Assessment of Alternative Earthen Final Covers for Florida Landfills

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Tarek Abichou,
Gustavo Langoni, and Kamal Tawfiq
FAMU – FSU College of Engineering

State University System of Florida
Florida Center for Solid and Hazardous Waste Management
University of Florida
2207-D NW 13th Street
Gainesville, FL 32609
www.floridacenter.org

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ABSTRACT

Landfills are at present the most widely used waste disposal facilities. The Resource Conservation and Recovery Act (RCRA) subtitle D requires the use of landfill covers to isolate waste, reduce the amount of water infiltration, and minimize gas migration. Prescribed covers permitted by current regulations are based on a barrier concept that requires them to employ resistive principles, i.e. a layer having low saturated hydraulic conductivity. A new concept, the focus of this study, is the evapotranspiration cover (ET) concept, which utilizes the water uptake capabilities of vegetation, and the storage capacity of fine-grained soils to reduce percolation into the underlying waste. ET covers provide many advantages over prescribed covers such as lower cost, good long-term performance, easy maintenance, congruence with nature, and flexibility to convert landfill cells into biocells in the future. However, within RCRA regulations alternative covers can only be used if they demonstrate equivalent reduction in water infiltration, and equivalent protection from wind and water erosion as prescribed covers. The objective of this study is to determine the feasibility of ET Covers in Florida.

The study consisted of collecting climate data, soil samples, and vegetation characteristics from several regions of Florida. Hydraulic properties of the soil samples along with vegetation root density function were evaluated in the laboratory. The accumulated data was then used as input into an unsaturated flow model (UNSAT-H) to simulate infiltration into the waste during peak weather events.

Simulations were performed to evaluate the effect of the weather period, the effect of soil thickness, the effect of vegetation, and finally to determine what regions in Florida observe potential to implement ET covers.
Results from this study showed that the Northwest and Northeast Regions of Florida were able to meet the preliminary requirements for hydrological performance as required by RCRA. However, field evaluation of these designs should be performed before full implementation of ET covers in these regions.
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J.R. Register          FDEP/ Hazardous Waste
Lee Martin             FDEP/Solid Waste
Peter Grasel           FDEP/Solid Waste
Andrew Dzurik          FAMU-FSU COE
John F. Wood           City of Thomasville
Jud Curtis             Leon County Solid Waste
Tarek Abichou          FAMU-FSU COE
Gustavo Langoni        FAMU-FSU COE
Kamal Tawfiq           FAMU – FSU COE

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SECTION ONE
INTRODUCTION

Final covers are frequently used to reduce the quantity of water that infiltrates into contaminated soils and or into waste deposits at solid waste facilities. Reducing the volume of infiltrating water reduces the amount of leachate that is generated and the risk of additional groundwater contamination. At many sites, the applicable rules and regulations (ARARs) require that the covers employ resistive principles, i.e., layers having low saturated hydraulic conductivity (compacted clay barriers, or geosynthetic clay liners with or without a geomembrane). These principles are used to provide the hydraulic impedance that limits flow into underlying contaminated materials or waste. This design philosophy is often referred to as the “rain coat” or “umbrella” approach.

The Resource Conservation and Recovery Act (RCRA) describes the requirements for traditional prescriptive landfill cover designs. In the US EPA final cover regulations, there is a provision for the use of alternative covers. This provision for the use of alternative covers states that the alternative cover must provide 1) an infiltration layer that provides equivalent reduction in infiltration to that of the prescribed cover, and 2) an erosion layer that provides equivalent protection from wind and water erosion as the prescribed cover. These regulations however, do not specify allowable percolation rates through any type of covers.

One type of “alternative earthen final cover” exploits the water storage capacity of finer textured soils and the water removal capability of vegetation. This type of cover is referred to as “evapotranspiration or ET” covers. ET covers work as follows: Water that infiltrates into the cover is stored by the soil and removed by vegetation via evapotranspiration, hence their name. Design of ET covers consists of two basic steps: (i) selecting a soil profile that has sufficient
capacity to store the infiltrating water while ensuring that percolation from the base of the cover is maintained below an acceptable maximum value and (ii) selecting vegetation that will efficiently remove the stored water from the profile during the growing season.

The objective of the proposed study was to assess the feasibility of using ET covers in the state of Florida. The proposed research plan is divided into four major tasks. Task 1 of the project consists of collecting soil samples, obtaining properties of the regional vegetation, and gathering the relevant climatological data at selected regions of the state. Task 2 of the project involves laboratory testing of collected soil samples to determine unsaturated hydraulic properties of each specimen and to characterize the root density functions of the vegetation at that region. Task 3 of this research effort consists of using the collected data from Task 1 and 2 as input into an unsaturated flow model to simulate the infiltration through several cover designs. Design guidelines and other means of technology transfer will be included in task 4.

This report describes the findings of this project and is organized in the following manner. Section Two describes the design process of ET covers and past experience with such covers throughout the U.S. Section Three describes the methods used to collect data, test soils, and perform all modeling activities during this study. Section Four encapsulates the results from simulations using UNSAT-H. A summary of results, along with recommendations based on this study is provided in Section Five.
SECTION TWO

BACKGROUND

2.1 Introduction To Alternative Covers

The awareness towards environmental issues has increased the concern for solid waste generation and disposal. At present engineered landfills are the most widely used waste disposal facilities. The main legislation regulating landfills and their components is the Resource Conservation and Recovery Act (RCRA). RCRA Subtitle D provides minimum standards for landfill liner and cover designs. The regulations in RCRA state that the main function of a landfill cover is to minimize infiltration of rainwater to the underlying waste. These regulations however, have not been specific when dealing with covers because they are costly to monitor and have not been given as much importance as landfill liners (E.P.D., 2000). Landfill covers play many important functions in waste containment such as controlling the water balance of landfill cells, and gas or even waste migration towards the environment. Landfill covers also affect the costs of construction to a great extent, representing approximately 30% of construction costs.

Prescribed covers permitted by current regulation are based on a barrier concept that requires them to employ resistive principles, i.e. a layer having low saturated hydraulic conductivity. This barrier concept is achieved with a compacted clay layer or a geosynthetic clay liner (GCL) with or without a geomembrane. RCRA subtitle D however, has a provision that permits the use of alternative landfill covers granted they are equivalent to prescribed covers. Alternative covers are defined as any cover used in place of prescribed covers. This broad definition encompasses many covering schemes provided they meet RCRA specifications. RCRA legislation requires that alternative covers be equivalent to prescribed covers. The equivalency concept stated in RCRA legislation does not set any detailed comparison standards
or specifications that can be used. However, based on the fact that the main purpose of landfill covers is to minimize percolation into landfill cells and provide waste isolation, criteria can be formulated to determine the equivalency of alternative landfill covers compared to prescribed covers. In order for an alternative cover to be equivalent to a prescribed cover, it must at least achieve the same percolation rates. An alternative cover must also provide equal protection from wind and water erosion than prescribed covers, but the focus of this study is hydrological performance. The equivalency criterion that is currently being used by the Alternative Cover Assessment Project (ACAP) is summarized by Benson et al. (2002). Table 2.1 shows this equivalency criterion.

Water balance for landfill covers is represented by the following equation:

\[ P_t = P - R - S - E - T - L \]  

(Eq. 2.1)

In this equation \( P_t \) is percolation, \( P \) is precipitation, \( R \) is runoff, \( S \) is storage, \( E \) is evaporation, \( T \) is transpiration, and \( L \) is lateral drainage (Khire 1995). The water balance of a landfill cover is shown in Fig. 2.1. Landfill covers have conventionally been designed to work against nature. The idea is to prevent the hydrological cycle from performing naturally and instead force it to work around landfills. Prescribed covers are designed as barriers to prevent the flow of water through and into the waste. The key is to minimize percolation by maximizing runoff and evaporation.
Table 2.1 Equivalency Criteria for Alternative Covers Based on Benson et al. (2000).

<table>
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<th>Prescribed Covers</th>
<th>Arid to Semi-Arid Climates</th>
<th>Humid Climates</th>
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<td>Compact Clay</td>
<td>10 mm/yr</td>
<td>30 mm/yr</td>
</tr>
<tr>
<td>Geomembrane</td>
<td>3 mm/yr</td>
<td>3 mm/yr</td>
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Fig. 2.1 Water Balance of a Landfill Cover (Winkler, 1999).
in the water balance equation. Examples of these covers are geo-membrane and soil barriers. This concept has many potential flaws that are mainly created because it works against nature. The main disadvantages of these covers are:

(1) Degradation due to exposure to the environment,
(2) Performance decreases with time, and
(3) High cost and difficulty of construction.

A new concept, the focus of this and many other studies, is the evapotranspiration cover (ET) concept shown in Fig. 2.2. This concept is based on working with nature to create better landfill covers (Benson et al. 2000). The idea behind ET covers is to manipulate the water balance on a landfill cover to limit percolation into the waste. ET covers maximize transpiration, evaporation, and storage in the water balance equation as a means to limit percolation. ET covers utilize the water uptake capabilities of vegetation, and the storage capacity of fine-grained soils to reduce percolation into the waste. These covers consist of a vegetation surface designed to enhance evapotranspiration, underlain by a soil layer that provides storage during periods of low evapotranspiration. Since ET covers are made of natural materials and are based on sound principles, they should perform well in the long-term and fit well with nature (Hauser et al. 2001). The two main alternative cover designs are monolithic covers and capillary barriers. Monolithic covers are composed of only one soil, while capillary barriers utilize two soil layers, fine grained above coarse grained, to enhance the storage capacity of the cover. ET covers provide many advantages over prescribed covers. Of outmost importance is their cost, since they are made with readily available natural materials the cost difference from prescribed
Fig. 2.2 Schematic of The Evapotranspiration Cover (ET) Concept.
covers is substantial. Savings of $50-75k per acre are achieved with the use of alternative covers (Benson et. al, 2000). With bio-cell technology being developed, ET covers provide more flexibility to convert existing landfills into bio-cells. Also very importantly, while performance of prescribed covers decreases with time due to water storage, the performance of ET covers increases due to increased root depth and evapotranspiration. Expected life of evapotranspiration covers is thousands of years because they operate on natural principles, while the life for prescribed covers is often uncertain (Abichou, 2001). ET covers require much less maintenance than prescribed covers, and most of it deals with vegetation, which is relatively easy to maintain. Vegetation provides better slope stability for evapotranspiration covers and slope stability is an issue for prescribed covers especially in areas of heavy rainfall. Most importantly, ET covers are congruent with nature and this is important in its performance, durability, and public acceptance.

2.2 Design Of Evapotranspiration Covers

The design of any landfill cover depends on the purpose it intends to serve; this is called a process-based design (Ankeny et al., 2000). Alternative covers are designed based on their function, which is mainly to control water percolation into landfill cells. The variables that can be manipulated during design are vegetation cover, soil properties, and thickness of soil layers. An appropriate combination of these variables is needed for the local climate to assure an appropriate design (Ankeny et al., 2000).

Alternative covers function as a sponge, retaining water in the soil. The vegetation cover is used to pump the stored water and release it via evapotranspiration into the atmosphere (Fig. 2.2). Therefore, the key in designing alternative covers is to provide enough storage during vegetation dormant months so that the stored water can be released during the growing season.
The design process consists of: (1) gathering data (unsaturated soil hydraulic properties, vegetation characteristics, and climatological data), (2) using the data to calculate an estimated thickness of the cover, and (3) using water balance models to verify the cover thickness. Given the vegetation and soil information, the thickness of cover needed is calculated and later verified using a water balance model. The thickness of landfill covers is calculated based on the precipitation during the vegetation dormant season, and the storage capacity of the soil. Using climatological data and the growing season of the vegetation cover, the total precipitation outside the growing season is calculated by the following equation:

\[ P_o = P_t - P_{gs} \]  \hspace{1cm} (Eq. 2.2)

where, \( P_o \) is the precipitation outside the growing season, \( P_t \) is the total precipitation, and \( P_{gs} \) is the precipitation during growing season. The soil must provide enough storage for this precipitation calculated. The storage capacity of soils is calculated using the soil-water characteristic curve (SWCC). A typical SWCC is shown in Fig. 2.3. The unit storage of a soil is the water content between the wilting point and field capacity. The wilting point (\( \theta_{wp} \)), as shown in Fig. 2.3, is the water content at which plants can no longer remove water from the soil, while the field capacity (\( \theta_{fc} \)), also shown in Fig. 2.3, is the water content at which the soil can no longer retain water. The unit storage is calculated by the equation

\[ \theta_a = \theta_{fc} - \theta_{wp} \]  \hspace{1cm} (Eq. 2.3)
Fig. 2.3 Sample Soil Water Characteristic Curve (SWCC).
where, $\theta_a$ is the unit storage capacity, $\theta_{fc}$ is the field capacity, and $\theta_{wp}$ is the wilting point (Abichou, Benson 1999). Having the unit storage capacity of the soil and the precipitation outside the growing season, the thickness is calculated by the following equation

$$\theta_a L = P_o \quad \text{(Eq. 2.4)}$$

where, $\theta_a$ is the unit storage, $L$ is the cover thickness, and $P_o$ is the Precipitation outside growing season (Abichou, Benson 1999). This equation is derived from the initial premise that the soil layer must provide storage for the precipitation during the dormant months of vegetation. This thickness calculated provides a rough approximation, the next step in the design process is to input this initial design into water balance models such as UNSAT-H to improve the design and increase the accuracy of design conditions.

### 2.3 Types Of Evapotranspiration Covers

#### 2.3.1 Monolithic Covers

The main purpose of landfill covers is to minimize water infiltration to minimize leachate. The water balance of a landfill cover shows that the factors determining infiltration into a landfill cover are runoff, storage capacity of the soil, and hydraulic conductivity. Monolithic covers are a layer of fine-grained soil, which have low hydraulic conductivity and a high storage capacity.

Fig. 2.4 shows a schematic of a monolithic cover. The design of these properties allows monolithic covers to manipulate the water balance by increasing the storage, evaporation, and limiting percolation. The water that does not runoff is readily stored near the surface where it can be evaporated. The amount of precipitation and the storage capacity of the soils determine the thickness of these covers. Evaporation is enhanced using finer-grained soils because of their
gradually changing unsaturated hydraulic conductivity-suction relationship (Khire et al., 1995). Lower water content near the base yields low hydraulic conductivity and a unit gradient condition, which limits percolation (Benson 1997). That is why monolithic covers must have enough thickness so that changes in water content do not occur near the base during periods of high infiltration. Monolithic covers are a less expensive option and their simplicity allows for easy construction.

2.3.2 Capillary Barriers

Capillary barriers are two-layer landfill covers designed to increase the storage capacity of the cover. By increasing storage near the surface, this design stimulates water loss through evaporation resulting in low percolation rates. Capillary barriers consist of a layer of fine-grained soil underlain by a layer of coarse soil. Fig. 2.5 shows a schematic of a capillary barrier ET cover. The storage rate in the uppermost layer is increased due to a surface tension phenomenon that prevents water from infiltrating into the coarse layer. The water will be stored above the capillary break until it can overcome this surface tension and percolate the coarse layer. This phenomenon will store water near the surface longer than monolithic covers and therefore result in higher evaporation rates.

The airflow through the coarse layer can dry the capillary barrier and therefore contribute to low percolation rates (Benson et al., 2000). The uppermost layer also has a low hydraulic conductivity since it is fine-grained soil. Therefore capillary barrier designs combine the low hydraulic conductivity of monolithic covers and the enhanced storage capacity caused by the capillary break.
Fig. 2.4 Schematic of a Monolithic ET Cover.
Fig. 2.5 Schematic of a Capillary Barrier ET Cover.
2.4 Selected ET Cover Studies

2.4.1 Long Term ET Cover Performance

2.4.1.1 Great Plains Water Balance (Cole and Mathews, 1939)

Cole and Mathews (1939) describes a study of the water balance of the Great Plains from 1907 to 1936. During this period water balance investigations were performed on five locations within the Great Plains. Two locations provided continuous monitoring, while the others provided partial measurements of the water balance in native sod. For the two locations that recorded full measurements, the soils were a silty clay loam at Mandan, North Dakota and a very fine sandy loam at North Platte, Nebraska. At Mandan, soil-water records were complete for 21 years on native sod, while at North Platte soil-water records were complete for 25 years. Results from these water balance measurements show that during the time periods monitored, water did not percolate past root zone depths. A review of data from all five locations during these 30 years demonstrated no evidence that water percolated past root zone depths for any of the five locations monitored. Native plants grew throughout the year on native sod removing water stored in the soil quickly using the same concept of evapotranspiration covers. In spite of the fallow period through which water accumulates in the soil, this study demonstrated no water movement past the root zone.

2.4.1.2 Pawnee National Grasslands (Sala et al., 1992)

The soil-water balance under the grasslands of Northeastern Colorado was studied for 33 years. The mean annual precipitation during this 33 year study period was 327 mm and the soil at the site is a sandy loam. Field and lysimeter measurements were collected at the site, and the conclusion of the study from the data collected is that it is unlikely that the soil profile within the
potential root depth of native grasses will ever be filled with water, as was the case during monitoring. The water balance for this site is similar to ET covers, and the water removal mechanism is the same. The data gathered during these 33 years shows no deep percolation below 135cm.

2.4.2 Short Term Studies

2.4.2.1 Lakeside Reclamation Landfill - Beaverton, Oregon (Licht et al., 2001)

Lakeside Reclamation Landfill was approved for ET cover capping using poplar trees in 1990. A performance-based study was done using a series of test pads to draw comparisons between a non-RCRA grass only cover, and an ET cover planted with poplar whips (Jarrell et al., 1995). Two test pads were constructed, one planted with poplar trees using the same design as the ET cover used in the landfill capping, and the other using grass only. Soil moisture was monitored at different depths underneath both test pads to compare their performance. Overall mean soil moisture underneath the ET test pad was less for 37 of the 43 testing dates in 1994 and 1995 (Licht et al., 2001).

Additionally, soil moisture at lower depths was consistently less underneath poplar trees. In excavations at the site, poplar root growth was recorded at 4 foot depths, while grass roots only reached one and a half feet maximum depth (Licht et al., 2001).

Based on the results from (Jarrell et al., 1995), the following can be concluded:

1. Water removal was higher for the ET cover than the grass-only cover during this study.

2. At lower depths, deep poplar root growth proved to be more effective removing soil moisture.
3. In the long term, percolation rates from the ET cover test pad will be lower than the grass-only cover due to higher root density and more efficient water removal mechanism.

2.4.2.2 Bluestem Landfill Site No. 2 – Marion, Iowa (Licht et al., 2001)

A performance-based study took place from 1995-1996 at the site of Bluestem Landfill between an ET cover and a clay cover. The clay cover test pad was designed according to IOWA regulations, with a clay layer having a hydraulic conductivity of $10^{-7}$. Vegetation on the clay cover consisted of grass only, while vegetation on the ET cover consisted of poplar trees and grass. Soil moisture was measured at different depths underneath both test pads using time domain reflectrometry sensors.

Measurements were taken for a year on both test pads, but due to calibration errors the soil moisture values recorded are not valid. However, soil moisture changes throughout the course of the experiment bring about interesting observations about ET covers. At lower depths soil moisture fluctuations were higher underneath the ET cover test pad, which suggest a higher water removal due to the root depth of the poplars (Licht et al., 2001). Monitoring during the rainy period (August 18-23, 1996) shows that water content for the clay cap fluctuated from 26 to 36 to 30%, while for the ET cover soil moisture went from 8 to 19 to 9%. These readings show that although soil moisture was lower at the beginning of the rainy period underneath the clay cap, it dried up to 1% of its initial moisture content while the clay cap ended 4% wetter than it started (Licht et al., 2001).
2.4.2.3 Alternative Cover Assessment Project (ACAP)

The test covers, as part of the Alternative Cover Assessment Program (ACAP), were constructed along and their water balance data is being collected to date. Data are being collected from 24 test sections at ten sites. Diverse climates are represented, ranging from arid (Apple Valley, CA, average precipitation = 138 mm/yr) to humid subtropical (Albany, GA, average precipitation = 1280 mm/yr). Fourteen test sections are located in semi-arid or arid climates, and ten are located in humid climates.

Percolation rates less than 1 mm/yr are being transmitted by all of the covers located in semi-arid climates, and all have met the equivalency criteria. The average percolation rate for the conventional covers with composite barriers is 0.09 mm/yr. For monolithic barriers, the average percolation rate is 0.16 mm/yr, and for capillary barriers it is 0.36 mm/yr. No data are available for conventional covers with clay barriers due to insufficient data.

Percolation rates for the alternative and conventional covers located in humid regions are higher than anticipated. The percolation rates vary significantly from site-to-site for all covers except the conventional covers with composite barriers. Percolation rates for the alternative covers range between 12.2 and 128 mm/yr. For the conventional covers with clay barriers, the percolation rates range between 3.1 and 315 mm/yr. The conventional covers with composite barriers have percolation rates between 1.0 and 7.1 mm/yr, with an average percolation rate of 4.6 mm/yr.

The relatively high percolation rates for the alternative covers in humid regions are attributed to immature vegetation. Percolation rates for these covers are expected to diminish as the vegetation matures. At one site, the percolation rate has dropped more than a factor of 25 as trees became established. The high percolation rate for the conventional cover with a clay
barrier is due to preferential flow through desiccation cracks. The percolation rate for this test section probably will not diminish unless the cracks are repaired.

The data collected to date for conventional covers with composite barriers provide a basis for tentative recommendations regarding equivalent percolation rates. Insufficient data are available for recommending a reasonable equivalency criterion for covers with clay barriers. The recommended percolation rates for covers with composite barriers are 1 mm/yr (semi-arid and arid climates) and 5 mm/yr (humid climates). These recommendations are based on the relatively short data record collected to date, and may change as more data are collected during the study.

2.5 Climate of Florida (Climatography of The US # 60, Climate of Florida, NCC)

Climate in Florida is influenced by its geographic position. The state extends 6.5 degrees in latitude and its northernmost point lies in the southern temperate zone, while its southernmost point is located in the northern part of the tropical zone. Therefore, general climatic conditions range from temperate and subtropical conditions in the northern portion of the State to tropical conditions in the south Florida Keys. Florida, while for the most part a warm state due to its southern latitude, experiences mild cold temperatures during winter months in its northern region, and its summers are characterized for being long, warm and humid.

Florida has plentiful rainfall, with rainfall and temperature varying seasonally, annually, and geographically (Water Resources Atlas, Fernald & Purdum, 1998). Almost half of the total annual rainfall can be expected during the period from June through September. Rainfall pattern in Florida is similar to tropical climates, except for the northwestern portions of the state, with the year divided into a long dry season and a short rainy season.
Floridian temperatures average about six degrees lower in northern than in southern Florida. Northern average temperature is 15.6 degrees Celsius while in the south average temperature is 21 degrees. July and August are the warmest months in all areas, and December and January are the coolest in the northern and central portions of the State (Climatography of The US # 60, NCC). During the warmest months, temperatures average near 32 degrees while winter temperatures average 5 to 10 degrees. However, cold fronts can occasionally bring freezing temperatures to the state generally lasting two to three days.

Precipitation in Florida is abundant, yet it is quite varied in annual amount and seasonal distribution. Annual precipitation averages vary from 1270 to 1651 mm per year, but the average precipitation fluctuates greatly from year to year with wet years sometimes producing twice as much precipitation. Fig. 2.6 shows the average precipitation throughout the state, the northwestern and southern portions of the state receive the largest amount of rainfall. Another very important factor concerning precipitation is Florida’s susceptibility to tropical storms, which produce high wind speeds and precipitation rates. Some of the world’s heaviest rainfalls have occurred during tropical storms, with rainfall over 508 mm in 24 hours not uncommon (Climatography of The US # 60, NCC).


Soils in Florida vary from place to place but are generally sandy and low in fertility (Brown et al., 1990). The reason for sandy soils in the state of Florida has to do with the processes that lead to the formation of current soils, which were mostly a consequence of fossil marine life. Clay minerals present in Florida soils are scarce and predominantly in the northern portions of the state, these minerals were deposited as a consequence of the erosion in the
Appalachian Mountains. Western Florida is the only area within Florida where sandy clays and clays are found at the surface (Water Resources Atlas of Florida, Fernald & Purdum, 1998). The areas of highest relief in north Florida are covered by sandy clay soils as these minerals were deposited from the Appalachian Mountains. However, somewhat poorly drained sandy soils with a dark sandy subsoil layer (Spodosols) are the most common soils in the state (Water Resources Atlas of Florida, Fernald & Purdum, 1998). The southern and coastal areas of the state are characterized by poorly drained thin sandy soils, except for the region of the Everglades, which is underlain by poorly drained organic soils.


As in any region, vegetation in Florida is mainly governed by its weather characteristics. Due to Florida’s tropical climate, south region vegetation will be dominated by tropical vegetation, while northern Florida vegetation will be more characteristic of template regions. Growing season for southern Florida regions is all year long with a progressive decrease towards the northern portions of the state.

Natural vegetation types are mostly freshwater marshes and wet prairies, which are still predominant in the Everglades of South Florida. This vegetation is a product of the warm temperatures and water balance throughout South Florida. The northern regions however, due to the temperature difference have different vegetation. Hardwood and conifer forests are predominant in the northern regions of the state. Besides these main types, mixed hardwood swamps, cypress swamps, and dry prairies can also be found along the panhandle (Water Resources Atlas of Florida, Fernald & Purdum, 1998).
Fig. 2.6 Mean Annual Precipitation Throughout the State of Florida (F.S.U. Climate Center).
SECTION THREE
MATERIALS AND METHODS

3.1 Regions Of The State

Florida was divided into four regions based on the length of the growing season and climatic conditions for the purpose of this study. The state was divided into the Northwest, Northeast, Central, and South Region. Four cities representing these four regions were selected. Soil, weather, and vegetation data for the selected city was assumed to be representative of the region. The representative cities were Tallahassee for the Northwest Region, Jacksonville for the Northeast Region, Orlando for the Central Region, and Miami for the South Region. These cities were selected because of the availability of data at these locations.

3.2 Soil Testing

Several soils were obtained from different regions of the state. Whenever possible, bulk samples of soil were shipped to the FAMU – FSU College of Engineering. Index property testing consisted of measuring the liquid and plastic limits, particle size distribution of each soil. The liquid and plastic limits were measured in accordance with ASTM D 4318-95A. Particle size distribution was determined using the wash sieve analysis and the hydrometer analysis in accordance with ASTM D 422. All soil samples were delivered at very low water contents. Prior to hydration, large objects were removed. The soils were then spread on a large pan and sprayed with tap water using a spray bottle to achieve the target water content. The soils were compacted using standard Proctor effort in accordance with ASTM D 698.

After the maximum dry unit weight and the optimum water content was determined for each soil, additional specimens were compacted at water contents 2% drier than optimum. These
compaction conditions simulate conditions at which alternative cover soils are compacted in the field. After compaction the compacted specimens were placed in rigid-wall (Fig. 3.1) for hydraulic conductivity testing. Falling head hydraulic conductivity tests were performed in accordance with ASTM D 5856-95. For the rigid-wall permeameters, the tests were terminated when the last four hydraulic conductivity values were within 25% and inflow equaled outflow. The falling head tests were performed at hydraulic gradients between 14 and 16. Tallahassee tap water was used as the permeant. The hydraulic conductivities obtained from these tests are to be used as saturated hydraulic conductivity ($K_s$) for input to the water balance model described later. The final step of the soil testing consisted of obtaining unsaturated hydraulic properties of each soil. The unsaturated hydraulic properties consisted of estimating the water characteristics curve for each soil and the unsaturated hydraulic conductivity function of each soil.

### 3.3 Climate Data Collection

Meteorological data collected include daily precipitation, daily maximum and minimum air temperatures, daily solar radiation, average daily dew point temperature, daily cloud cover, and average daily wind speed. Most of the data was obtained from weather data collected by the U.S. National Weather Service and compiled on compact disks by Earthinfo Inc. Other data was collected from websites maintained by Florida State University department of meteorology. Gaps in data were filled based on historical trend at that location.
Fig. 3.1 Schematic of a Rigid-Walled Permeameter.
3.4 Vegetation Data Collection

Vegetation data needed by UNSAT-H include Leaf Area Index (LAI), length of growing season, percent bare area (PBA), rooting depth (RD), and parameters describing the root density function (RLD). Daily LAI is used to partition Potential Evapotranspiration (PET) into Potential Transpiration (PT) and Potential Evaporation (PE). Before PT is distributed over the root depth, PT is reduced by (1-PBA). The root density function used during this study based on experimental data from the ACAP project. Below ground biomass distribution of local vegetation was determined by collecting undisturbed sections of the root zone using the Weaver-Darland Box method as described by Bohm (1979). Once in the laboratory, the roots are washed from the soil and the biomass distribution is obtained using a method described in Liang et al (1989). Root Density functions were obtained for grass alone, warm and cold weather grasses, crested grasses, grass and poplar trees, grasses and shrubs.

Daily LAI was difficult to find. In most cases, only maximum seasonal LAI was reported with root length density and the length of the growing season. For most plants however, LAI is very small at the beginning of the growing season and increases exponentially during early growing season. The LAI then decreases after reaching a maximum and approaches zero at the end of the growing season. Maximum LAI and leaf duration are reduced by environmental stresses such as temperature, lack of water, or nutrients. However, the effects of such stresses were not considered in the reported values of LAI (Williams et al., 1990).

The suction at which plants stop transpiring is defined as the wilting point. This suction corresponds to a water content (from the SWCC). At the same time, plants stop transpiring when the soil is very wet and oxygen is not available.
3.5 Water Balance Model

The first step of this task was the selection of the unsaturated flow model to be used to simulate the water balance through alternative earthen covers. The objective of any model is to simplify real word phenomena by describing only the relevant constitutive principles governing the problem. The critical requirement of a water-balance model is the accurate representation of the following principles:

- Relationship for unsaturated soil-water flow, storage, effects of soil texture, layering and multi-dimensional flow, including flow over the surface slope, down-slope infiltration of runoff and preferential flow
- Methods to describe water uptake by plants
- Relationship between hydraulic conductivity and suction
- Field verification

The model UNSAT-H was selected because it met most of the above criteria.

3.5.1 Description of UNSAT-H

UNSAT-H was developed by Fayer and Jones (1990) and it is a computer program used to simulate the flow of water, vapor, and heat in soils. The UNSAT-H model has several options for the boundary conditions. For water flow, the user can specify Dirichlet or Neumann conditions, or a unit gradient condition. For heat flow, the user can specify Dirichlet or Neumann conditions, or a temperature gradient.

The UNSAT-H model simulates infiltration in a two-step process. First, infiltration is set equal to the precipitation rate during each time step. Second, if the surface soil becomes saturated, the solution of that time step is repeated using a Dirichlet boundary condition (with the
surface node saturated, \( h = 0 \). The resulting flux from the surface into the profile is the infiltration rate. The UNSAT-H model does not simulate runoff explicitly. Instead, it equates runoff to the precipitation rate that is in excess of the infiltration rate. There is no provision for runoff.

The UNSAT-H model simulates liquid water flow using equation 3.1 (Richards’ equation):

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K_r(h) \frac{\partial h}{\partial z} + K_l(h) + q_{VT} \right] - S(z,t) \quad (\text{Eq. 3.1})
\]

Where \( \theta \) represents the water content, \( h \) is the total head, \( K_r \) is a term representing the liquid and the hydraulic conductivity of the soil \( (K_r = K_l + K_v) \), \( q_{VT} \) is the thermal vapor flux density, and \( S(z,t) \) represents the water uptake by plants at a depth \( z \).

Water vapor diffusion is calculated using Fick's law, and sensible heat flow using the Fourier equation. Convective airflow is not considered. Options for describing soil water retention include linked polynomials, the Haverkamp function, the Brooks and Corey function, and the Van Genuchten function. Options for describing hydraulic conductivity include linked polynomials, the Haverkamp model, the Mualem model, and the Burdine model.

The UNSAT-H model simulates evaporation in two ways. In the isothermal mode, UNSAT-H uses the PET concept. The user supplies either daily values of PET or daily weather data, with which the code calculates daily PET values using the Penman equation. During each time step, the code attempts to apply the potential evaporation rate. If the soil surface dries to or beyond a user-defined matric head limit, the time step is re-solved using a Dirichlet condition at the surface. In this situation, the surface pressure is held constant at the matric head limit and evaporation is set equal to the flux from below. In the thermal mode, UNSAT-H calculates evaporation as a function of the difference in vapor density between the soil and the reference
height (the height at which air temperature and wind speed are measured) and the resistance to vapor transport. The resistance to vapor transport is a function of several factors, including air temperature, wind speed, and atmospheric stability.

The UNSAT-H model simulates the effects of plant transpiration using the PET concept. There is no provision to simulate both water and heat flow in a plant canopy. Plant information is supplied to the code to partition the PET into potential evaporation and potential transpiration. PET is partitioned into PT using equation 3.2 (Ritchie and Burnett, 1971):

\[
PT = PET \left[ 0.52 (LAI^{0.5}) \right]
\]

(Eq. 3.2)

Where LAI is the leaf area index for the vegetation. The potential transpiration is applied to the root zone using the root distribution to apportion it among the nodes with roots. The withdrawal of water from a particular node is dependent on the matric head of the node. The user provides matric head values that define how the potential transpiration rate applied to a particular node is reduced. Below the minimum value, sometimes known as the wilting point, transpiration is unable to remove any water. When all nodes with roots reach this level of matric head, transpiration is reduced to zero.

The mathematical equations that describe the state and dynamics of the modeled system are written in an implicit finite-difference form. The user must specify an averaging scheme for inter nodal hydraulic conductivities; choices include arithmetic (and arithmetic-weighted), geometric, and harmonic. Vapor and heat inter nodal conductances are calculated as arithmetic means. The resulting equations are solved using the modified Picard iteration technique with the Thomas algorithm. The solution strategy is to solve the water flow equations first, then the heat flow equations.
The user controls the spatial detail of the solution by specifying the node spacing via the input file. As configured on the web site, the code allows the user to have up to 250 nodes and five soil types. By editing the parameter file, the user can increase the number of nodes and soil types. The user also controls the temporal domain by specifying the time step size. The minimum time step size should be no less than $10^{-7}$ hours in single precision mode. The maximum time step size must be no more than 24 hours under any condition, and it should be no more than 1 hour if time-varying evaporation or transpiration is being simulated. The user can control the solution accuracy by specifying an acceptance criterion for the solution to a particular time step. The available criteria are the maximum allowable change in water content per time step, or the maximum allowable mass balance error per time step.

Simulation inputs include number of nodes (up to 250 unless the code is recompiled for more), node depths and associated material types (up to five materials unless the code is recompiled for more), boundary condition choices, output frequencies, and maximum and minimum time step size. Site data include slope, aspect, latitude, elevation, and surface roughness parameters.

The boundary conditions inputs include daily PET values, daily weather conditions (maximum and minimum temperature, average dew point temperature, average wind speed, average humidity, and solar radiation), precipitation (hourly or daily), and lower boundary condition choices (e.g., water and temperature fluxes, variable temperature and matric head, gradients)

The plant parameters includes details about the seasonal variation of leaf area index and maximum rooting depth, root density variations with depth, and soil matric head limits that
impact the withdrawal efficiency of plants. UNSAT-H also has a specific function for partitioning PET into evaporation and transpiration for *Bromus tectorum* (cheatgrass).

### 3.5.2 Verification

Fayer and Jones (1990) compared UNSAT-H predictions with several known analytic and numerical solutions to specific problems. They successfully matched solutions for infiltration and redistribution for two soil types (a sand and a clay), soil temperature variations in response to an imposed sinusoidal temperature pulse at the surface, and drainage during a one-step pressure test to determine hydraulic properties. Fayer and Jones (1990) contains the theory documentation and user manual for UNSAT-H. Baca and Magnuson (1990) conducted verifications and benchmark tests of UNSAT-H. In addition to repeating the tests reported by Fayer and Jones (1990), they conducted additional tests that included horizontal infiltration, imposition of a constant heat flux at the surface, infiltration of a stratified vadose zone, and coupled heat and water flow in a field test plot. Baca and Magnuson judged UNSAT-H operationally verified.

### 3.5.3 Validation

Fayer et al. (1992) tested the UNSAT-H model using data from a 1.7-m deep lysimeter containing a specific cover design. They found that the model reproduced much of the observed water-balance changes. The largest discrepancies occurred in winter (when evaporation was over-predicted) and summer (when evaporation was under-predicted). Fayer et al. (1992) demonstrated the model sensitivity to $K_s$, the pore interaction term, PET, and the presence of a snow cover (mimicked by setting PET to zero). When optimal values of these parameters were
used in a single simulation, i.e., the calibrated model, the root-mean-square error was reduced by 63% from that determined with the uncalibrated model. Additional simulations were performed that indicated that hysteresis is also important to modeling of covers.

Magnuson (1993) used UNSAT-H simulations to evaluate two landfill cover designs for a disposal facility in Idaho. He examined the sensitivity of UNSAT-H to changes in the hydraulic property parameters of the cover soil and the underlying gravel and cobble layers. In most cases, the changes were factors of 0.5 and 2.0 about the base value. Drainage through this cover during the 10-year simulations was nil, so he used the maximum predicted storage as a surrogate measure of performance, reasoning that drainage was most likely under those conditions when storage was at a maximum. Magnuson found that the hydraulic properties of the surface soil layer had the greatest impact on maximum storage. Changing the $\theta_s$ by 0.1 cm$^3$/cm$^3$ yielded a similar 10% change in maximum storage. Increasing ha of the surface soil decreased maximum storage, whereas increasing the value for the gravel or cobble layers increased maximum storage slightly. Increasing the $K_s$ value of the surface soil decreased maximum storage. Apparently, precipitation could infiltrate the soil more deeply, but it was easier for evaporation to extract that water later. Changes to the $K_s$ of the gravel and cobble layers had no discernible effect on maximum storage.

### 3.5.4 Sensitivity Analysis

Magnuson (1993) also evaluated the sensitivity to the same parameters for the case where the cover was a single soil material with no layering. For these simulations, drainage was detectable so it was used as the performance measure. Magnuson found that drainage changed inversely with changes in $\theta_s$. For example, as $\theta_s$ was changed from 0.5 to 0.4, drainage increased
by 89% (from 1.36 to 2.58 cm/yr). Changing $\theta_r$ from 0.007 to 0.056 increased drainage by 36%. Increasing $h_c$ from 21 to 60 cm reduced drainage by 91%. Magnuson looked at a second soil type and found that the model responses to the parameter changes were inconsistent. For example, increasing the $K_s$ of the second soil type increased drainage, while increasing the $K_s$ of the first soil type decreased drainage. The importance of this result is that parameter sensitivities can be dependent on the scenario tested and so should be determined on a case-by-case basis.

Fayer and Gee (1997) used a six-year record of water storage, suction, and drainage data to test UNSAT-H. This comparison was an extension of the work by Fayer et al. (1992). These data were collected from a non-vegetated weighing lysimeter containing 1.5 m of silt loam over sand and gravel. This capillary-barrier configuration was designed to promote water storage in the upper layer for removal by evapotranspiration. Four simulations were conducted with the Richards'-equation-based UNSAT-H: 1) standard parameters, 2) calibrated parameters, 3) heat flow, and 4) hysteresis. The water storage results showed little difference among the four simulations; the root mean square (RMS) errors were all between 23.4 and 23.7 mm. Fayer et al. (1992) reported a RMS error of 8.1 mm for the calibrated simulation during the first 1.5 years. Beyond the calibration period, however, the calibrated model was not much more successful than the other models in predicting total water storage.

The standard parameters, heat flow, and hysteresis simulations had the largest maximum storage difference (75 to 80 mm); the calibrated simulation had the smallest (59.3 mm). This result may be one benefit of the calibration, the goal of which was to match the peak water storage in winter. In contrast, the calibrated simulation had the largest mean and median differences (19.6 and 16.4 mm, respectively). The other simulations had values between -6.0 and 3.0 mm for the 1.65 m profile.
Simulations usually over-predicted suction values, more so in the summer than the winter. The hysteresis simulation gave the best qualitative match of suction data throughout the six-year period. At times, the predictions coincided with the measurements, most importantly during the one and only drainage event observed in six years. The other three simulations predicted suctions that were generally at least a factor of 3 greater than the measured values.

The hysteresis simulation was the only one to predict drainage. The cumulative amount was predicted within 52% of the measured amount and the timing matched the observations. Fayer and Gee (1997) attributed the success of the drainage prediction to the ability to simulate matric head values at the interface. They suggested that soil water matric head is better than water storage as an indicator of conditions at the interface of the silt loam and sand layers that control drainage.

Based on the comparisons, Fayer and Gee (1997) reached several conclusions. First, UNSAT-H can reasonably predict the water-balance components of a capillary barrier-type cover. The predictions improve if the hysteresis phenomenon is included. Second, the inclusion of heat flow has only a minor effect on surface evaporation and vapor flow within the soil. The impacts of heat flow on snow accumulation and melt and on soil freezing were not evaluated, but Fayer and Gee (1992) speculated that these impacts could be important. Finally, a calibrated model will not necessarily apply well outside of the calibration period. Fayer and Gee (1997) offered suggestions for improving the calibration process: 1) include a more complete conceptual model (e.g., including hysteresis), 2) use multiple performance measures, and 3) calibrate with a period of time sufficiently long to encompass the range of conditions envisioned for the design life of the cover.
3.5.5 Application to Landfill Covers

Khire et al. (1997) applied the UNSAT-H and HELP models to resistive barrier test cells at the Greater Wenatchee Regional Landfill in Washington and the Live Oak Landfill in Georgia. The Wenatchee landfill is in a semi-arid climate; the Live Oak landfill is in a humid climate. The authors tested the models using a three-year record of data that included overland flow, soil water storage, evapotranspiration, and percolation. The results, in the form of time series plots, showed that the models generally mimicked the seasonal trends. The authors stated that the UNSAT-H predictions tended to be more accurate than those using HELP. With respect to UNSAT-H, the authors noted several conceptual features that were important to the Wenatchee site but were not included in the model: snow cover, snow melt, and freezing soil. Based on their experience with simulating these two landfill covers, Khire et al. (1977) suggested that practitioners use a simpler model (e.g., HELP) during the iterative design phase and a more complex model (e.g., UNSAT-H) for final performance assessment.
SECTION FOUR

RESULTS AND ANALYSIS

4.1 Soil Testing

A summary of the index properties of the soils tested in this study is shown in Table 4.1. Fig. 4.1 shows the grain size distribution for all soils tested during this study. The soils obtained from the Northern regions of Florida, namely Albany (Georgia), Jacksonville, and Tallahassee, have similar grain size distribution curves characterized by a high presence of fines, ranging from 20 to 25 %. These soils were classified as clayey sands (SC) by the Unified Soil Classification System (USCS). The soils of the Southern regions of Florida namely Orlando and Sarasota, were sandy in appearance with a uniform particle size distribution curve. The coefficient of uniformity ($C_u$) is 1.875 for the soil from Orlando and 2.29 for the soil from Sarasota. These soils where classified as poorly graded sands (SP) by the Unified Soil Classification System (USCS).

A plasticity chart showing all soils is provided in Fig. 4.2. The presence of fines in the clayey sands of Tallahassee (Northwest Region), Albany (Northwest Region), and Jacksonville (Northeast Region) are the reason for their plasticity. The soils of Orlando (Central Region) and Sarasota (South Region) have no plasticity due to the lack of clay particles in these soils. As was earlier noted in the background, Northern regions in Florida have clayey soils that were deposited by erosion from the Appalachian Mountains. However, with the exception of the Northern regions, sandy soils are prevalent in Florida. The analysis of the soils tested for this study coincides with the geological contour of Florida discussed in the background section.
Table 4.1 Summary of Soil Properties for The Soil Samples from Florida’s Climatic Regions.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Classification</th>
<th>Optimum Water Content (%)</th>
<th>Max Dry Unit Weight (KN/m³)</th>
<th>PI</th>
<th>LL</th>
<th>K_sat (90%) cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest Region 2</td>
<td>SC (Clayey Sand)</td>
<td>15.0</td>
<td>18.2</td>
<td>18</td>
<td>33</td>
<td>1.00E-05</td>
</tr>
<tr>
<td>(Albany)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northwest Region 1</td>
<td>SC (Clayey Sand)</td>
<td>14.5</td>
<td>18.4</td>
<td>9</td>
<td>27</td>
<td>1.00E-05</td>
</tr>
<tr>
<td>(Tallahassee)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northeast Region 1</td>
<td>SC (Clayey Sand)</td>
<td>19.5</td>
<td>16.2</td>
<td>20</td>
<td>35</td>
<td>1.00E-08</td>
</tr>
<tr>
<td>(Jacksonville)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northeast Region 2</td>
<td>SP (Poorly Graded Sand)</td>
<td>13.5</td>
<td>17.3</td>
<td>NP</td>
<td>NP</td>
<td>1.00E-04</td>
</tr>
<tr>
<td>(Jacksonville)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Region</td>
<td>SP (Poorly Graded Sand)</td>
<td>6.0</td>
<td>15.9</td>
<td>NP</td>
<td>NP</td>
<td>6.60E-03</td>
</tr>
<tr>
<td>(Orlando)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Region</td>
<td>SP (Poorly Graded Sand)</td>
<td>11.0</td>
<td>17.5</td>
<td>NP</td>
<td>NP</td>
<td>1.00E-03</td>
</tr>
<tr>
<td>(Sarasota)</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4.1 Grain Size Distribution of Soils From The Different Regions of The State (Mechanical Grain Size Analysis & Hydrometer Analysis).
Fig. 4.2 Plasticity Chart with Soils From The Different Regions of The State.
Compaction curves using Standard Proctor effort were obtained for each soil. Fig. 4.3 shows the compaction curves for each soil. Curves obtained using the clayey sand soils are bell-shaped and show a definite optimum water content and maximum dry unit weight. Curves from the other soils are flat and reflect the compaction behavior of poorly graded sands. The dry unit weight of poorly graded soils is less dependent on compaction water content. Table 4.1 shows the maximum dry unit weight, compaction water content, and the hydraulic conductivity obtained for each soil collected during the study. The maximum dry unit weight ranged from 16.2 to 18.2 KN/m$^3$ for clayey soils and 15.9 to 17.5 KN/m$^3$ for the sandy soils. The optimum water content varied from 14.5 to 19.5 % for the clayey soils and 6 to 13.5 % for the sandy soils. The hydraulic conductivity varied from $10^{-5}$-$10^{-8}$ cm/sec for soils from the Northern regions to $10^{-3}$ cm/sec for soils from the Southern region. However, during simulations the hydraulic conductivity of soils from the Northeast Region was increased to $2e-6$ cm/s. The increase was performed to simulate the increase in hydraulic conductivity in the field due to desiccation in clayey soils.

The soil water retention characteristics were obtained using the methods described in Saxton et al. (1985). Saxton et al. (1985) uses the texture of the soil to estimate the generalized soil water characteristics curve (SWCC). In this method the volumetric water content is correlated to soil water potential based on % sand, % silt, % clay, % organic matter, and bulk density of the soil. Van Genuchten functions were then fitted to the data. Fig. 4.4 shows the SWCC for each soil obtained during this study.
Fig. 4.3 Compaction Curves for Soils From The Different Regions of The State and The Corresponding Zero Air Voids Curve.
Table 4.2 shows the Van Genuchten parameters for soils from each region. The saturated water content ($\theta_s$) is 0.36, 0.39, 0.47, 0.39, for soil from the Northwest, Northeast, Central, and Southern regions respectively. The residual water content ($\theta_r$) was 0 for soils from the Northwest, Northeast, Central regions, and 5% for soils from the Southern regions. The Van Genuchten parameter $\alpha$ is 0.015, 0.015, 0.043, 0.31, for soils from the Northwest, Northeast, Central, and Southern Regions respectively, while the n parameter for the same regions is 1.76, 1.76, 1.61, and 3.0 respectively. The soil from the Southern region shows no prospect for the implementation of alternative covers. The poorly graded sands encountered in the Southern region have a high hydraulic conductivity (Table 4.1), not suitable for the implementation of alternative covers. The SWCC of the soil from the southern region is shown in Fig. 4.4, this curve represents the storage capability of this soil. The mechanism of alternative covers requires water to be stored in the soil layer so that the plants can pump it out via evapotranspiration (Benson, 2000). As described in Section Two, the storage capacity of the soil is the portion of the SWCC between the wilting point ($\theta_w$), and the field capacity ($\theta_f$).

The SWCC from the Southern region is distinctively flat as can be seen in comparison to the SWCC from the three other regions, this means that the storage portion of the curve is very small. Typical values for $\theta_w$ and $\theta_f$ correspond to suction values of 15000KPa and 10KPa respectively. In Fig. 4.4 the water contents corresponding to these suctions for the Southern region are 0.04 and 0.09. Using the storage design procedure described in the background it would require a 6m cover to store 254 mm of infiltrating rainfall. Due to these soil properties determined for the Southern region soils, the implementation of alternative covers in this region is unfeasible. It would be impossible to meet the criteria stated in RCRA with such soil properties in a humid climate.
Fig. 4.4 Soil Water Characteristic Curve for Soils From The Different Regions of The State.
Table 4.2 Summary of the Van Genuchten Function Parameters for Soils of Different Regions of The State.

<table>
<thead>
<tr>
<th>Region</th>
<th>Residual Water Content ($\theta_r$) (%)</th>
<th>Saturated Water Content ($\theta_s$) (%)</th>
<th>$\alpha$ (1/cm)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest region</td>
<td>0</td>
<td>0.36</td>
<td>0.015</td>
<td>1.76</td>
</tr>
<tr>
<td>Northeast region</td>
<td>0</td>
<td>0.39</td>
<td>0.015</td>
<td>1.76</td>
</tr>
<tr>
<td>Central region</td>
<td>0</td>
<td>0.47</td>
<td>0.043</td>
<td>1.61</td>
</tr>
<tr>
<td>Southern region</td>
<td>0.05</td>
<td>0.39</td>
<td>0.31</td>
<td>3.0</td>
</tr>
</tbody>
</table>
The Southern region is therefore not a candidate for the implementation of alternative covers. The low storage capacity and high hydraulic conductivity of the soil is not adequate for the implementation of alternative covers. Subsequent analysis will be directed to the other three regions of the state and the Southern region is excluded from this study from here on.

4.2 Climatic Data

4.2.1 Regions of the State

Four climatic regions were identified in the state of Florida. The state was then divided into four regions (Northeast, Northwest, Central, and Southern region). The weather station chosen for the Northeast Region is the city of Jacksonville. The latitude of this weather station is N 30° 29’ and the longitude is W 81° 41’. The average annual precipitation is 1300 mm/year, and the maximum annual precipitation on record is of 2090 mm/year, which was recorded in 1947. The wettest 10-year period on record is the period between 1944 to 1953. The average precipitation during this period is 1500 mm/year. The average growing season starts Julian Day 58 and ends Julian Day 332. Despite having a Northern latitude, the climate of Jacksonville is influenced by its proximity to the coast.

The weather station chosen for the Northwest region is the city of Tallahassee. The latitude is N 30° 23’ and the longitude is W 84° 21’. The average annual precipitation is 1670 mm/year, and the maximum annual precipitation on record is of 2650 mm/year, which was recorded in 1964. The wettest 10-year period on record is the period between 1964 and 1973. The average precipitation during this period is 1850 mm/year. The average growing season starts Julian Day 77 and ends Julian Day 317. The climate of the Northwest region is influenced by its
high latitude, close to the temperate zone. The Northwest region experiences the coldest
temperatures of the state.

The weather station chosen for the Central region is the city of Gainesville. The latitude
is N 29° 39’ and the longitude is W 82° 21’. The average annual precipitation is 1310 mm/year,
and the maximum annual precipitation on record is of 1950 mm/year, which was recorded in
1964. The wettest 10-year period on record is the period between 1944 and 1953. The average
precipitation during this period is 1490 mm/year. The average growing season starts Julian Day
69 and ends Julian Day 322. The city of Gainesville as many cities in Central Florida is not a
coastal city. For this reason it experiences lower temperatures than Northeast coastal regions and
has a shorter growing season. As in the Northwest region the influence of the temperate zone is
more apparent and the climate is similar to that described for the Northwest region.

The weather station chosen for the South region is the city of Miami. The latitude is N
25° 49’ and the longitude is W 80° 17’. The average annual precipitation is 1420 mm/year, and
the maximum annual precipitation on record is of 2270 mm/year, which was recorded in 1959.
The wettest 10-year period on record is the period between 1990 and 1999. The average
precipitation during this period is 1690 mm/year. The average growing season is all year around.
The South region is the warmest region of Florida, and because it is surrounded by the coast, it
has a tropical climate with high annual rainfall. The south region of Florida is also exposed to
tropical storms because of its location between the subtropical Atlantic and the Gulf of Mexico.
In particular, hurricanes can approach from the Atlantic Ocean to the east, from the Caribbean
Sea to the south, and from the Gulf of Mexico to the west. This means that the Southern region
has a great chance of receiving very high rainfall rates and hurricane force winds, about one in
seven probability at Key West and Miami for every year.
4.2.2 Difference in Climate

Latitude and proximity to the coast are the main factors controlling climatic conditions within the state of Florida (Climatography of the US # 60). Although the state has mostly subtropical conditions due to coastal surroundings and Southern latitude, the northwest region of the state experiences some climatic conditions characteristic of the temperate zone.

The average cumulative yearly precipitation is shown in Fig. 4.5 for the regions addressed in this study. The Northwest region of the state has the highest average precipitation with 1600 mm, followed by the Southern region with 1500 mm, and the Central and Northeast regions with 1300 mm. Also shown in Fig 4.5 is that the months of June through August experience the most precipitation as the slope during days 150-273 is higher on all regions.

The wettest 10 years in record is conservatively used to model landfill covers (Winkler, 1999). The alternative cover research performed in the western region of the United States and by ACAP serves as a precedent for the use of the wettest 10 year period. For the regions in this study, Fig. 4.6 shows the average precipitation per rainy day for the yearly average of the 10 year wettest period for all regions. The Northern regions of Florida experience a higher precipitation per rainy day (5 mm per rainy day) due mostly to their higher yearly precipitation. This ratio gives insight to the rainfall distribution throughout the year when used with the total precipitation. For example, the Southern region has a higher yearly precipitation than the Northwestern region yet its precipitation per rainy day is lower, this means that there are more rainy days in the Southern region and therefore precipitation is more evenly distributed. Distribution of rainfall can influence water balance parameters, especially runoff which will be higher for high rates of precipitation. Runoff in turn has a direct influence on percolation.
Fig. 4.5 Average Cumulative Precipitation of The Different Regions of The State Throughout The Year.
The average maximum and minimum daily temperatures are shown in Fig. 4.7. The Southern region due to its low latitude has higher and less fluctuating temperatures as is characteristic of tropical regions. The average minimum and maximum temperatures are close in range and fairly constant throughout the year. The Central and Northwest regions have similar temperature patterns with the Northwest region, but experience slightly lower temperatures due to their higher latitude. The Northeast region although higher in latitude experiences higher average temperatures than the Central region. Also shown in Fig. 4.7 is the temperature distribution throughout the year. Peak temperatures occur mid year during the summer months followed by a gradual temperature decrease into the winter months. Temperature remains constant throughout the winter until it gradually increases and peaks mid year in the summer months of June and July. The proximity to the coast influences the temperature of the Northeast region and this explains its higher temperatures compared to the Central region, which is lower in latitude. Fig. 4.7 shows that the proximity to the coast and the latitude are the key parameters that influence the weather characteristics of Floridian regions.
Fig. 4.6 Average Precipitation per Rainy Day for The Different Regions of The State (average of the wettest 10 year period).
Fig. 4.7 Average Daily Maximum and Minimum Temperatures for The Different Regions of The State.
Fig. 4.8 shows the average growing season length for all regions. The growing season is in direct correlation with the average temperature described previously in Fig. 4.7. Due to the proximity to the coast and higher average temperatures, the Southern and Northeast regions have the longest growing seasons in Florida. The warm climate and tropical weather of the Southern region permits vegetation to grow all year long. The average Northeast growing season lasts for 274 days, while in the Northwest and Central the growing season lasts 241 and 253 days respectively. Longer growing seasons allow the vegetation to remove more water via evapotranspiration reducing percolation.

Alternative covers rely on the ability of plants to remove water during their growing season and the storage capacity of fine textured soils. For this reason the distribution of rainfall is crucial to the performance of alternative covers. Fig. 4.9 shows the amount of precipitation falling during the growing season and outside the growing season for the average of the wettest 10 years. For the south region the growing season is all year long so Fig. 4.9 shows all precipitation falling during the growing season. The northwest region having the shortest growing season has the most rainfall outside the plants’ growing season. Thirty two percent of the rainfall in the northwest region (586 mm) falls during the vegetation dormant months. Twenty one percent of the rainfall in the Central region (267 mm) and thirteen percent (206 mm) in the Northeast region fall outside the growing season. These values give insight of the storage capabilities the soil must have in each region in order to retain the infiltrating water until the growing season begins. Fig. 4.10 shows the average yearly cumulative solar radiation for all regions presented in this study. Solar radiation also varies throughout the state with the South having the highest cumulative solar radiation followed by the Northeast, Northwest, and Central Regions respectively.
Fig. 4.8 Average Growing Season of The Different Regions of The State Florida.
Fig. 4.9 Total Precipitation Occurring Inside & Outside the Growing Season Per Year (average of the wettest 10 year period).
Fig. 4.10. Average Cumulative Solar Radiation for The Different Regions of The State.
4.3 Vegetation Data

Three types of vegetation schemes were considered during this study. The test sections were considered to have either a grass cover, grass and tree cover, or local shrubs with grasses vegetation. The leaf area index for each vegetation scheme is shown in Fig. 4.11. The distribution of the leaf area index throughout the year is the same for all vegetation types as can be seen in Fig. 4.11. At the beginning of the growing season leaf area index increases linearly until it reaches its peak value 30 days into the growing season. The leaf area index then maintains its peak value throughout the growing season until it begins to decrease linearly 30 days before the end of the growing season. After the growing season ends the leaf area index is zero until the growing season begins again.

Finally, the peak leaf area index from Fig. 4.11 for trees and grasses used in this study is 4.5, for grasses it is 1.5, and for grasses and shrubs it is 2. These values were chosen based on the work being performed by ACAP in similar climate to the humid climate of Florida. Fig. 4.12 shows the root density function for each vegetation scheme. The different vegetation schemes differ in their root density function. The root density function describes the distribution of roots with depth. The values were chosen based on the work being performed by ACAP. Fig. 4.12 shows that after 50 centimeters, root density remains constant at its minimum value for all vegetation types. Trees and grasses have the highest root density near the surface, followed by grasses, and grasses and shrubs. Higher root density provides a higher water intake by roots, which will in turn increase evapotranspiration. During the collection of the vegetation data, it was evident that the root density function and the leaf area index are rarely found in the literature because of the difficulty of measuring such quantities.
Fig. 4.11 Leaf Area Index Throughout The Year For Trees & Grasses, Shrubs & Grasses, and Grasses Only.
Fig. 4.12 Root Length Density Function for Trees & Grasses, Shrubs & Grasses, and Grasses Only.
The problem becomes more challenging when daily values are needed. In humid regions, such as Florida, vegetation may play the dominant role in the design and implementation of landfill alternative covers. Further studies to collect more vegetation data may be required before the full implementation of such covers in this region.

4.4 Simulations

4.4.1 Selection of Governing Climatic Conditions

Previous research studies in arid and semi-arid climates recommend the use of the wettest 10 year period on record for simulations performed during the design phase of alternative covers. Other schools of thought use climatic data of the wettest year on record and simulate consecutive years of the wettest year on record. One also can argue that since these are for preliminary design, consecutive years of the average yearly climatic data can also be used. Since Florida’s climate is not arid or semi-arid, an investigation of the most conservative climate data to be used was needed. The effects of the weather scenario on the performance of alternative covers is discussed below. Simulations for this purpose were performed only on monolithic covers. Monolithic covers are devoid of vegetation and save considerable computing time during alternative cover simulations. Simulations were performed on 1 m thick covers with the Northwest climate data.

Three cases were considered during these simulations:

- Wettest 10-year period data was collected for each year of the wettest 10 year period on record. The simulations in this case are performed for each year. The soil water potentials from each year are then used as initial conditions for the next
year. Data input in this case is intensive since each year of simulation is treated separately.

- Consecutive 10 years of the average year during the wettest 10 year period on record. During this case the climate data obtained for the wettest 10 year period is averaged over the entire 10 year period. Simulations can be performed for as many consecutive years as possible using WinUnsat-H without re-entering the initial conditions each year.

- Consecutive 10 years of the wettest year on record

Fig. 4.13 shows the percolation rates through monolithic covers with the three weather conditions described above. Using data from the Northeast Region for a 1 m thick cover, simulations performed with yearly data of the wettest 10 year period on record show the lowest percolation rate after the fifth year. The percolation obtained using the other two consecutive scenarios gradually increases until year 5 where it remained constant. Another interesting observation from Fig. 4.13 is that the simulations performed using the yearly data of the wettest 10 year period on record yielded higher lower percolation rate. At the same time the simulation performed using 10 consecutive average years of the wettest 10 year period on record yielded the highest percolation rate.

Percolation is the governing parameter in the design of alternative covers. So Fig. 4.13 shows that for humid climates, the use of 10 consecutive years of the average year of the wettest 10 year period on record, is more conservative in predicting the highest percolation rate through alternative covers.
Fig. 4.13 Percolation Through Monolithic Covers 1 m Thick in The Northwest Using Different Weather Cases (Average Year of The Wettest 10 Year Period, Wettest Year on Record, and The Wettest 10 Year Period).
Fig. 4.14 shows the effect of the weather conditions on runoff. The runoff for the simulations using the climate data of 10 consecutive years of the average year of the wettest 10 year period on record yields the lowest runoff. Fig. 4.14 helps explain the results of Fig. 4.13, and shows that the 10 consecutive years of the average year of the wettest 10 year period on record has a higher percolation because it produces less runoff. These results indicate that the most conservative weather period is not necessarily the period with the highest precipitation.

Fig. 4.15 shows the infiltration rate through the modeled cover. Figure 4.16 shows the evaporation for the same simulations. These quantities and storage represent the remaining quantities in the water balance. The infiltration was highest for simulations performed with consecutive years of the average year of the wettest 10 year period. Infiltration was least for the simulations performed using yearly data of the wettest 10 year period. This is consistent with the observations from Fig. 4.14 discussed previously. The highest runoff was observed on simulations using the wettest year on record, consequently the water balance for these covers experiences a reduction in infiltration. From Fig. 4.15, the weather case with the least runoff led to the highest infiltration.

Evaporation is shown in Fig. 4.16 for the different weather conditions. Evaporation was highest for simulations performed with consecutive years of the average year of the wettest 10 year period. Evaporation was least for the simulations performed using yearly data of the wettest 10 year period. This consistent with the infiltration data, in that, more infiltration to the soil will lead to more water available for evaporation from the soil. Unlike the other parameters, evaporation remained fairly constant with time for all weather conditions. The average of the wettest 10 years produced the highest evaporation, roughly 96 cm of evaporation per year. The worst year followed with about 60 cm of evaporation constantly every year.
Fig. 4.14 Runoff Through Monolithic Covers 1 m Thick in The Northwest Region Using Different Weather Cases (Average Year of The Wettest 10 Year Period, Wettest Year on Record, and The Wettest 10 Year Period).
Fig. 4.15 Infiltration Through Monolithic Covers 1 m Thick in The Northwest Region Using Different Weather Cases (Average Year of The Wettest 10 Year Period, Wettest Year on Record, and The Wettest 10 Year Period).
Fig. 4.16 Evaporation Through Monolithic Covers 1 m Thick in The Northwest Region Using Different Weather Cases (Average Year of The Wettest 10 Year Period, Wettest Year on Record, and The Wettest 10 Year Period).
Fig 4.17 shows the effect of weather conditions on storage. Storage in humid regions is governed mainly by soil thickness since steady conditions are achieved earlier in humid climates. So it is observed that storage did not vary substantially from one weather scenario to another. This is consistent with the fact that storage is mainly a soil property.

**4.4.2 Preliminary Thickness Design**

The effect of soil thickness on the performance of alternative covers was determined using the selected weather period (average of the wettest 10-years) for 10 consecutive years. Table 4.3 shows a summary of the modeling output. Four simulations were conducted at each region with 0.5, 1, 1.5, and 2 meters thickness to observe the effect thickness had on percolation. Fig. 4.18 shows the percolation at different thickness for all regions. The percolation rates obtained from these simulations were around 0 cm for the Northeast Region, 17.8 cm for the Northwest Region, and 36.5 cm for the Central Region. These rates were the same for all modeled thickness. Results from these simulations suggest that thickness is not crucial in the design of alternative covers for humid climates. At varying thickness percolation remained the same for all regions (Fig. 4.18), meaning that soil saturation was achieved and steady state conditions governed. At such high infiltration rates, the design of soil thickness based on storage (Section 2), does not apply. Since soil storage has no effect, the design process shifts to maximizing the removal capabilities of the vegetation so as to create a balance between infiltration and evapotranspiration.
Fig. 4.17 Storage of Monolithic Covers 1 m Thick in The Northwest Region Using Different Weather Cases (Average Year of The Wettest 10 Year Period, Wettest Year on Record, and The Wettest 10 Year Period).
Table 4.3 Simulation Summary for Florida’s Climatic Regions Using Monolythic Covers of Varying Thickness.

<table>
<thead>
<tr>
<th>Region</th>
<th>Cover Thickness (m)</th>
<th>Precipitation (cm)</th>
<th>Percolation (cm)</th>
<th>Infiltration (cm)</th>
<th>Runoff (cm)</th>
<th>Evaporation (cm)</th>
<th>Storage (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>0.5</td>
<td>184.33</td>
<td>17.78</td>
<td>114.02</td>
<td>70.3</td>
<td>97.78</td>
<td>13.25</td>
</tr>
<tr>
<td>Northwest</td>
<td>1</td>
<td>184.33</td>
<td>17.84</td>
<td>114.13</td>
<td>70.19</td>
<td>97.89</td>
<td>25.79</td>
</tr>
<tr>
<td>Northwest</td>
<td>1.5</td>
<td>184.33</td>
<td>17.86</td>
<td>114.13</td>
<td>70.2</td>
<td>97.88</td>
<td>38.67</td>
</tr>
<tr>
<td>Northwest</td>
<td>2</td>
<td>184.33</td>
<td>17.86</td>
<td>114.13</td>
<td>70.22</td>
<td>97.86</td>
<td>51.55</td>
</tr>
<tr>
<td>Northeast</td>
<td>0.5</td>
<td>152.91</td>
<td>0</td>
<td>9.25</td>
<td>143.68</td>
<td>10.29</td>
<td>0.05</td>
</tr>
<tr>
<td>Northeast</td>
<td>1</td>
<td>152.91</td>
<td>0</td>
<td>2.82</td>
<td>150.15</td>
<td>2.4</td>
<td>0.055</td>
</tr>
<tr>
<td>Northeast</td>
<td>1.5</td>
<td>152.91</td>
<td>0</td>
<td>2.02</td>
<td>150.95</td>
<td>2.31</td>
<td>0.22</td>
</tr>
<tr>
<td>Northeast</td>
<td>2</td>
<td>152.91</td>
<td>0</td>
<td>2.02</td>
<td>150.95</td>
<td>2.31</td>
<td>1.3</td>
</tr>
<tr>
<td>Central</td>
<td>0.5</td>
<td>126.19</td>
<td>36.6</td>
<td>107.93</td>
<td>18.26</td>
<td>71.98</td>
<td>17.3</td>
</tr>
<tr>
<td>Central</td>
<td>1</td>
<td>126.19</td>
<td>36.71</td>
<td>107.93</td>
<td>18.26</td>
<td>71.99</td>
<td>33.19</td>
</tr>
<tr>
<td>Central</td>
<td>1.5</td>
<td>126.19</td>
<td>36.79</td>
<td>107.93</td>
<td>18.26</td>
<td>71.99</td>
<td>49.14</td>
</tr>
<tr>
<td>Central</td>
<td>2</td>
<td>126.19</td>
<td>36.85</td>
<td>107.93</td>
<td>18.26</td>
<td>71.99</td>
<td>65.52</td>
</tr>
</tbody>
</table>
Fig. 4.18 Percolation With Increasing Thickness at The End of The 10\textsuperscript{th} Simulated Year (Northwest, Northeast, and Central Region).
The thickness selected for the regions to simulate with vegetation was based on practical aspects of landfill construction. For the Northwest Region a thickness of 0.5, 1, and 1.5 meters was chosen to determine the most practical and efficient design. For the Northeast region, the thickness required was below .5 m, but for practical reasons covers less than 0.5 meters thick are not feasible. Consequently a thickness of 0.5 and 1 m was chosen for the Northeast Region. The percolation rate for the Central Region was considerably high compared to the other regions. This region is unlikely to qualify for implementation of alternative covers. The Central Region was given a design thickness of 2 m. Covers with higher thickness would be too expensive and unlikely to be used as an alternative cover.

4.4.3 Selection of Vegetation

4.4.3.1 Northwest Region

Upon selection of governing climatic conditions and design thickness, simulations were performed using three vegetation covers. Trees and grasses, grasses, and shrubs and grasses were simulated on covers with different thickness for the selected weather period. Simulations were performed at 0.5, 1, and 1.5 m using the vegetation schemes described above. Fig. 4.19 shows the percolation at different cover thickness using these vegetation schemes.

The equivalency criterion stated in section 2 is also shown in Fig. 4.19 to illustrate the performance of alternative covers in comparison to prescribed covers. For non-vegetated monolithic covers the percolation did not change with thickness and is shown in Fig. 4.19. Percolation for non-vegetated monolithic covers is 18 cm in the Northwest Region.
Fig. 4.19 Percolation with Increasing Thickness at The Northwest Region for The Different Vegetation Cases and No Vegetation.
The effect of vegetation is substantial as a drastic reduction in percolation is observed. For trees and grasses percolation was reduced from 18 cm with no vegetation for a thickness of 1.5 m to virtually no percolation. For shrubs and grasses percolation was reduced from 18 cm with no vegetation for a thickness of 1.5 m to 5.3 cm by adding vegetation. For grasses percolation was reduced by 11 cm.

From these simulations several observations can be made. At equal soil thickness, covers with trees and grasses have a lower percolation than covers using shrubs and grasses, and covers using grasses only. Fig. 4.20 shows the evapotranspiration for these simulations. Evapotranspiration for covers using trees and grasses is higher than those using shrubs and grasses, or grasses only. The higher evapotranspiration accounts for the lower percolation in the covers vegetated with trees and grasses.

The equivalency criterion for alternative covers is met at the Northwest Region using trees and grasses for a thickness of 1.5 m. This design provided no percolation and performed better than both compacted clay and geomembrane prescribed covers. It is observed that vegetation plays a very important role in the success of the alternative covers modeled in the Northwest Region. To investigate if vegetation with longer growing season can perform better, simulations were performed using an extended growing season. The growing season was extended to cover the whole year to see the effect this may have on percolation. Fig. 4.21 shows the effect of an extended growing season to the percolation of alternative covers in the Northwest Region.
Fig. 4.20 Evapotranspiration with Increasing Thickness at The Northwest Region for The Different Vegetation Cases.
Fig. 4.21 Effect of an Extended Growing Season on Percolation for a 1.5 m Thick Cover in The Northwest Region.
The simulations performed were conducted on a 1.5 m cover only to see if there is a significant reduction in percolation. This thickness was selected because it satisfied the equivalency requirement. For grasses, percolation was reduced from 7 cm to 4 cm by extending the growing season to cover the entire year. For shrubs and grasses, percolation was reduced by roughly 3 cm as well. The reduction in percolation also shows evidence of the importance of vegetation in the humid climate of the Northwest Region.

The Northwest region shows potential for the implementation of alternative covers. Simulations using trees and grasses with a 1.5 m thickness showed a balance between infiltration and evapotranspiration that neutralized drainage. The vegetation data however, proved to have a significant effect on percolation and to improve the design of alternative covers in humid climates the vegetation must be optimized. Due to the uncertainty of vegetation data available for the design of alternative covers and the effect of vegetation data on the performance of alternative covers in humid climates, the accuracy of the vegetation data may be very significant.

4.4.3.2 Northeast Region

For the Northeast Region, simulations were performed using the same vegetation used in the Northwest Region. Trees and grasses, grasses, and shrubs and grasses, were simulated on covers with different thickness. Simulations were performed at 0.5, and 1 m using the vegetation scheme described above. Table 4.4 shows a summary of the simulation parameters obtained for simulations with a cover thickness of 0.5 m. Table 4.5 shows a summary of the simulation parameters obtained for simulations with a cover thickness of 1 m.
Table 4.4 Northeast Region Simulation Summary at a 0.5m Cover Thickness.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Precipitation (cm)</th>
<th>Drainage (cm)</th>
<th>Infiltration (cm)</th>
<th>Runoff (cm)</th>
<th>Evapotranspiration (cm)</th>
<th>Storage (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees &amp; Grasses</td>
<td>152.9</td>
<td>0</td>
<td>67.7</td>
<td>85.2</td>
<td>68.3</td>
<td>1.78</td>
</tr>
<tr>
<td>Grasses</td>
<td>152.9</td>
<td>0</td>
<td>67.46</td>
<td>85.45</td>
<td>68.22</td>
<td>2.08</td>
</tr>
<tr>
<td>Shrubs &amp; Grasses</td>
<td>152.9</td>
<td>0</td>
<td>68.22</td>
<td>84.7</td>
<td>68.9</td>
<td>2.03</td>
</tr>
</tbody>
</table>
Testing showed that the hydraulic conductivity is \(10^{-8}\) cm/sec. This value was increased to \(2 \times 10^{-6}\) to account for the increase in hydraulic conductivity due to desiccation cracks. However, the hydraulic conductivity of the soil from this region is still low enough that it does not require the use of plants, e.g. the soil acts as a barrier. Testing showed that the hydraulic conductivity is \(10^{-8}\) cm/s. This value was increased to \(2 \times 10^{-6}\) to account for the increase in hydraulic conductivity due to desiccation cracks. However, simulations performed previously using monolithic covers showed no percolation as shown in Table 4.3, therefore simulations with plants were expected to produce no percolation. Simulations performed on this region observed no percolation at any thickness as a consequence of the soil’s low hydraulic conductivity. The simulations for both 0.5 m and 1 m produced similar outputs because water did not reach past 0.5 m. Precipitation for these simulations was 153 cm, Runoff was 85 cm, infiltration was 68 cm, and evapotranspiration was 68 cm. From these values it can be seen that most of the applied water is eliminated as runoff.

The infiltration rate is equal to the evapotranspiration rate and is removed at the surface of the covers. Based on these simulations, covers with these soils in the Northeast Region meet the equivalency criteria for compacted clay and geomembrane prescribed covers using any vegetation at a thickness of 0.5 m. The high magnitude of runoff is typical of locations where rainfall occur in very intensive rain events. On the other hand, it is not clear if UNSAT-H overestimates runoff when rainfall is not uniform throughout the day.
Table 4.5 Northeast Region Simulation Summary at a 1m Cover Thickness.

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Precipitation (cm)</th>
<th>Drainage (cm)</th>
<th>Infiltration (cm)</th>
<th>Runoff (cm)</th>
<th>Evapotranspiration (cm)</th>
<th>Storage (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees &amp; Grasses</td>
<td>152.9</td>
<td>0</td>
<td>67.6</td>
<td>85.31</td>
<td>68.24</td>
<td>2.07</td>
</tr>
<tr>
<td>Grasses</td>
<td>152.9</td>
<td>0</td>
<td>67.44</td>
<td>85.48</td>
<td>68.31</td>
<td>3.57</td>
</tr>
<tr>
<td>Shrubs &amp; Grasses</td>
<td>152.9</td>
<td>0</td>
<td>68.18</td>
<td>84.73</td>
<td>69.01</td>
<td>4.26</td>
</tr>
</tbody>
</table>
4.4.3.3 Central Region

Because of the significantly higher percolation rate, a two meter design was used for the Central Region. Despite previous simulations showing that thickness in these climates did not affect drainage, the thickness was increased to 2 m to verify these findings. Simulations were performed using trees and grasses, shrubs and grasses, and grasses only. Additional simulations were performed using an extended growing season, e.g. all year long, to evaluate the effect on percolation. Given the importance of vegetation on previous simulations in these humid climates, the idea behind these additional simulations is to try to maximize the effect of the vegetation.

Fig. 4.22 shows a comparison of the percolation from simulations in the Central Region. Percolation using trees and grasses is 31.92 cm, for shrubs and grasses is 34.15 cm, and using grasses only is 34.37 cm. Fig. 4.22 shows the reduction in percolation obtained by extending the growing season to the whole year, which was roughly 0.5 cm. Additionally Fig. 4.23 shows the evapotranspiration for these simulations. The additional evapotranspiration obtained by extending the growing season is evident from Fig. 4.23. This additional evapotranspiration is also equal to the reduction in drainage observed in Fig. 4.22. From Fig. 4.23 the additional evapotranspiration is roughly 0.5 cm, which is equal to the reduction in percolation. Also confirmed by these simulations, the increase in thickness did not affect percolation as it remained at 34 cm for grasses at 1 m and 2 m thickness. The percolation is excessive in part due to the higher hydraulic conductivity of the soil sample obtained from this region. From this experiment it is determined that the Central Region is not suitable for the implementation of alternative covers due to the sandy soils that are prevalent in this region. Percolation is too high for the vegetation to manage and therefore a better soil is needed to provide storage for the vegetation.
Fig. 4.22 Percolation for The Different Vegetation Cases at a 1m Cover Thickness in The Central Region.
Fig. 4.23 Evapotranspiration for Different Vegetation Cases at 1m Cover Thickness in The Central Region.
SECTION FIVE
SUMMARY AND CONCLUSIONS

Using the traditional design procedure described in Section Two used in arid and semi-arid climates, alternative covers were designed for the four regions of the state. The traditional design of alternative covers used in arid and semi-arid climates is based on providing storage for all of the precipitation that falls outside the growing season, provided the vegetation will remove this water during the growing season. Table 5.1 shows the design parameters and results for each region. The design thickness of alternative covers was also determined using UNSAT-H and is shown in Table 5.2. These designs were determined by trial and error with UNSAT-H using different vegetation covers. The preliminary thickness was obtained by simulations performed previously on non-vegetated monolithic covers at increasing thickness and is addressed in Section Four of this study. The design procedure was an iterative procedure in which the design thickness was gradually increased if simulations failed to meet the equivalency criteria. Numerous simulations using UNSAT-H were also performed for each region of the state and provide the basis for the recommendations for implementation of alternative covers. Based on the traditional design and results from the numerous simulations performed for each region the following recommendations were made.

5.1 Northwest Region

For the Northwest region, the precipitation outside the growing season ($P_o$) is the greatest. The cover thickness of the Northwest Region calculated according to the traditional design is 202.37 cm.
Table 5.1 Design Results for Florida’s Climatic Regions using the Traditional Alternative Cover Design Procedure.

<table>
<thead>
<tr>
<th>Region</th>
<th>$\theta_{wp}$</th>
<th>$\theta_{fc}$</th>
<th>$\theta_a$</th>
<th>$P_o$ (cm)</th>
<th>L (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>0.037</td>
<td>0.332</td>
<td>0.295</td>
<td>59.7</td>
<td>202.37</td>
</tr>
<tr>
<td>Northeast</td>
<td>0.037</td>
<td>0.307</td>
<td>0.27</td>
<td>20.7</td>
<td>76.67</td>
</tr>
<tr>
<td>Central</td>
<td>0.04</td>
<td>0.303</td>
<td>0.263</td>
<td>25.1</td>
<td>95.44</td>
</tr>
<tr>
<td>South</td>
<td>0.051</td>
<td>0.058</td>
<td>0.007</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 5.2 Design Results for Florida’s Climatic Regions Determined by Computer Modeling Using UNSAT-H.

<table>
<thead>
<tr>
<th>Region</th>
<th>Thickness</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>1.5</td>
<td>Trees &amp; Grasses</td>
</tr>
<tr>
<td>Northeast</td>
<td>0.5</td>
<td>Any Vegetation</td>
</tr>
<tr>
<td>Central</td>
<td></td>
<td>Not Feasible</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td>Not Feasible</td>
</tr>
</tbody>
</table>
Results from simulations using UNSAT-H showed that using a cover thickness of 1.5 m vegetated with trees and grasses, alternative covers can meet the equivalency criteria. No percolation was obtained for the Northwest region using trees and grasses and a thickness of 1.5 m. This cover thickness is smaller than that calculated according to the traditional alternative cover design procedure. This can be explained by the fact that traditional alternative cover design is very conservative and provides storage for all precipitation falling outside the growing season neglecting the effects of runoff, which may significantly reduce infiltration. The thickness design obtained for these simulations therefore is 1.5 m. Results at 0.5 and 1 m for the Northwest region, are discussed in Section Four. It is noted though that simulations at 1m using trees and grasses as a vegetation cover met the equivalency criteria for compacted clay covers in the Northwest Region but did not for composite covers.

5.2 Northeast Region

For the Northeast Region a cover thickness of 76.67 cm was determined using the traditional design. The growing season for the Northeast Region is relatively longer than for the Northwest region, therefore less precipitation falls outside the growing season and consequently \( P_0 \) is smaller from Table 5.1. The Northeast Region therefore does not need to provide as much storage and therefore the design thickness using the traditional alternative cover design is smaller than the Northwest Region.

Simulations using UNSAT-H showed that the Northeast Region had no percolation at 0.5 m regardless of vegetation. The soil was such that it had a low hydraulic conductivity and acted as a barrier. For these simulations water was removed at the surface and no infiltration was detected past 0.5 m. The design thickness determined by UNSAT-H modeling therefore was 0.5 m.
5.3 Central Region

For the Central region a cover thickness of 95.44 cm was determined using the traditional alternative cover design. The growing season for the Central Region is also fairly short; precipitation outside the growing season therefore is small and consequently so is $P_\circ$. The Central Region therefore as the Northeast Region does not need to provide as much storage and therefore the design thickness using the traditional design is smaller. Simulations using UNSAT-H showed the Central Region could not meet the equivalency criteria. Simulations were performed at 1 m, and then further at 2 m showing no reduction in percolation with increased thickness. The percolation using trees and grasses was 32 cm, 22 cm higher than the percolation for compacted clay covers, therefore a design in the Central Region using alternative covers failed to meet the equivalency criteria. Simulations therefore concluded that the Central Region is not feasible for the implementation of alternative covers.

5.4 South Region

For the South Region, according to the traditional design, no thickness is required as the growing season is all year long. In the South region, by definition there is no precipitation outside the growing season since it is all year long, therefore according to the traditional design no storage is required. However, the soil of the Southern Region has no storage capabilities as shown by its SWCC (Fig. 4.4), this combined with a very high hydraulic conductivity deemed design in the Southern Region impossible.
5.5 Importance of Vegetation

Vegetation played an important role in several cases during simulations. The Northwest Region for example, simulations using the design thickness of 1.5 m did not all meet the equivalency criteria. Only using Trees and Grasses, which evapotranspirate at a rate high enough to balance the flux of infiltration, could covers simulated in the Northwest region meet the equivalency criteria. Fig.5.3 shows percolation throughout the year for the Northwest Region using the three vegetation types and no vegetation at 1.5 m. Percolation with no vegetation is much higher than its counterparts with vegetation, while infiltration is constant. The data in Fig. 5.1 suggests that for these regions in order to reduce or change percolation, the vegetation should be optimized because soil thickness will not have a significant impact on it. Percolation decreases from grasses, to shrubs and grasses, to trees and grasses respectively. The most significant reduction occurred from no vegetation to the use of vegetation. During the growing season vegetation is expected to remove all stored water, but in humid regions it is observed that this task is harder. The volume of precipitation managed is very high and therefore the vegetation may or may not handle the infiltration rates for the humid regions in this study.

This fact again places a great deal of focus on vegetation design in humid climates, because it is pointless to provide enough storage for rainfall during vegetation dormant months if during the growing season the vegetation will not remove keep up with infiltrating water. Shrubs and grasses, and grasses only showed a decrease in percolation compared to no vegetation, however due to the high precipitation obtained during the growing season the reduction was not enough for successful implementation.
Fig. 5.1 Percolation Throughout the Year During The 10th Simulated Year for The Northwest Region Using The Different Vegetation Cases and No Vegetation at a Thickness of 1.5 m.
The water content throughout the year for different vegetation cases at 1.5 m is shown in Fig. 5.2. During the growing season, water content is not reduced by vegetation but rather is controlled by climatic conditions due to high precipitation. Vegetation is not able to control the flux of water during the growing season. For trees and grasses, there was no percolation throughout the year. The volumetric water content remained constant at 0.0049 at a 1.5 m depth, meaning that the vegetation kept-up with infiltration. Fig. 5.3 shows water content at several depths for a 1.5 m cover using trees and grasses in the Northwest Region. Nearest the surface, the effect of climatic conditions and vegetation can be observed in Fig. 5.3, which progressively decreases approaching the boundary at 1.5 m.
Fig. 5.2 Volumetric Water Content Throughout The Year During The 10th Simulated Year for The Northwest Region Using The Different Vegetation Cases and No Vegetation at a Thickness of 1.5 m.
Fig. 5.3 Water Content at Different Depths using a Cover 1.5 m Thick With Trees and Grasses at The Northwest Region.
Abichou, T., Benson, C., Gee, G., and Albright, W., “Design Considerations for Lysimeters Used to Evaluate Alternative Earthen Final Covers,” In Review.


National Climate Center. “Climatography of the US # 60 (Climate of Florida).”


Appendix (Files in CD)

A. Climate Data for The Different Regions of The State

B. Simulation Results