover system performance, it is important to understand the time-scale of these processes and stressors. Short-term stresses, such as fire or an El Niño, would typically only affect cover system performance for a short period, such as one to five years. Long-term stresses, however, such as climate change can have a much greater impact on the water balance of a cover system. Factors that may affect the reliability of long-term performance assessments of evapotranspirative cover systems and that were discussed in this dissertation are listed in Table 7.2. While facilities that manage municipal solid waste have had to consider the effects of short-term and, sometimes, intermediate-term changes on the performance of containment facilities, facilities that manage radioactive wastes have had to consider the these effects as well as the effects of long-term changes.

Table 7.2: Factors that May Affect the Reliability of Long-Term Predictions of the Water Balance for Evapotranspirative Cover Systems.

Climate change
Change in soil structure (wetting and drying cycles, freezing and thawing cycles, earthworm action, root penetration)
Soil calcification
Effect of climate change on vegetation
Effect of soil change on vegetation
Vegetation succession
Vegetation competition (exotics)
Vegetation herbivory

An evaluation of the suitability of the short-term performance assessments of the Yucaipa, Albuquerque, and Sierra Blanca cover systems to predict the intermediate-term (10 to 30-year) performances of these cover systems is presented in Section 7.2. This evaluation was conducted by simulating the water balances of the cover systems with 30 years of historical weather data from nearby weather stations and comparing the results of these simulations to the results of the short-term performance assessments. The intent of the evaluation was to reveal: (i) whether the short-term performance assessments were controlled by the initial soil matric potentials and water contents that existed after construction; and (ii) if the meteorological conditions that existing during the monitoring periods were representative of intermediate-term conditions. Other important factors that may affect the intermediate-term performance assessment, such as changes in the saturated hydraulic conductivity over time, were not considered.

The long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems at the Albuquerque site was also evaluated. One cover system is constructed with loosely placed soil to promote plant growth and the other is designed with a compacted soil having a low saturated hydraulic conductivity. The possible long-term performance of these cover systems was evaluated using interval analysis that considers long-term soil density, vegetation, and precipitation. The results of this analysis are presented in Section 7.3.

7.2 INTERMEDIATE-TERM PERFORMANCE ASSESSMENT

7.2.1 MODEL INPUT

The intermediate-term water balances of the evapotranspirative cover systems at the Yucaipa, Albuquerque, and Sierra Blanca sites were simulated with UNSAT-H using 30 years of historic weather data. UNSAT-H was selected for these simulations because, based on the comparison of monitoring and modeling results for these sites presented in Chapter 6, UNSAT-H predicts the water balance of these cover systems better than the HELP and LEACHM models. Unless otherwise noted, the soils, vegetation, and modeling data used as input for UNSAT-H are the same as previously presented in Section 6.2.

Measured daily weather data from 1961 to 1990 were obtained from the United States Department of Agriculture's (USDA's) Generation of weather Elements for Multiple applications (GEM) database (USDA, 2004). For the Yucaipa site, historical 30-year meteorological data for the Daggett FAA Airport weather station, located about 90 km north-northwest of the site, were used for the simulation. However, the precipitation data for Daggett were replaced with data from Beaumont, California weather station (Beaumont 1E), located about 15 km south of the site. The daily precipitation for the Daggett station is not representative of the Yucaipa site as the Daggett site is located on the eastern slopes of the Sierra range and is protected from some of the coastal rain that falls at the Yucaipa site. For the Albuquerque site, 30-year weather data for the Albuquerque WFSO Airport weather station, located about 11 km northwest of the site, were used. For the Sierra Blanca site, data from the El Paso weather station, located about 150 km northwest of Sierra Blanca, were used.

For the Albuquerque and Sierra Blanca cover systems, daily precipitation was applied in the simulations at an intensity of 10 mm/hr. Based on the results of the numerical modeling presented in Chapter 6, the simulated water balances for these cover systems are not that sensitive to precipitation intensities ranging from 1 to 10 mm/hr. The water balance simulated for the Yucaipa cover system is sensitive to precipitation intensity. Therefore, precipitation intensities of 1 and 10 mm/hr were used in the water balance simulations conducted for this cover system.

A unit gradient was used as the boundary condition for the bottom of the cover systems in all simulations. Depending on the characteristics of the material underlying a cover system, this assumption may be conservative, i.e., drainage would be overestimated. For example, if the Albuquerque cover system were placed over municipal solid waste, the large pore openings in the waste may cause the waste to act as a capillary break beneath the cover system, i.e., the lower boundary may be more like a seepage face boundary than a unit gradient boundary. It is noted that this simplification of the boundary condition between a monolithic cover system and municipal solid waste does not address the effects of water vapor and heat flow through the cover system from the landfill to the atmosphere.

The results of the 30-year simulations are summarized in Tables 7.3 to 7.6 and shown in Figures 7.2 to 7.5.

7.2.2 MODELING RESULTS FOR YUCAIPA SITE

The dominant parameters in the simulated water balance for the Yucaipa cover system are precipitation, runoff, and evapotranspiration (Figures 7.2 and 7.3). Annual precipitation at the Yucaipa site is influenced by periodic El Niños and La Niñas and is more variable than annual precipitation at the Albuquerque and Sierra Blanca sites (Figures 7.4 and 7.5, respectively). Therefore, it is more likely that, in comparison to the Albuquerque and Sierra Blanca sites, the intermediate-term precipitation pattern at the Yucaipa site would generally not be captured in short-term monitoring and simulation periods.

Consistent with the short-term performance assessment of this cover system, Runoff (93 to 655 mm) and drainage (0.9 to 51 mm) were predicted each year of the 30-year simulation period and varied with annual precipitation when daily precipitation was applied at an intensity of 1 mm/hr. When daily precipitation was applied at an intensity of 10 mm/hr, the Yucaipa cover system exhibited a drying trend, with soil water storage and annual drainage decreasing over time (Figure 7.3). Only daily precipitation data are available for the intermediate-term simulations. Depending on the actual intensity of daily precipitation over the 30-year record, the short-term water balance for this cover system may have been affected by the relatively high water content of the cover system soils after construction. When precipitation intensities are relatively high, more runoff is predicted and less infiltration occurs. Consequently, soil water storage decreases. Over time, as the cover system loses more water and approaches equilibrium conditions, the rate of evapotranspiration will decrease and the soil water storage will stabilize.

Table 7.3: Intermediate-Term Water Balance Simulated for the Yucaipa Monolithic Cover System with UNSAT-H and a Precipitation Intensity of 1 mm/hr.

Year	Precipitation (mm)	Potential Evapotrans. (mm)	Runoff (mm)	Evapotrans. (mm)	Storage (mm)	Change in Storage (mm)	Drainage (mm)
					195[1]		
1961	200	1255	105	88	202	6	0.9
1962	353	1266	210	134	204	2	2
1963	400	1222	232	166	202	-2	3
1964	250	1227	130	113	205	4	2
1965	614	1185	410	140	257	52	3
1966	393	1245	301	104	234	-23	9
1967	492	1215	297	187	232	-2	7
1968	216	1266	109	129	205	-27	5
1969	754	1246	567	155	212	7	16
1970	422	1253	280	107	237	25	6
1971	297	1253	160	131	236	-0.5	4
1972	184	1246	93	106	218	-19	3
1973	447	1255	287	139	222	4	12
1974	414	1296	269	130	224	2	9
1975	376	1258	218	157	216	-8	6
1976	434	1217	297	127	216	0.6	6
1977	433	1206	288	128	227	10	4
1978	917	1198	655	174	244	17	51
1979	437	1205	287	146	216	-28	26
1980	819	1216	606	154	215	-0.7	42
1981	311	1275	164	135	220	4	6
1982	724	1168	489	201	238	19	10
1983	860	1163	563	232	243	5	45
1984	362	1244	201	148	247	4	6
1985	292	1230	163	146	222	-24	6
1986	405	1240	246	155	217	-5	6
1987	442	1214	260	165	229	12	4
1988	310	1252	184	124	226	-3	3
1989	272	1275	163	131	200	-26	3
1990	302	1248	156	143	199	-1	3
Average	438	1235	280	143	222	-	10
Standard Deviation	196	32	154	30	15	-	13

[1] Measured storage at beginning of monitoring period

Table 7.4: Intermediate-Term Water Balance Simulated for the Yucaipa Monolithic Cover System with UNSAT-H and a Precipitation Intensity of 10 mm/hr.

Year	Precipitation (mm)	Potential Evapotrans. (mm)	Runoff (mm)	Evapotrans. (mm)	Storage (mm)	Change in Storage (mm)	Drainage (mm)
					195[1]		
1961	200	1255	146	58	191	-5	0.9
1962	353	1266	281	79	182	-8	1.0
1963	400	1222	316	88	177	-5	0.8
1964	250	1227	189	61	177	-0.3	0.6
1965	614	1185	516	90	185	8	0.5
1966	393	1245	352	48	178	-7	0.4
1967	492	1215	392	104	174	-4	0.3
1968	216	1266	162	62	166	-8	0.3
1969	754	1246	661	93	164	-1	0.2
1970	422	1253	354	60	172	8	0.2
1971	297	1253	231	65	173	1	0.2
1972	184	1246	134	58	164	-9	0.2
1973	447	1255	367	83	161	-3	0.2
1974	414	1296	339	72	164	3	0.1
1975	376	1258	284	96	160	-4	0.1
1976	434	1217	373	62	159	-0.3	0.1
1977	433	1206	363	65	165	5	0.1
1978	917	1198	803	113	166	1	0.1
1979	437	1205	359	84	160	-6	0.09
1980	819	1216	721	97	161	1.1	0.09
1981	311	1275	233	76	162	2	0.09
1982	724	1168	606	115	166	3	0.09
1983	860	1163	717	142	167	1	0.09
1984	362	1244	280	80	169	2	0.09
1985	292	1230	223	77	161	-8	0.09
1986	405	1240	327	80	158	-3	0.08
1987	442	1214	349	91	160	2	0.08
1988	310	1252	245	66	160	-0.6	0.08
1989	272	1275	216	65	151	-9	0.07
1990	302	1248	225	77	151	0.6	0.07
Average	438	1235	359	80	167	-	0.2
Standard Deviation	196	32	178	20	9	-	0.3

[1] Measured storage at beginning of monitoring period

Even though the short-term performance of the Yucaipa cover system was only evaluated with 30-months of monitoring data, it was generally representative of intermediate-term performance, assuming that the intensity of precipitation during the short-term monitoring period, i.e., approximately 1 mm/hr, is similar to the intensity of precipitation over the 30-year record. The Yucaipa cover system was monitored during a relatively wet year, as well as during a relatively dry year, thereby capturing the climatic variations of the site.

Table 7.5: Intermediate-Term Water Balance Simulated for the Albuquerque Monolithic Cover System with UNSAT-H and a Precipitation Intensity of 10 mm/hr.

Year	Precipitation (mm)	Potential Evapotrans. (mm)	Runoff (mm)	Evapotrans. (mm)	Storage (mm)	Change in Storage (mm)	Drainage (mm)
					184[1]		
1961	225	2027	0.0	237	175	-9	1
1962	137	1945	0.0	137	173	-2	2
1963	190	2173	0.0	199	162	-11	1
1964	189	1905	0.0	191	158	-4	1
1965	236	1945	0.0	216	177	19	1
1966	173	2157	0.0	194	156	-22	1
1967	204	2284	0.0	202	157	1	1
1968	271	2122	0.0	261	166	9	1
1969	268	2183	0.0	247	187	21	2
1970	160	2230	0.0	182	163	-24	2
1971	204	2316	0.0	177	188	26	1
1972	257	2270	0.0	255	189	1	4
1973	276	2069	0.0	290	172	-17	3
1974	250	2201	0.0	231	187	15	3
1975	203	2151	0.0	219	169	-19	2
1976	132	2217	0.0	141	157	-11	1
1977	201	2155	0.0	194	163	5	1
1978	279	2149	0.0	254	187	24	2
1979	263	2073	0.0	261	187	0	2
1980	225	2096	0.0	228	182	-5	2
1981	195	2127	0.0	200	174	-8	2
1982	188	2049	0.0	186	175	1	2
1983	197	1982	0.0	195	175	0	2
1984	307	2068	0.0	270	211	35	2
1985	273	1898	0.0	285	194	-17	5
1986	330	1931	0.0	325	193	-1	5
1987	212	2006	0.0	225	176	-17	4
1988	333	2036	0.0	326	181	5	3
1989	127	2339	0.0	135	170	-11	3
1990	260	2069	0.0	255	173	4	2
Average	226	2106	0.0	224	176	-	2
Standard Deviation	55	121	0.0	49	13	-	1

[1] Measured storage at beginning of monitoring period

Table 7.6: Intermediate-Term Water Balance Simulated for the Sierra Blanca Capillary Barrier with UNSAT-H and a Precipitation Intensity of 10 mm/hr.

Year	Precipitation (mm)	Potential Evapotrans. (mm)	Runoff (mm)	Evapotrans. (mm)	Storage[1] (mm)	Change in Storage (mm)	Drainage (mm)
					390[2]		
1961	195	2329	10	166	410	11	0.0
1962	210	2140	16	204	380	12	0.0
1963	125	2207	0.3	131	384	-40	0.0
1964	136	2328	10	120	396	12	0.0
1965	137	2204	8	133	387	-7	0.0
1966	235	2104	17	224	383	-4	0.0
1967	145	2265	2	135	398	-13	0.0
1968	305	1951	27	267	402	3	0.0
1969	110	2181	0.1	117	383	-18	0.0
1970	154	2253	0.1	168	376	-1	0.0
1971	184	2341	10	164	399	5	0.0
1972	229	2168	13	206	400	7	0.0
1973	191	2201	9	202	370	-20	0.0
1974	354	2173	34	250	460	82	0.0
1975	158	2179	12	188	348	-55	0.0
1976	258	2025	9	241	397	-16	0.0
1977	140	2149	3	148	378	-15	0.0
1978	319	2080	29	254	426	62	0.0
1979	148	2100	3	189	346	-59	0.0
1980	186	2053	4	167	404	8	0.0
1981	321	1975	22	298	390	9	0.0
1982	279	1949	29	200	440	62	0.0
1983	203	1965	3	247	343	-69	0.0
1984	411	1967	36	335	429	13	0.0
1985	207	1671	7	235	356	-9	0.0
1986	309	1719	20	267	412	-3	0.0
1987	278	1871	18	253	397	-6	0.0
1988	281	1925	11	301	360	14	0.0
1989	184	2075	6	191	377	-14	0.0
1990	326	2053	27	261	428	62	0.0
Average	224	2087	13	209	392	-	0.0
Standard Deviation	79	165	11	58	28	-	0.0

[1] Storage in upper 2-m of cover system
[2] Measured storage in upper 2-m of cover system at beginning of monitoring and simulation periods

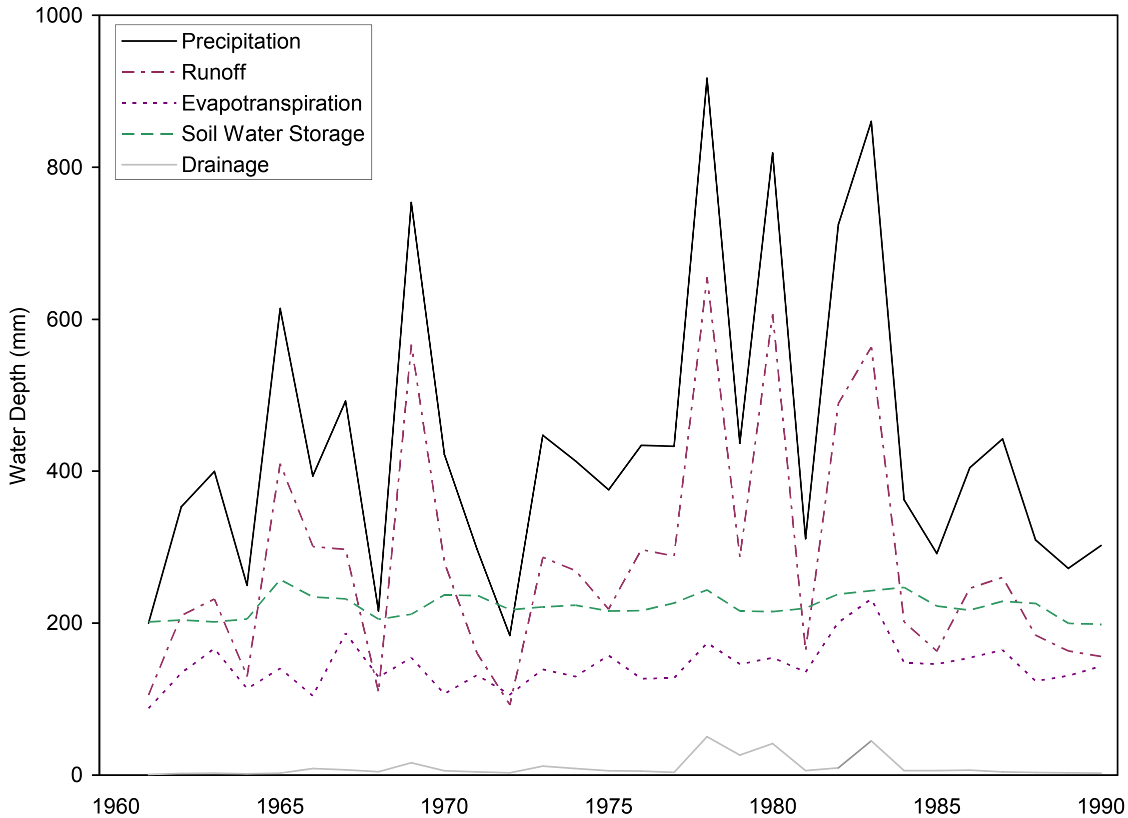

Figure 7.2: Intermediate-Term Water Balance Simulated for the Yucaipa Monolithic Cover System with UNSAT-H and a Precipitation Intensity of 1 mm/hr.

7.2.3 MODELING RESULTS FOR ALBUQUERQUE SITE

The dominant parameters in the simulated water balance for the Albuquerque cover system are precipitation and evapotranspiration (Figure 7.4). Zero runoff and small amounts of drainage (1 to 5 mm) were predicted each year of the 30-year simulation. When storage approached 170 mm, drainage occurred. In his evaluation of monitoring data for the Albuquerque site, Dwyer (2003) concluded that the monolithic cover system would store about 210 mm of water before draining when the lower boundary is a seepage face. If that is the case, then the capillary barrier at this site appears to increase storage by about 40 mm.

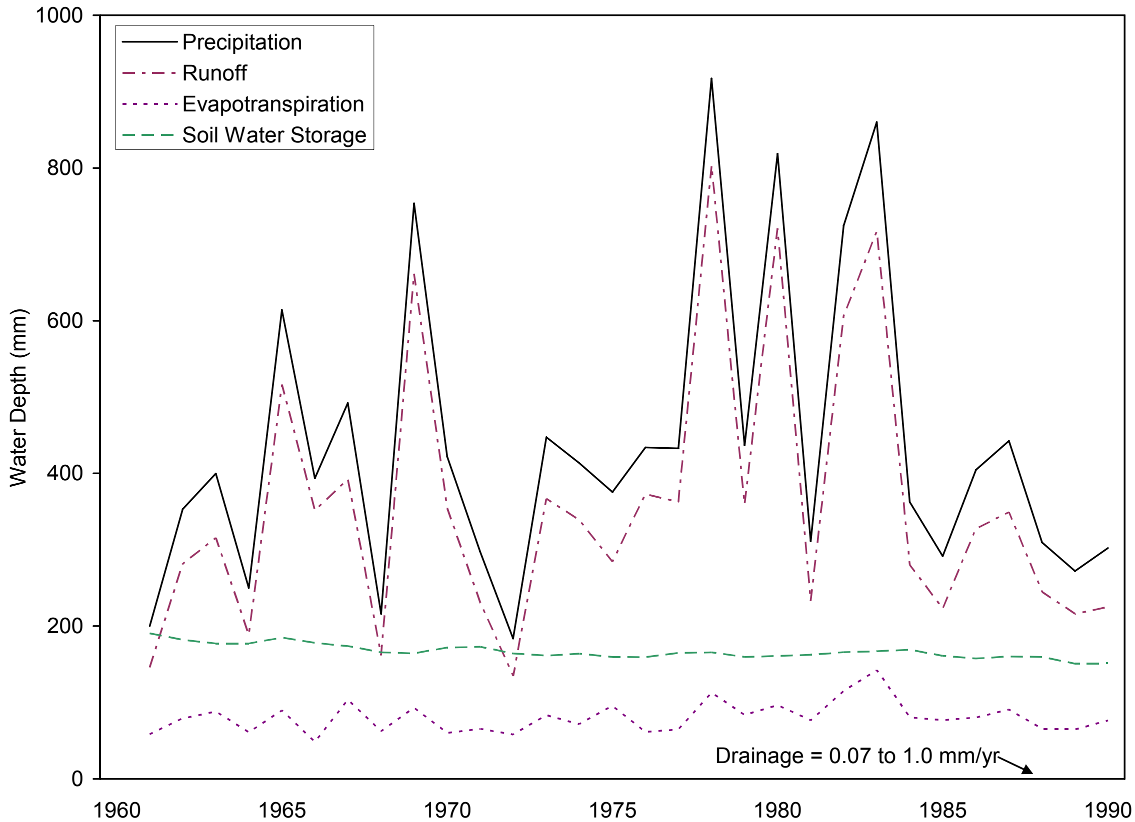

Figure 7.3: Intermediate-Term Water Balance Simulated for the Yucaipa Monolithic Cover System with UNSAT-H and a Precipitation Intensity of 10 mm/hr.

The short-term performance assessment for the monolithic cover system at the Albuquerque site was conducted with the cover system underlain by a capillary break induced by a lysimeter. Drainage was not measured or predicted during the short-term performance assessments. Because the Albuquerque cover system was designed as a monolithic cover, not as a capillary barrier, the capillary break was not included in the intermediate-term simulations. Consequently, small amounts of drainage were predicted in these simulations. Even through the Albuquerque cover system was monitored during relatively wet years, as well as during a relatively dry years, thereby capturing the climatic variations of the site, the short-term assessment of drainage was not representative of intermediate-term performance presumably due to the capillary break. Even so, the annual drainage rates predicted in the intermediate-term performance assessment were small.

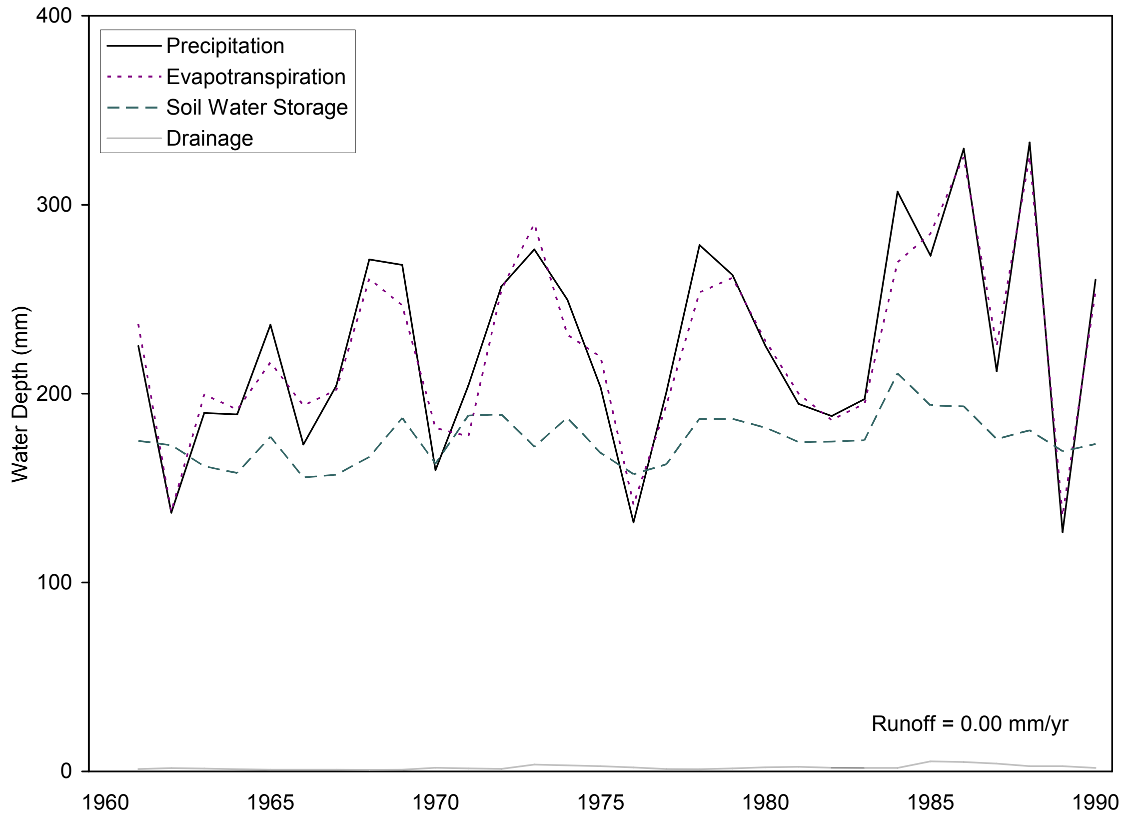

Figure 7.4: Intermediate-Term Water Balance Simulated for the Albuquerque Monolithic Cover System with UNSAT-H and a Precipitation Intensity of 10 mm/hr.

7.2.4 MODELING RESULTS FOR SIERRA BLANCA SITE

The dominant parameters in the simulated water balance for the Sierra Blanca cover system are precipitation and evapotranspiration and, secondarily, change in storage (Figure 7.5). Consistent with the short-term performance assessment of this cover system, small amounts of runoff (0.1 to 36 mm) and zero drainage were predicted each year of the 30-year simulation.

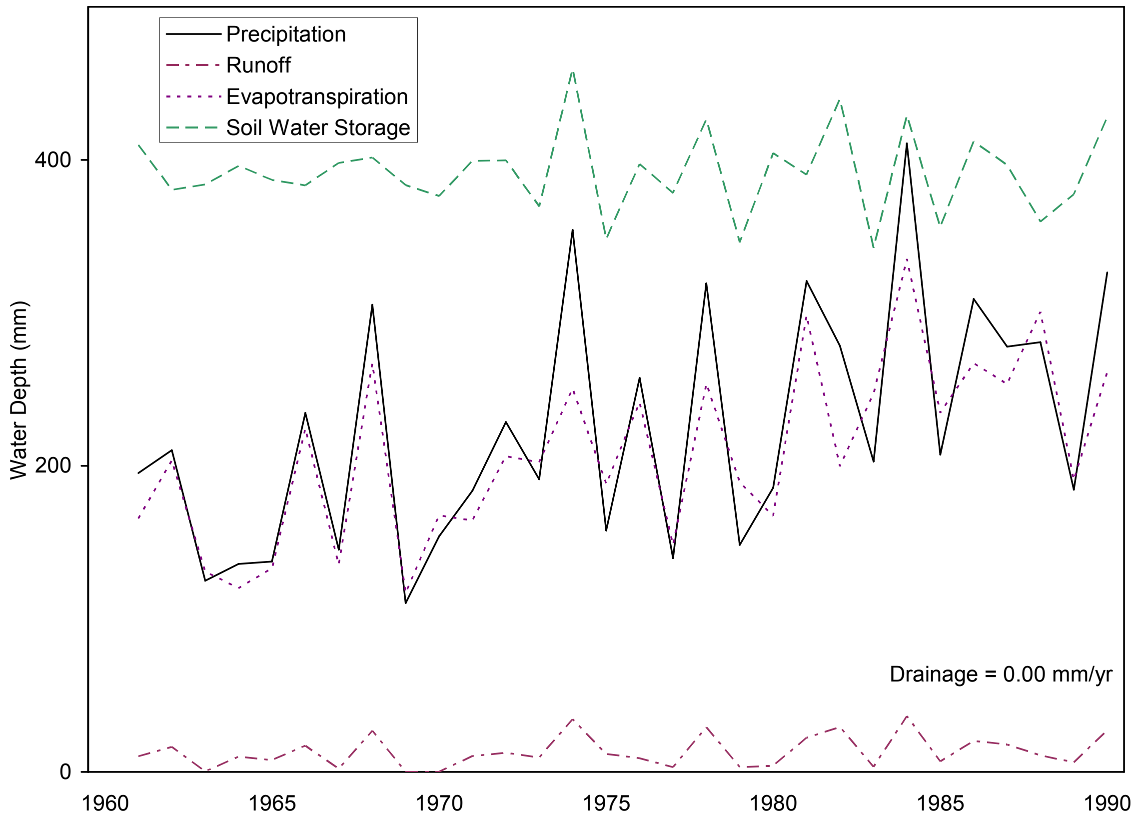

Figure 7.5: Intermediate-Term Water Balance Simulated for the Sierra Blanca Capillary Barrier with UNSAT-H and a Precipitation Intensity of 10 mm/hr.

The short-term performance assessments for the Sierra Blanca cover system did not capture the relatively wet years or larger changes in storage predicted with the intermediate-term simulations. Although both short-term and intermediate-term performance assessments demonstrated that essentially no drainage would be anticipated for this cover system, this was fortuitous. While the results of the short-term performance assessments suggest that a thinner cover system could be use, a thinner cover system may exhibit drainage when subjected to the precipitation stresses expected in the intermediate term.

7.3 Interval Analysis of Long-Term Performance of Two Hypothetical Evapotranspirative Cover Systems at the Albuquerque Site

The purpose of this section is to evaluate the long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems at the Albuquerque site. One of the cover systems has the same profile as a monolithic cover system that was constructed at the Albuquerque site, i.e., 15-mm of uncompacted loamy sand overlying 900-mm of compacted loamy sand. The cover system is referred to herein as the monolithic cover with dense soil. The second cover system, referred to herein as the monolithic cover with loose soil, consists of 1050-mm of uncompacted loamy sand. These cover systems were selected to test two competing philosophies regarding the compaction of soils used to construct evapotranspirative cover systems. By definition, it would seem that any evapotranspirative cover system would include a relatively thick uncompacted soil layer that has the capacity to support vegetation and, even more than that, create conditions for vegetation to thrive. However, this has not often been the case, at least in the past when the three cover systems evaluated herein were constructed. All three of the cover systems were constructed with compacted soils that, according to the NRCS (Table 2.1), had sufficiently high bulk densities to impede root growth. It is noted that the cover system soils at the Yucaipa site were required to be compacted to provide slope stability under seismic loading.

The Albuquerque site was selected for this numerical study because the 30-year simulations conducted for this site with UNSAT-H were stable, had low mass error, and could be conducted in a reasonable time, i.e., 6 hours versus about 36 hours for each 30-year simulation of the Yucaipa cover system. In addition, this site was one with a relatively thin (150 mm) uncompacted soil layer overlying a compacted soil layer that could be used to develop the input data needed for the simulations.

The water balances of the two cover systems were simulated with UNSAT-H using 30 years of historic weather data for the Albuquerque WFSO Airport weather station. Unless otherwise noted, the soils, vegetation, meteorological, and modeling data used as input for UNSAT-H are the same as previously presented in Section 7.2 for the Albuquerque cover system. Daily precipitation was applied at an intensity of 10 mm/yr.

The long-term reliability of the two cover systems was assessed using an interval analysis that considered the impacts of potential long-term soil density, vegetation, and precipitation. An interval analysis is an uncertainty analysis technique that is used to bound possible output scenarios based on the bounds of the model input. It is different from a sensitivity analysis in that is it focused on the uncertainty of the system rather than on the effect of a parameter on the performance of a system. The conditions of a cover system will change over time. Understanding the bounds for these changes is important in designing evapotranspirative cover systems that function for hundreds or even thousands of years. As shown in Figure 7.1, the uncertainty of the performance of a cover system increases as it extrapolated further in time. The reliability of the cover systems was assessed by simulating the potential range of drainage from these cover systems that could occur under potential long-term scenarios.

Factors that may affect the reliability of long-term performance predictions for evapotranspirative cover systems were presented in Table 7.2. The potential effects of two of these factors, climate change and the effect of climate change on vegetation, were considered for the interval analysis. Climate change was assumed to result in a three-fold increase in average annual precipitation. Three times average annual precipitation is currently used for long-term simulations of the cover systems at the Hanford Site (Gee et al., 1997a). The increased precipitation may increase the depth of roots in the monolithic cover with loose soil, but was assumed to have no impact on depth of roots in the monolithic cover with dense soil, i.e., the dense soil was assumed to impede vertical growth of roots.

The monolithic cover with dense soil and the monolithic cover with loose soil have a maximum depth that roots can penetrate. For the monolithic cover with dense soil, this depth was assumed to be 150 mm, the thickness of uncompacted soil in the cover system profile. For the monolithic cover with loose soil, the rooting depth was assumed to depend on rainfall. Based on maximum root depth data presented in Schenk and Jackson (2002), under average annual rainfall conditions at the Albuquerque site, grasses can have a maximum root depth of approximately 450 mm. This rooting depth was assumed to apply to the monolithic cover with loose soil. If average rainfall is increased by a factor of three and maintained for a sustained period, it is anticipated that the vegetation type would change from grasses to deeper-rooted plants, such as shrubs. A root depth of 900 mm was used for this scenario.

The precipitation and root depth also influence the leaf area index of vegetation. For the monolithic cover with dense soil and roots that penetrate only 150 mm, the leaf area index was assumed to be 0.32, i.e., the value measured by Dwyer (2003). Under enhanced precipitation conditions, i.e., three times average annual precipitation, the maximum leaf area index of the dense cover was assumed to double to 0.64 based on the geographic distribution of maximum leaf area indicies presented in the HELP model documentation (Schroeder et al., 1994b). For the monolithic cover with loose soil, the leaf area index was assumed to be 1.0 under conditions of average annual precipitation and 2.0 under conditions of enhanced precipitation based on the geographic distribution of maximum leaf area indicies presented in Schroeder et al. (1994b).

Plant roots may increase the hydraulic conductivity of the soil, and more vigorous plants with a higher leaf area index may increase soil hydraulic conductivity more than plants with a lower leaf index (Schroeder et al., 1994b). The effect of plant roots on soil hydraulic conductivity was not considered in the interval analysis, but would have resulted in greater differences in drainage between the vegetated cover system with loose soil and the vegetated cover system with dense soil.

One of the disadvantages to using a cover system with loosely placed soil is that the performance of the cover system becomes more dependent on the vitality of the vegetation. Because it is more permeable than a cover system with denser soil, more water can infiltrate a cover system with loosely placed soil when vegetation is dormant or disturbed. During the cover system's life, the vegetation may be disturbed at times by range fires, droughts, disease, or some other phenomenon. In these circumstances, late successional vegetation may not reestablish itself on the cover system for a long time, e.g., up to 100 years (Waugh et al., 1994; Link et al., 1994). Therefore, the effect on cover system performance of having no plants was also evaluated.

The cover system scenarios that were considered for the interval analysis and the results of the water balance simulations with UNSAT-H are outlined in Figure 7.6. The effect of a capillary break on average annual drainage was also evaluated to determine if installation of a capillary break, e.g., a gravel layer, beneath a monolithic cover could increase the reliability of the cover under extreme conditions. The capillary break was modeled using the same procedures as in Chapter 6: a 0.1-m thick gravel layer was added to the bottom of the cover system, and a unit gradient boundary was applied at the bottom of the gravel layer.

As shown in Table 7.6, under conditions of average annual precipitation, simulated drainage from the vegetated cover system with loose soil and deep roots is somewhat less than simulated drainage from the vegetated cover system with dense soil and shallow roots. However, simulated drainage from both vegetated systems is small, i.e., less than 2 mm/yr. If vegetation is lost, e.g., due to fire, simulated drainage rates increase, with the calculated drainage rate from a cover system with loose soil being almost two times greater than than from a cover system with dense soil, i.e., 29 mm/yr versus 16 mm/yr.

Cover System	**Precipitation**	**Vegetation**	**Capillary Break**	**Average Annual Drainage (mm)**
Monolithic Cover with Dense Soil	Average Annual Precipitation	No Plants	No Capillary Break	16
			Capillary Break	0.8
		Leaf Area Index = 0.32 Root Depth = 150 mm	No Capillary Break	2
			Capillary Break	0.0
	Three Times Average Annual Precipitation	No Plants	No Capillary Break	165
			Capillary Break	152
		Leaf Area Index = 0.64 Root Depth = 150 mm	No Capillary Break	97
			Capillary Break	76
Monolithic Cover with Loose Soil	Average Annual Precipitation	No Plants	No Capillary Break	29
			Capillary Break	2
		Leaf Area Index = 1 Root Depth = 450 mm	No Capillary Break	0.1
			Capillary Break	0.0
	Three Times Average Annual Precipitation	No Plants	No Capillary Break	301
			Capillary Break	275
		Leaf Area Index = 2 Root Depth = 900 mm	No Capillary Break	34
			Capillary Break	9

Figure 7.6: Results of Interval Analysis of Long-Term Performance of Hypothetical Cover Systems.

Because a looser soil is more conductive and promotes relatively deep rooting, it is easier for water to evaporate and transpire from a looser soil as compared to a denser soil. It is also easier for plants to become established in looser soils. In semi-arid and arid climates, a cover system with loosely placed soil that will promote plant growth may be preferred over a cover system with dense soil when the cover system is only required to maintain its functionality for intermediate timeframes or less, e.g., have a service life of 30 years. As is evidenced from the Albuquerque and Sierra Blanca cover systems, which were constructed with dense soils, even four to five years after vegetation was planted, it was not established at these sites. It may be that a looser soil would promote plant growth and result in more vigorous vegetation in the same period. The enhanced vegetation associated with loose soils also provides erosion control and esthetic qualities.

The advantage of having a monolithic cover with looser soil and deeper roots may not carry over into wet climates where precipitation can exceed evapotranspiration, unless the plant roots are sufficiently deep. In these wetter climates, the performance of cover systems with loose soil is controlled by vegetation. As shown in Figure 7.6, if vegetation is lost, e.g., due to fire, high rates of drainage can occur.

The effect of a capillary break on average annual drainage was evaluated to determine if installation of a capillary break beneath a soil cover increases the reliability of the cover under extreme conditions. The results of the simulations, which are presented in Figure 7.6, indicated that a capillary break would reduce drainage from monolithic cover systems under ambient precipitation conditions. However, it would have less effect on drainage when precipitation with three times greater than the average annual precipitation. The capillary break is more beneficial for cover systems with loose soil than for cover systems with dense soil because there is a greater potential to increase the water storage capacity of loose higher porosity soils than for dense soils.

7.4 SUMMARY AND SYNTHESIS

An evaluation of the suitability of the short-term performance assessments of the Yucaipa, Albuquerque, and Sierra Blanca cover systems to predict the intermediate-term (10 to 30-year) performances of these cover systems was presented in Section 7.2. This evaluation was conducted by simulating the water balances of the cover systems with 30 years of historical weather data from nearby weather stations and comparing the results of these simulations to the results of the short-term performance assessments presented in Chapters 4 and 6. The long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems at the Albuquerque site was also evaluated using interval analysis with UNSAT-H simulations that consider long-term soil density, vegetation, and precipitation. Conclusions drawn from the evaluations are as follows:

- Even though the short-term performance of the Yucaipa cover system was only evaluated with 30-months of monitoring data, it was generally representative of intermediate-term performance, assuming that the intensity of precipitation during the short-term monitoring period is similar to the intensity of precipitation over the 30-year record. The Yucaipa cover system was monitored during a relatively wet year, as well as during a relatively dry year, thereby capturing the climatic variations of the site.
- The short-term performance assessment for the monolithic cover system at the Albuquerque site was conducted with the cover system underlain by a capillary break induced by a lysimeter. Because the Albuquerque cover system was designed as a monolithic cover, not as a capillary barrier, the short-term performance assessment is not representative of intermediate-term performance of this cover system.
- Small amounts (1 to 5 mm/yr) of drainage were predicted for the Albuquerque cover system in the intermediate-term performance assessments. Drainage was not

measured or predicted during the short-term performance assessments presumably due to the presence of a capillary break.

- The short-term performance assessments for the Sierra Blanca cover system were conducted during relatively dry years and did not capture the relatively wet years or larger changes in storage predicted with the intermediate-term simulations. Both short-term and intermediate-term performance assessments demonstrated that essentially no drainage would be anticipated for this cover system.
- In semi-arid and arid climates, a cover system with loose soil that promotes plant growth may be preferred to a cover system with dense soil when the cover system is only required to have an intermediate-term, e.g., 30-year, service life.
- The advantage of having a monolithic cover with looser soil and deeper roots may not carry over into wet climates where precipitation can exceed evapotranspiration, unless the plant roots are sufficiently deep. In these wetter climates, the performance of cover systems with loose soil is controlled by vegetation.
- If a longer service life, e.g., 100 years or more, is required, a cover system with dense soil may be preferred to a cover with loose soil because a dense soil provides more control of drainage than loose soil in the event that vegetation is lost or precipitation significantly increases.
- The results of the UNSAT-H simulations indicate that a capillary break would reduce drainage from the considered monolithic cover systems under ambient precipitation conditions. However, a capillary break is not as beneficial when precipitation with three times greater than the average annual precipitation.

Chapter 8: Conclusions and Recommendations

8.1 Scope of Dissertation

The focus of this dissertation is the water balance of monitored evapotranspirative cover systems constructed at sites in Yucaipa, California, Albuquerque, New Mexico, and Sierra Blanca, Texas. The short-term (2 to 5-year) performance of these cover systems was evaluated using the data from field monitoring programs and the results of numerical modeling conducted for this study and presented herein. The suitability of using short-term performance assessments to predict intermediate-term (10 to 30-year) performance of these cover systems was evaluated by comparing the short-term water balances to water balances simulated with 30 years of historical weather data from nearby weather stations. The long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems in Albuquerque, one designed with loosely placed soil to promote plant growth and the other designed with compacted soil having a low saturated hydraulic conductivity, was evaluated using numerical modeling with interval analysis and considering the effects of soil compaction, leaf area index, vegetation root depth, and amount of precipitation.

The objectives of the study are listed in Section 1.2. Contributions made by the research are listed in Section 8.2. Conclusions and recommendations developed from the work are presented in Sections 8.3 and 8.4, respectively. Future research is outlined in Section 8.5.

8.2 CONTRIBUTIONS OF DISSERTATION

The contributions of this dissertation are:

- a comprehensive assessment of the status of performance evaluations of evapotranspirative cover systems;
- an evaluation of the short-term (2 to 5-year) performance of three monitored evapotranspirative cover systems in the southwest U.S. with different precipitation patterns, i.e., winter precipitation versus summer precipitation;
- an evaluation of the suitability of using short-term performance assessments to predict intermediate-term (10 to 30-year) performances of the three cover systems; and
- a comparison of the long-term (100 years or more) reliability of two hypothetical evapotranspirative cover systems in Albuquerque, one designed with loosely placed soil to promote plant growth and the other designed with compacted soil having a low saturated hydraulic conductivity.

8.3 CONCLUSIONS

This section presents conclusions developed from this dissertation on the water balance of three monitored evapotranspirative cover systems in the semi-arid and arid southwest U.S. Specifically, conclusions are presented on computer models for water balance, field monitoring programs, the suitability of using short-term performance assessments to predict intermediate-term performance, the anticipated performance of the three evapotranspirative cover systems based on the results of the short-term and intermediate-term performance assessments, and the long-term comparative performance of evapotranspirative cover systems with loosely placed soil and with compacted soil. Summaries and syntheses of the work conducted for this dissertation were presented in Sections 4.6, 5.8, 6.6, and 7.4 and are not repeated herein.

8.3.1 Computer Models for Water Balance

Conclusions on computer models for water balance of evapotranspirative cover systems developed from the research presented in this dissertation are as follows:

- As demonstrated by the case studies for monitored evapotranspirative cover systems presented in Chapter 5 and by a comparison of the short-term monitoring and modeling results presented in Chapters 4 and 6, respectively, for the Yucaipa, Albuquerque, and Sierra Blanca sites, it is difficult to accurately simulate the field water balance of evapotranspirative cover systems. Part of the inaccuracy may be attributed to the methods used by the computer models to analyze the different water balance processes, e.g., the unit gradient assumption for vertical drainage layers that is coded in HELP. Inaccuracies may also be related to the difficulty in estimating key design parameters, such as unsaturated hydraulic conductivity as it varies with water contents measured in the field or even the saturated hydraulic conductivity existing in the field. Furthermore, a number of key design parameters, e.g., saturated hydraulic conductivity of soil and vegetation rooting depth, are expected to change over time.
- While calculated drainage from an evapotranspirative cover system may not be reliable in an absolute sense, cover system design often only requires consideration of the relative drainage between different cover system configurations. When evaluating relative drainage between different cover systems, the inaccuracies in water balance simulations are often less important than when evaluating the absolute water balance of a cover system.
- Runoff was often not accurately predicted by the HELP, LEACHM, or UNSAT-H models in any of the studies described in Chapter 5 or in the results of the water balance simulations for the Yucaipa, Albuquerque, or Sierra Blanca sites presented in Chapter 6. Part of the differences between measured and simulated runoff may be

attributed to not being able to accurately assess the hydraulic conductivity of the surface layer and to not using the true precipitation intensity in the model. If runoff is significantly overestimated or underestimated, infiltration into the cover system will not be predicted accurately and the remaining water balance components will not be estimated accurately.

- As demonstrated in Chapters 6 and 7 for the evapotranspirative cover system at the Yucaipa site, applying daily precipitation at an intensity of 10 mm/hr, a value often used as a default with the UNSAT-H model, may not be appropriate for cover systems with a relatively low permeability surface layer, i.e., with a saturated hydraulic conductivity that is less than the precipitation intensity. If the precipitation intensity assumed for the simulations is significantly greater than the representative precipitation intensity for a site, runoff may be over-predicted and drainage may be under-predicted. Conversely, as shown in Chapter 6 for the evapotranspirative cover systems at the Albuquerque and Sierra Blanca sites, applying daily precipitation at an intensity of 10 mm/hr may be sufficient, i.e., applying precipitation at a lower intensity has negligible effect on the simulated water balance, when the cover systems have shallow slopes and relatively permeable surface layers that exhibit negligible runoff in relation to the amount of water infiltrating the cover system.
- From the results of the water balance simulations for the Yucaipa, Albuquerque, and Sierra Blanca sites presented in Chapter 6, when air is assumed to be entrapped in soil voids, the simulated rate of runoff may increase significantly. This important effect is not considered in most water balance models and is not accounted for when soil hydraulic conductivity is measured using laboratory testing of saturated soil samples.
- Based on the results of water balance simulations presented in Chapters 6 and 7 for the Albuquerque site, if a capillary break is present, even in the form of a lysimeter

beneath the cover system, the effect of the capillary break should be considered. If water is moving deeply enough into the cover system profile to be affected by the capillary break, the capillary break should be incorporated into the water balance model for the cover system. Conversely, if a cover system is monitored in a test plot with a lysimeter, but ultimately constructed at full scale without an underlying capillary break, water balance simulations for the cover system should be conducted with and without the capillary break to understand the effect of the capillary break on the performance of the cover system.

- The results of uncalibrated simulations of the water balance of the Yucaipa, Albuquerque, and Sierra Blanca cover systems presented in Chapter 6 generally bound the measured water balances for these cover systems presented in Chapter 4. Of the three computer models for water balance used in this study, UNSAT-H was found to provide the best predictions of measured water balance.
- Based on the results of previous studies of the water balance of monitored evapotranspirative cover systems summarized in Chapter 5 and on the results of water balance simulations of the Yucaipa, Albuquerque, and Sierra Blanca cover systems presented in Chapter 6, HELP frequently under-predicts storage and over-predicts drainage. The discrepancy between simulated and measured drainage is generally greater for capillary barriers and cover systems underlain by lysimeters because water movement through these systems is greatly affected by matric potential gradients, and HELP only considers unit gradient conditions.
- The current version of HELP is not recommended for simulating the water balance of evapotranspirative cover systems in arid and semi-arid climates, and especially the water balance of capillary barriers. Because of the unit gradient assumption coded in HELP and the assumption that water in the evaporative zone can drain by gravity to

the water content corresponding to wilting point, the model has been shown to consistently overestimate drainage in studies by others and in the simulations for the Albuquerque cover system presented herein. In addition, the HELP model has some coding deficiencies, e.g., a vegetation growth and decay algorithm is not fully incorporated into the code.

8.3.2 Field Monitoring Programs

Conclusions on field monitoring programs developed from the research in this dissertation are as follows:

- Localized preferential flow along and adjacent to sensors used to monitor evapotranspirative cover systems sometimes occurs. As described in Chapter 4, this phenomenon apparently occurred at all three of the sites evaluated in this dissertation.
- It is important to monitor the water content and/or matric potential profiles in an instrumented cover system to better understand the water balance processes. However, from the results of the field monitoring programs for the Yucaipa, Albuquerque, and Sierra Blanca cover systems presented in Chapter 4, monitoring these parameters with only one measurement technique may not be sufficient because of the number of factors (Table 7.1) that can affect sensors used for monitoring water content and matric potential.
- Based on the results of water balance simulations presented in Chapters 6 and 7 for the Albuquerque site, if an evapotranspirative cover system in the semi-arid or arid southwest U.S. is monitored in a test plot with a lysimeter, the capillary break of the lysimeter may eliminate drainage. Furthermore, even if small amounts of drainage were to occur, the drainage may be retained by capillarity in the drainage layer component of the lysimeter or be captured in small wrinkles or depressions of the

lysimeter. Therefore, it is not conclusive that lysimeters provide much value as a monitoring tool in these climates.

8.3.3 Suitability of Short-Term Performance Assessments

Conclusions on short-term performance assessments developed from this dissertation are as follows:

- Based on the monitoring and modeling results presented in Chapters 4, 6, and 7 for the Albuquerque cover system, short-term performance assessments of evapotrasnpirative cover systems may not be representative of intermediate-term performance if the bottom boundary condition, e.g., lysimeter boundary condition, assumed for the short-term assessments is not representative of intermediate-term conditions.
- Based on the monitoring and modeling results presented in Chapters 4, 6, and 7 for the Yucaipa and Sierra Blanca cover systems, short-term performance assessments of evapotranspirative cover systems may not be representative of intermediate-term performance if the precipitation quantity, intensity, and distribution for the short-term assessments is not representative of intermediate-term conditions.

8.3.4 Anticipated Performance of Evapotranspirative Cover Systems

Based on the results of the short-term and intermediate-term performance assessments presented in Chapters 4, 6, and 7 for the three cover systems, a monolithic cover system constructed with at least 1 m of soil capable of supporting vegetation and having a saturated hydraulic conductivity on the order of 1×10^{-7} m/s should limit drainage to near zero levels at sites in the semi-arid and arid southwest U.S.

8.3.5 Long-Term Performance of Monolithic Covers with Loose Soil and Dense Soil at the Albuquerque Site

Conclusions developed from numerical modeling conducted to evaluate drainage through two hypothetical evapotranspirative cover systems in Albuquerque, one designed with loosely placed soil to promote plant growth and the other designed with compacted soil having a low saturated hydraulic conductivity, are as follows:

- In semi-arid and arid climates, a cover system with loose soil that promotes plant growth may be preferred to a cover system with dense soil when the cover system is only required to have an intermediate-term, e.g., 30-year, service life.
- If a longer service life, e.g., 100 years or more, is required, a cover system with dense soil may be preferred to a cover with loose soil because a dense soil provides more control of drainage than loose soil in the event that vegetation is lost or precipitation significantly increases.
- A capillary break can significantly reduce drainage from an evapotranspirative cover system in a semi-arid or arid climate. However, a capillary break may provide little benefit when precipitation is relatively high, e.g., three times greater than the average annual precipitation, and drainage without the capillary break is moderate.

8.4 RECOMMENDATIONS

Based on the work herein, the following recommendations are made to improve the assessment of evapotranspirative cover system performance and to increase performance reliability of evapotranspirative cover systems:

- If cover system soils are assumed to have a certain saturated hydraulic conductivity for design, the saturated hydraulic conductivity should be verified during construction because saturated hydraulic conductivity is a key parameter affecting performance. As described in Chapter 4, only the cover system for the municipal solid waste landfill at the Yucaipa site had to meet a saturated hydraulic conductivity criterion (approximately 1×10^{-7} m/s) during construction. A hydraulic conductivity criterion was not specified for the cover systems for the proposed low-level radioactive waste landfills at the Albuquerque or Sierra Blanca sites.

- When evaluating the performance of an evapotranspirative cover system via modeling:
  - The processes important to the site should be included in the model. If all the important processes are not available in one model, simulations should be conducted with several different models to try to bound the solution.
  - The effects of precipitation quantity, distribution, and intensity and the effects of hysteresis on the water balance should be evaluated.
  - The effects of soil compaction should be considered when estimating the maximum root depth of vegetation in a cover system.
  - Potential future conditions of the cover system over its design life should be considered to bound the possible performance during that time period. For example, increases in saturated hydraulic conductivity and variations in plant root depths could be considered.
- If an improved computer model for water balance were to be developed, it should include the following processes and features in addition to the processes and features in UNSAT-H:
  - snow accumulation and melt;
  - frozen ground;
  - interception;

  - a method to specify precipitation intensity in increments smaller than an hour;
  - a method of applying precipitation at variable intensity, e.g., according to a specified hydrograph;
  - two-dimensional flow;
  - dynamic plant growth model;
  - a database of unsaturated soil properties, including properties for compacted soils;
  - input parameters that are measurable or that can be readily estimated from published data;
  - excellent documentation; and
  - mesh generator.
- When evaluating the performance of an evapotranspirative cover system via monitoring:
  - monitoring of soil water content/matric potential should generally be conducted with more than one type of instrument: if only one instrument is used and the instrument proves to be unreliable, the monitoring serves little purpose; for example, monitoring could be conducted with neutron probe access tubes and heat dissipation sensors, as was performed at the Sierra Blanca site;
  - attention should be paid to the potential for preferential flow around sensors and measures should be taken to reduce preferential flow, e.g., anti-seep collars could be used;
  - if monitoring includes a lysimeter, the lysimeter should only be placed beneath a portion of the cover system and a separate portion of the cover

system should be monitored without a lysimeter to avoid the creation of a capillary break beneath the cover system and to allow upward movement of water vapor, if any, from the materials beneath the cover system; data from both monitored portions could be compared to better understand the site water balance;

- more attention should be paid to assessing the characteristics of vegetation; as a minimum some of the key plant parameters needed for modeling, including vertical and lateral root extent, leaf area index, and bare area, should be assessed;
- to improve the reliability of short-term performance assessments that include monitoring, cover systems may need to be stressed by irrigating to simulate potential intermediate-term or long-term climatic conditions;
- to provide more assurance that the important processes of a water balance are understood, cover systems should be initially monitored without plants, if possible; and
- if the cover system is being constructed on a relatively flat slope with a relatively permeable material, runoff may not need to be monitored.

8.5 FUTURE RESEARCH

In the course of this study, several topics were identified for further study:

- Long-term monitoring of evapotranspirative cover systems is needed to develop a better understanding of the processes that affect cover system performance over the required service life of a cover system.
- Results of field monitoring programs for some evapotranspirative cover systems, such as the ones at the Yucaipa site and the Albuquerque site, indicate that flow in macropores may be a significant contributor to subsurface flow. For example,

preferential flow in the monolithic barrier at the Albuquerque site may be a primary case of the small amounts of drainage measured from the west subplot of this cover system. Preferential flow is currently not considered in design and even when it is considered in the development of field monitoring programs, preferential flow along sensors apparently occurs. There needs to be a better understanding of when preferential flow occurs, how important it is at different sites with evapotranspirative cover systems, how best to simulate the water balance for this condition, and how to construct cover systems to limit preferential flow without having to compact the soils like barrier layers.

- Cables from sensors installed in the soil and the sensors themselves may affect the measured and actual field water balance. Reliable wireless sensors need to be developed.
- Comparisons of monitoring and modeling results for cover systems suggest that the representative sample size required to accurately evaluate the hydraulic conductivity of a soil compacted dry of optimum is larger than the size of the soil samples currently being tested. Similar to the research that has been conducted on the hydraulic conductivity of compacted clay liners, basic research on the hydraulic conductivity of soils compacted dry of optimum moisture content is needed.
- The ability of an improved German adaptation of the HELP model (Berger, 2004) to assess the water balance of evapotranspirative cover systems without capillary barriers should be evaluated. This version (3.80 D) includes corrections and enhancements to the latest U.S. version, 3.07. One of these enhancements consists of modifying the algorithm for unsaturated flow in the evaporative zone to allow flow only when the soil water content exceeds field capacity, rather than

wilting point. With this modification, the soil in a user-specified evaporative zone is wetter than with the current algorithm in version 3.07. Thus, the model can predict more runoff, more evapotranspiration, and less drainage. This may improve the water balance predictions made with HELP. Even though the HELP model does not incorporate Richards' equation, if HELP could better assess the water balance of evapotranspirative cover systems, this user-friendly model would be more useful for comparing cover system alternatives that do not incorporate a capillary break. The selected alternative or a small subset of alternatives can then be evaluated using a more rigorous model.

Appendix A: Description of Models Selected for Simulations

A.1 Overview

The purpose of this appendix is to provide brief descriptions of three water balance models: (i) Hydrologic Evaluation of Landfill Performance (HELP), version 3.07 (version 3 documentation, Schroeder et al, 1994a,b); (ii) Leaching Estimation and Chemistry Model (LEACHM), version 4.0 (version 3.0 documentation, Hutson and Wagenet, 1992; version 4.0 documentation, Hutson, 2003); and (iii) UNSAT-H, version 3.01 (version 3.0 documentation, Fayer, 2000). These models were used in Chapter 6 to evaluate the water balance of the evapotranspirative cover systems at three study sites in the southwest U.S. Only the components of the models that are relevant to evapotranspirative cover systems in the southwest U.S. are presented. For example, the algorithms in the HELP model for calculating leakage through geomembrane liners and simulating snow storage and melt are not discussed.

Most water balance models, including the HELP, LEACHM, and UNSAT-H models, contain specific simplifying assumptions or lack certain processes, e.g., snow cover, that may make the models particularly unreliable for certain scenarios. Some of the more general assumptions that apply to the HELP, LEACHM, and UNSAT-H models are:

- the fluid (water) is incompressible;
- the soil matrix is rigid;
- the soil air flow is of no consequence (air flow is continuous);
- water flow in the subsurface is one-dimensional or, in the case of the HELP model, quasi two-dimensional, i.e., only certain layers in the soil profile can exhibit lateral flow;

- Darcy's law is valid (flow velocity is linearly proportional to hydraulic gradient); and
- water flow is uniform (no preferential flow).

It is important to realize that even some of the general assumptions may not be met. For example, some of the soils that have been used to construct evapotranspirative cover systems may swell when wetted, which affects the hydraulic properties of the soil and the gradients within the soil. As another example, when capillary barriers are used, flow across the interface between the finer-grained soil and the coarser-grained soil may not be uniform. Unstable flow can occur at the interface, due to hydraulic perturbations, and cause flow in fingers into the soil below the capillary break (Hillel, 1998). Some researchers have hypothesized that air pressures at the interface may sometimes play a role in the development of this unstable flow.

A.2 HELP MODEL

The HELP model was developed by the U.S. Army Corps of Engineers Waterways Experiment Station for EPA to enable design engineers to compare the relative hydraulic performance of alternative waste containment system designs (Schroeder et al., 1994a, 1994b). Version 3.07, released in 1997, is the most recent revision in the U.S. Since this time, a German adaptation of the model, version 3.80 D, which includes corrections and enhancements to the U.S. version, has been developed (Berger, 2004). Interestingly, one of the enhancements is the option to change material and vegetation properties over time to simulate the aging of a landfill profile. Version 3.80 D is not in the public domain, and the detailed user documentation is written in German. In addition, this version was only recently released (Schroeder and Berger, 2004). Therefore, Version 3.07 of the model was used in this study.

HELP simulates hydrologic processes for landfills by performing sequential water balance calculations using a quasi two-dimensional, gradually varying, storage-routing approach. According to Peyton and Schroeder (1993), the model is considered quasi two-dimensional because it allows only vertical flow in all layers except lateral drainage layers, where flow can be vertical or lateral. The model is considered gradually varying because the simulation moves through time with the water balance processes being considered steady over each time step.

With HELP, the general routing of water through a soil layer is dependent on the designation it has been given. HELP requires that each layer be specified as a vertical drainage layer, lateral drainage layer, barrier layer, or geomembrane liner depending on the function and hydraulic properties of the layer. Barrier layers (defined in HELP as compacted soil layers that maintain 100% saturation at all times and have a low saturated hydraulic conductivity) and geomembranes are typically not used in evapotranspirative cover systems and, therefore, are not discussed further. Lateral drainage layers are also not discussed further because HELP requires that a lateral drainage layer be underlain by a barrier layer. Thus HELP, when used to evaluate evapotranspirative cover systems, is a one-dimensional model, except at the soil surface when runoff is evaluated. HELP considers flow in vertical drainage layers to be unsaturated, with the soil water content maintained between the soil's field capacity and wilting point. It is assumed that at its wilting point, the soil can lose no more water by drainage or evapotranspiration, and at its field capacity, the soil can store no more water. HELP also uses the field capacity and wilting point values in simultaneous equations to determine the water retention function parameter, λ, in the Brooks and Corey (1964) water retention function (Equation 3.5). This parameter is subsequently used to calculate unsaturated hydraulic conductivity.

The relevant hydrologic processes considered in HELP include precipitation, interception of precipitation by plants, runoff, evaporation of interception, infiltration, soil water evaporation, plant transpiration, soil water storage, and unsaturated vertical flow. The daily water balance starts with a surface water balance, then considers evapotranspiration in the subsurface, first evaporation and then transpiration, and finally evaluates water redistribution from the surface downward, one soil layer at a time. Water is distributed through each segment of each layer using a water balance routine that is evaluated at the mid-point of each time step (5-minutes to 6-hours for the uppermost soil layer and 30-minutes to 6-hours for deeper layers), the length of which is determined by the model. Because drainage into a segment does not depend on its water content, a segment may receive more water than it can hold. If the water in a segment becomes greater than soil porosity, the excess water in the segment is routed back up to the overlying segment or ground surface. If the entire profile becomes saturated, any excess water at the surface is added to the runoff for the day. Because it calculates downward flux by storage routing and requires that any upward flux occur only within the pre-defined user-specified evaporative zone depth, HELP is not considered a particularly accurate simulation model for evapotranspirative cover systems located in semi-arid or arid climates, where the subtleties of unsaturated flow dominate the water balance. Underestimating the static evaporative zone depth could result in over-prediction of drainage by not allowing deeper water to return to the surface. Overestimating the evaporative zone depth could result in under-prediction of drainage, particularly during a rainy season when the soil is relatively wet.

Runoff in HELP is computed using the Soil Conservation Service (SCS) runoff curve number method, an empirical model based on field data for large storms on small experimental watersheds (i.e., about 10 to 200 ha) with relatively shallow slopes (i.e., about 3 to 7%). (Note that the SCS is now the National Resources Conservation Service (NRCS).) The method empirically correlates total runoff with total rainfall based on daily rainfall records, vegetation type, soil type, antecedent moisture conditions (level of soil moisture prior to rainfall), and other factors. The method does not consider the time distribution of rainfall intensity and, therefore, does not give accurate estimates of runoff volumes for individual storm events. The effects of slope length and inclinations are taken into account using a regression equation developed by Schroeder et al. (1994b) using kinematic wave theory. There is an option in the HELP model to specify no runoff. In this case, precipitation is considered to pond on the surface until it can be removed by evaporation or it infiltrates into the soil. This option is not applicable to evapotranspirative cover systems (though it may be applicable to certain types of lysimeter experiments) and is not discussed further.

Interception of rainfall by plants is calculated as a function of daily rainfall using a decreasing exponential equation and maximum interception. Maximum interception is a function of above-ground biomass and is limited in the HELP model to 1.3 mm per day.

Precipitation that is not intercepted by plants, does not runoff, and does not evaporate infiltrates into the soil profile. From Equation 3.3, the fate of infiltration is evapotranspiration, soil water storage, or drainage.

Evapotranspiration is calculated in HELP using a potential evapotranspiration approach similar to that described by Ritchie (1972). Potential evapotranspiration is computed using a modified Penman equation (Penman, 1963) that is based on energy balance and aerodynamic transport considerations and, as previously discussed, neglects thermal gradients. It is first applied to any free water available on the surface, then to soil evaporation, and lastly to plant transpiration. The latter two processes occur within a user-specified evaporative zone. Evaporation and transpiration from the subsurface can only occur within this zone. HELP divides this zone into seven equal segments and uses the relationship developed by Knisel (1980) to distribute the evapotranspiration demand between the segments. Soil segments closer to the ground surface are subjected to more of the demand, while segments deeper within the soil profile are subjected to less.

Soil evaporation proceeds in two stages and can extend a maximum of 0.45 to 1.2 m into the soil profile, depending on the saturated hydraulic conductivity of the soil in the evaporative zone. In the first stage, evaporation is limited by atmospheric demand. The upper limit on cumulative first-stage evaporation within HELP, calculated as the cumulative difference between soil water evaporation and infiltration, ranges from 5.4 to 13.2 mm based on experimental results reported by Ritchie (1972). In stage two, evaporation is limited by the soil's conductivity. The model assigns an evaporative coefficient, related to the ease with which water can be drawn upward through a soil layer by evaporation, to each soil layer in the system. The evaporative coefficient is related to the unsaturated hydraulic conductivity at a matric potential of -1 m (-10 kPa), but also has imposed lower and upper limits that are based on the range of capillary fluxes for soils reported by Knisel (1980).

Plant transpiration is modeled using a function of leaf area index and equals potential transpiration or potential evapotranspiration minus all previously calculated evaporative demands, whichever is less. Transpiration is also limited to 25% of the plant available water capacity (field capacity minus wilting point) and any available drainable water (soil water above field capacity) after the soil evaporation demand has been met. Potential transpiration is determined as a function of potential evapotranspiration and leaf area index, which varies throughout the year. The variation is calculated using the perennial plant growth and senescence algorithm taken from the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold et al., 1989).

The vegetative growth model is used to calculate total plant biomass, which, in turn, is partitioned into above-ground and below-ground (root) biomass. Root biomass is not used further to assess the water balance processes; it is treated as a biomass sink. The active (living) above-ground biomass is used to determine leaf area index, and the active and inactive above-ground biomass is used to calculate interception and soil water evaporation (because vegetation shades the soil surface and reduces evaporation). Vegetation growth is assumed to begin at the start of the growing season and continue for 75% of the growing season. After this time, vegetation declines until the end of the growing season is reached and leaf area index is zero. During the growth period, plant biomass increases as a function of the interception of radiant energy, which is itself a function of the active above-ground plant biomass expressed as leaf area index. The maximum leaf area index for a site is an input parameter. In HELP, plants may not achieve the specified maximum leaf area index if they are subjected to significant water or temperature stresses. Growth only occurs when the daily temperature is above the assumed plant base temperature of 5 °C and when the daily mean temperature is no more than 10 °C below the average annual temperature. In addition, the growth rate is reduced by multiplying it by a temperature or water stress factor, whichever is lower, when the growing conditions are less than optimal. The temperature stress factor decreases exponentially as the daily temperature deviates from the assumed optimum growth temperature of 25 °C, and the water stress factor is calculated as the actual transpiration divided by the plant transpiration demand.

Vertical flow for unsaturated flow conditions is computed using Darcy's equation. HELP assumes that soil matric potential is constant within a vertical drainage layer. Therefore, the hydraulic gradient is due to change in elevation head only and is thus equal to 1.0. HELP does, however, use the Campbell (1974) unsaturated hydraulic conductivity function for calculating unsaturated flow (Equation 3.7).

Because of the hybrid formulation given above, HELP cannot be used to explicitly simulate the physics of water movement through an unsaturated soil layer. However, as described by Berger (2000), the model does implicitly consider matric potential gradients that cause upward flow of water through the user-specified evaporative zone depth.

In version 3.80 D of HELP, Schroeder and Berger (2004) have implemented changes to the interception, frozen soil, actual evapotranspiration, unsaturated vertical flow, and vegetation growth and decay algorithms used in version 3.07 of the model. They also incorporated the option to change the vegetation and soil properties during a simulation. This latter change, as well as one of the changes to the evapotranspiration algorithm, may make HELP more useful for simulating the water balance of evapotranspirative cover systems in the southwest U.S. The former modification is briefly discussed below.

HELP version 3.07 currently differentiates between vertical flow in the evaporative zone and vertical flow below the evaporative zone. Outside of the evaporative zone, vertical flow only occurs when the soil water content exceeds field capacity. Within the evaporative zone, vertical flow occurs when the soil water content exceeds some lower limit, which is typically the wilting point. Berger (2000) compared simulated and measured water balance parameters for lysimeters and cover system test plots in Germany and concluded that HELP underestimated actual evapotranspiration. When the unsaturated flow algorithm for the evaporative zone was modified to allow flow only when the soil water content exceeded field capacity, Berger obtained much better estimates of actual evapotranspiration.

Model validation studies have suggested that HELP overestimates drainage from evapotranspirative cover systems in semi-arid and arid climates (Fayer and Gee, 1997; Berger, 2000; Scanlon et al., 2002; Dwyer, 2003). With above modification in HELP, simulated drainage from evapotranspirative cover systems should decrease because more water is lost by evapotranspiration and less water flows below the evaporative zone.

A.3 LEACHM MODEL

LEACHM (Hutson, 2003) is a one-dimensional finite difference model that is finding increasing use in the western United States, particularly California, for design and performance analysis of evapotranspirative cover systems. Version 4, which was released in 2003, is the most recent revision. LEACHM was developed as a research tool to simulate the effects of agricultural management alternatives on the movement of water and chemicals [pesticides, nutrients (nitrogen and phosphorus), and salinity] in a shallow soil profile. Only the hydrologic component of the model, which is evaluated using the pesticide module LEACHP, is discussed further.

The relevant hydrologic processes considered in the LEACHM model include precipitation, runoff, soil water evaporation, plant transpiration, soil water storage, and drainage. Unlike the HELP model, LEACHM does not consider interception of water by plants. Runoff is computed using the SCS runoff curve number method described by Williams (1991). This method empirically correlates total runoff with rainfall, antecedent moisture conditions, slope, and other factors. The curve number algorithm used in the LEACHM model is similar to that used in the HELP model. Consequently, the LEACHM runoff algorithm exhibits some of the same weaknesses as mentioned above for the runoff routine used by HELP.

Infiltration of water into the soil profile and water redistribution and drainage can be simulated using a steady-state approach, the Addiscott (1977) storage routing approach that incorporates preferential flow, or a finite difference solution to Richards' partial differential equation (Richards, 1931). Only the Richards' formulation is described below. Water that does not infiltrate within a considered time step is considered a component of runoff.

Evapotranspiration is determined in LEACHM using the potential evapotranspiration approach described by Childs and Hanks (1975). Potential evapotranspiration is specified (as potential evapotranspiration or as a pan evaporation rate and pan factor) or is computed using meteorological data and the Linacre (1977) algorithm. Potential evapotranspiration is then partitioned into potential transpiration and potential evaporation based on a crop cover factor, the fraction of the ground covered by the plant canopy. It is assumed that both evaporation and transpiration start at 0.3 day and end 12 hours later at 0.8 day, and that potential evapotranspiration flux density varies sinusoidally. LEACHM allows three options for the crop cover factor: (i) no plants (crop cover factor equal zero); (ii) constant plant cover (crop cover factor equals user-specified value); and (iii) a growing plant cover (crop cover factor increases to a user-specified maximum value within the growing season using an exponential time function). Plant cover is only used to partition evapotranspiration and has no other function in the model.

Similar to HELP, soil evaporation in LEACHM occurs in two stages: (i) a stage limited by atmospheric demand, where evaporation can proceed at the potential evaporation rate; and (ii) a stage limited by water availability, where actual evaporation is a function of the matric potential gradient between the soil and atmosphere and the soil hydraulic conductivity.

Water uptake through plant roots follows the approach described by Nimah and Hanks (1973) with transpiration determined as a function of matric potential and root and water resistance. The root water potential is varied until the extracted water is equal to the potential transpiration. However, the water potential of the roots cannot be less than a user specified value (Hutson (2003) suggests -300 m (-3,000 kPa)) or less than the soil matric potential (so water does not flow from the roots into the soil). In addition, the soil water cannot be depleted by transpiration to a matric potential less than -150 m (-1500 kPa), the conventional wilting point.

For constant cover conditions, crop cover and root distribution data are required as model input. For a growing cover, LEACHM uses equations similar to those used by Tillotson et al. (1980) that are based on equations presented by Davidson et al. (1978) for corn root growth. Crop cover fraction and root distribution at maturity are required input for this option. The plant and root growth routines in LEACHM are representations of plant cover and root distribution as a function of time and depth. They are based on empirical equations, and there is no feedback between soil conditions and plant growth.

Water redistribution is calculated using Richards' equation with the Campbell (1974) water retention function, as modified by Hutson and Cass (1987), and the Campbell hydraulic conductivity function. The Campbell retention function is simply the Brooks-Corey retention function (Equation 3.5) with the residual water content set equal to zero and different fitting parameters:

$$\frac{\theta}{\theta_s} = \left(\frac{a}{h}\right)^{b^{-1}} \qquad \text{(Eq. A.1)}$$

The Campbell fitting terms a and b^{-1} equal the Brooks-Corey fitting terms h_b and λ, respectively. Hutson and Cass modified the Campbell water retention relationship along the wetter part of the curve, where there is a discontinuity, by replacing the exponential function with a parabolic function to facilitate numerical modeling:

$$(\theta_c / \theta_s)\left(\frac{1-\theta/\theta_s}{1-\theta_c/\theta_s}\right)^{1/2} = \left(\frac{a}{h}\right)^{1/b} \quad \text{for } \theta_c > \theta > \theta_s \qquad \text{(Eq. A.2)}$$

where θ_c = volumetric water content at the point of intersection of the exponential and parabolic curves, which occurs at:

$$h_c = 2b\theta_s / (1 + 2b) \qquad \text{(Eq. A.3)}$$

The Campbell (1974) hydraulic conductivity function is determined by:

$$k_u = k_s \left(\frac{\theta}{\theta_s} \right)^{2b+2+p} \qquad \text{(Eq. A.4)}$$

where p = Campbell pore interaction parameter, often taken as one. This formulation is slightly different than the Campbell hydraulic conductivity function used in the HELP model (Equation 3.7).

To set up the finite difference grid used by LEACHM, the soil profile is divided into a number of horizontal layers of equal thickness with nodes at the center of each layer. The upper boundary condition can be changed with time using meteorological forcing or by adjusting the head to simulate ponded or non-ponded infiltration, evaporation, or zero flux. The lower boundary condition can be selected as a constant head, variable head, free drainage (or unit gradient), zero flux, or seepage face. The initial condition is specified by assigning an initial head or water content to each node in the finite-difference nodal grid. To reduce the potential for numerical difficulties, LEACHM does not allow matric potentials between 0 and - 0.002 m (0 and -0.02 kPa). Matric potentials in this range are reset as -0.002 m (-0.02 kPa).

A.4 UNSAT-H MODEL

UNSAT-H is a one-dimensional finite-difference water balance model developed at Pacific Northwest Laboratory (Fayer, 2000) to assess the water dynamics of waste disposal facilities at the DOE Hanford Site. The model also simulates sensible heat flow using the Fourier equation and isothermal and thermal vapor flow using Fick’s law. The fact that UNSAT-H has the ability to simulate vapor flow makes it a desirable model for semi-arid and arid sites. However, the model is limited because it cannot simulate heat flow (needed to evaluate thermal vapor flow) and transpiration at the same time. The UNSAT-H model was derived from the UNSAT model of Gupta et al. (1978) and has retained many of the same routines. Version 3.01 of UNSAT-H is the most current revision.

The UNSAT-H model considers precipitation, runoff, evapotranspiration, soil water storage, and drainage in the water balance. Unlike HELP and LEACHM, UNSAT-H does not incorporate a runoff algorithm that considers surface slope, soil texture, and vegetation. Instead, only precipitation in excess of the infiltration capacity of the soil is shed as runoff. Like the LEACHM model, water infiltration, redistribution, and drainage are governed in the UNSAT-H model by a finite difference solution to Richards' partial differential equation. However, as shown in Table 3.1, the UNSAT-H model has more equations available to describe the water retention and hydraulic conductivity functions than the LEACHM model or other models screened in Table 3.1. UNSAT-H also has the option to consider hysteresis.

For the cover system simulations conducted using UNSAT-H and presented in Chapters 6 and 7, the van Genuchten (1980) water retention function (Equation 3.6) and the van Genuchten - Mualem hydraulic conductivity function (Equation 3.8) were used.

Evaporation in the UNSAT-H model is calculated using one of two approaches: (i) an integrated form of Fick's law of diffusion that considers the flow of heat to and from the soil surface, the flow of water from the subsurface to the soil surface, and the transfer of water vapor from the soil surface to the atmosphere; or (ii) in the isothermal mode, the potential evapotranspiration concept using a modified Penman equation (Doorenbos and Pruitt, 1977) that is a modification of the diffusion equation and is dependent on net radiation and soil heat flux rather than on soil surface temperature.

Transpiration is treated as a sink term in the Richards' equation and is modeled using the potential evapotranspiration concept. Potential evapotranspiration is first partitioned into potential evaporation and potential transpiration using an equation developed for cotton and grain sorghum and dependent on leaf area index (Ritchie and Burnett, 1971) or using *Bromus tectorum* (cheatgrass) data (Hinds, 1975). The potential transpiration is then applied to the root zone using the root distribution to apportion it among the nodes with roots. The root length density function, RLD, used by UNSAT-H is:

$$RLD = fe^{-gd} + i \qquad \text{(Eq. A.5)}$$

where f, g, and i are coefficients that describe root length density and d is the root depth.

Water withdraw from a node is dependent on the matric head of the node and the plant water stress function defined by Feddes et al. (1978), which gives the ratio of actual transpiration and potential transpiration as a function of matric potential.

UNSAT-H does not have a plant growth algorithm. Variations in leaf area index and increases in root depth over time are inputs to the model. Thus, like the LEACHM model, plant growth is uncoupled from site conditions, such as soil water content, which control plant growth.

The finite difference grid used by UNSAT-H is set up in a manner similar to that for LEACHM. The soil profile is divided into a number of horizontal layers with nodes located at the center of each layer. Two additional nodes, one above the ground surface and one below the profile being modeled, are used to set boundary conditions. The upper boundary condition can be changed with time by adjusting the head to simulate ponded or non-ponded infiltration, evaporation, or zero flux. The lower boundary condition can be selected as a fixed water table, free drainage (or unit gradient), zero flux, or specified flux boundary. The initial condition is specified by assigning an initial head or water content to each node in the finite-difference nodal grid. The solution strategy is to solve the water flow equations first and then the heat flow equations.

Glossary

ACRONYMS

ACAP	=	Alternative Cover Assessment Program
CERCLA	=	Comprehensive Environmental Response and Liability Act
DOE	=	U.S. Department of Energy
EPA	=	U.S. Environmental Protection Agency
ET	=	evapotranspiration
FAO	=	Food and Agricultural Organization of the United Nations
GUI	=	graphical user interface
LAI	=	leaf area index
NOAA	=	National Oceanic and Atmospheric Administration
NRCS	=	Natural Resources Conservation Service
PET	=	potential evapotranspiration
PTF	=	pedotransfer function
RCRA	=	Resource Conservation and Recovery Act
SCS	=	Soil Conservation Service
SWCC	=	soil water characteristic curve
TDR	=	time domain reflectometry
USDA	=	U.S. Department of Agriculture

VARIABLES

a	=	Campbell water retention function parameter
b	=	Campbell water retention function parameter

$C(h)$	=	specific moisture capacity
D	=	vertical drainage (drainage) from the cover system
d	=	root depth
ET	=	evapotranspiration
f	=	coefficient that describes root length density
g	=	coefficient that describes root length density
h	=	matric potential
h_b	=	Brooks and Corey fitting parameter (also called bubbling potential or air-entry potential)
h_c	=	point of intersection of exponential and parabolic curves defined by Hutson and Cass
I	=	infiltration
i	=	coefficient that describes root length density
k_s	=	saturated hydraulic conductivity
k_u	=	unsaturated hydraulic conductivity
L	=	lateral drainage
m	=	van Genuchten water retention function parameter
n	=	van Genuchten water retention function parameter
P	=	precipitation (rain, snow, irrigation)
p	=	Campbell pore interaction parameter
R	=	runoff
RLD	=	root length density function
S	=	sink term representing water uptake by vegetation
t	=	time
ΔW_{plants}	=	change in water storage on plants

ΔW_{soil}	=	change in water storage in soil
$\Delta W_{surface}$	=	change in water storage on soil surface
z	=	vertical coordinate, positive downward
α	=	van Genuchten water retention function parameter
ℓ	=	Mualem pore interaction term for hydraulic conductivity functions
λ	=	Brooks and Corey water retention function parameter (also called pore-size distribution index)
θ	=	volumetric water content
θ_c	=	volumetric water content at the point of intersection of exponential and parabolic curves defined by Hutson and Cass
θ_r	=	residual water content
θ_s	=	saturated water content

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Vita

Beth Ann Gross was born on 23 August 1962 in Akron, Ohio, and was the first child of Betty Jo Hammons Gross and John Allen Gross. She has one brother, Allen Paul Gross, and two sisters, Laura Ann Gross and Rachel Ann Gross. She moved from Ohio to Florida several times as her father finished medical school and began his career as a neurologist. Her mother was a teacher, poet, and artist and actively involved in promoting the arts in the community. Both parents are now retired.

Ms. Gross has spent the majority of her life in the south. From Gainesville, Florida, she left high school early in 1979 to attend New College, an honors college in Sarasota, Florida. While she was there, she excelled in mathematics and had a strong interest in the natural sciences. With these interests, she elected to become a civil engineer and transferred to the University of Florida in Gainesville, Florida. She received a Bachelor of Science in Civil Engineering degree from the university in 1985 and a Master of Engineering degree in 1987.

In early 1987, Ms Gross accepted a position as a Staff Engineer with GeoSyntec Consultants (GeoSyntec) in Boynton Beach, Florida. She later transferred to their Atlanta, Georgia office. By 1993, she was a Senior Project Engineer and was managing large landfill design and remediation projects. The work was challenging; however, she felt that she wanted more time to broaden her knowledge and investigate certain phenomena in more detail. In August 1993, Ms. Gross took a leave of absence from GeoSyntec to pursue a Doctor of Philosophy degree at the University of Texas at Austin. Her GeoSyntec work, however, followed her and she opened a GeoSyntec office in Austin, Texas while she was working on her dissertation.

Ms. Gross has authored over 40 published technical publications, including U.S. Environmental Protection Agency research reports and guidance documents, journal articles, and conference papers. She has also been an invited speaker or participant at EPA workshops and roundtables, NSF workshops and panels, TCEQ conferences, and ASCE conferences. She is currently the Chairperson of the Geoenvironmental Engineering Technical Committee for the American Society of Civil Engineers.

Permanent address: 1004 E. 43rd Street, Austin, Texas 78751

This dissertation was typed by the author.