EVALUATION OF PLANTS ON WATER BALANCE OF EARTHEN LANDFILL COVERS

by

Banafsheh Saghaei

A dissertation submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in
Infrastructure and Environmental Systems

Charlotte

2019

Approved by:

____
Dr. Milind V. Khire

____
Dr. James Bowen

____
Dr. Jay Wu

____
Dr. Sandra Clinton

____
Dr. John Diemer

ABSTRACT

BANAFSHEH SAGHAEI. Evaluation of Plants on Water Balance of Earthen Landfill Covers. (Under the direction of DR. MILIND V. KHIRE)

Landfilling is one of the most common methods to dispose municipal solid waste (MSW) and coal combustion residues (CCRs) in the U.S. Sustainable landfilling will be the key for the future advancement of solid waste management. Sustainable landfilling will include zero discharge of leachate constitutes, converting the methane into energy and sequestering carbon dioxide to reach the ideal target of zero greenhouse gas (GHG) emissions. While we are far from zero leachate and zero GHG emissions goals, my research is the next step towards both of those goals.

Alternative final covers (AFCs) have been increasingly permitted due to the financial benefits and environmental sustainability offered using native soil. However, often due to lack of validated plant data and transpiration models, practitioners ignore effect of plants when designing AFCs. This dissertation focused on evaluating the effect of plants on hydrological performance and water balance of earthen final covers by conducting field-scale and laboratory-scale experiments coupled with numerical modeling.

The field-scale experiment was carried out in the southcentral U.S. It consisted of two 11 m long x 11 m wide x 0.9 thick earthen cover test sections, one planted with vetiver and the other was bare representing control. Each test section had a lysimeter to collect percolation. Both test sections were fully instrumented. About 14 sensors were installed in each test section to monitor matric suction, water contents, soil temperature, and lysimeter water levels. A weather station was installed at the site. The hydrological performance of

each test section was monitored over a period of one year. Field data shows that the average ET rates for control and vetiver test sections were 0.31 cm/day and 0.30 cm/day, respectively. Twenty-two (22) water removal events of the field test sections were analyzed starting October 2017 to August 2019 when the lysimeters were allowed to flood by turning off the drainage valves. This analysis showed that the average ET rates during the 23-month period were 0.34 cm/day and 0.25 cm/day for control and vetiver test sections, respectively. More than 3-year field-scale data analysis indicates that the difference between soil water storage and evapotranspiration (ET) of the two test sections was less than 2%. The water balance model UNSAT-H was used to simulate the field water balance. The percolation predictions of UNSAT-H model for both test sections were relatively accurate. While the model predicted percolation accurately, it under-estimated ET for the vetiver test section by about 9% and overestimated ET for control by about 19%.

A large-scale column experiment was set up in the southeastern U.S. Three identical laboratory soil columns (one without vegetation, second planted with vetiver grass and third planted with switchgrass) consisting of two layers of soil: topsoil (35 cm) underlain by compacted sandy silt (76 cm) were built and instrumented to mimic an ET landfill cover. The diameter of the soil columns was 25.5 cm. Data collected over a 14-month period showed that ET from switchgrass and vetiver columns was greater than ET from the bare column by 2% and 9%, respectively. By the end of the 14-month large-scale study, vetiver grass and switchgrass canopies were about 50% and 75% of their mature height, respectively. The columns experienced a 25-day drought starting mid-May 2019. Consequently, ET from vetiver grass and switchgrass columns increased significantly due to plant root water uptake. The four-month ET from switchgrass and vetiver columns was 23% and 37% higher than ET from control, respectively.

The results indicate that in humid geo-climatic regions, the use of plants with canopies that restrict solar radiation to the surface of the cover may restrict evaporation and it does not enhance ET. However, if the plants go through drought and are under stress, the plant water increases while evaporation may be impeded due to relatively low unsaturated hydraulic conductivity of the uppermost dry exposed soil. More research on plants with smaller canopies and extensive root systems is recommended as it may enhance ET from ET covers.

ACKNOWLEDGMENTS

I would like to thank my graduate advisor Dr. Milind V. Khire for his guidance and support over the last four and half years. I learned a lot from working with him on various projects and gained valuable experience and knowledge in the field of geoenvironmental engineering. I really appreciate the time he spent to mentor me.

I also would like to express my appreciation to my committee members Dr. James Bowen, Dr. Jay Wu, Dr. Sandra Clinton, and Dr. John Diemer for their help and support to improve my work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFC	Alternative Final Cover
ASTM	American Society for Testing for Materials
CB 10	TDR sensor located at 10-cm from the surface in lower nest of the control test section
CB 33	TDR sensor located at 33-cm from the surface in lower nest of the control test section
CB 56	TDR sensor located at 56-cm from the surface in lower nest of the control test section
CB 79	TDR sensor located at 79-cm from the surface in lower nest of the control test section
CL	low plasticity clay
EPA	Environmental Protection Agency
ET	evapotranspiration/evapotranspirative
ET_C	evapotranspiration of the control test section during the drying event
ET_V	evapotranspiration of the Vetiver test section during the drying event
GT	nonwoven geotextile.
GM	geomembrane
IPM	instantaneous profile method
LAI	leaf area index
LL	liquid limit
MSW	municipal solid waste

NOAA	National Oceanic and Atmospheric Administration
PE/P	potential evaporation to precipitation ratio
PI	plasticity index
RCRA	Resource Conservation and Recovery Act
RH	relative humidity
RO	runoff
S_B	degree of saturation at the beginning of the drying event
S_E	degree of saturation at the end of the drying event
SM	sandy silt
SWCC	soil-water characteristic curve
SWS	soil water storage
SWS_B	soil water storage value at the beginning of the drying event
SWS_E	soil water storage value at the end of the drying event
Temp	temperature (℃)
TDR	time-domain reflectometry
UNSAT-H	unsaturated soil water and heat flow model
US	United States
USCS	Unified Soil Classification System
USEPA	United States Environmental Protection Agency

LIST OF SYMBOLS

a	fitting coefficient for normalized root-density function
b	fitting coefficient for normalized root-density function
c	fitting coefficient for normalized root-density function
C_c	coefficient of gradation
C_u	uniformity coefficient
D	depth of the storage layer
D_{10}	effective size in the particle-size distribution curve corresponding to 10% finer
D_{50}	particle-size diameter corresponding to 50% finer
D_{60}	particle-size diameter corresponding to 60% finer
E	evaporation
ET	evapotranspiration
G_s	specific gravity of solids
K_ψ	unsaturated hydraulic conductivity
K_S	saturated hydraulic conductivity
n	fitting parameter for van Genuchten (1980) function
P	precipitation; percolation in the lysimeter calibration equation (cm)
P_r	percolation
R	runoff; root-length density

R_{rL}	normalized root biomass
S	degree of saturation; sink term representing plant uptake in Richard's equation
t	time
x	temperature measured by the TDR sensor (℃)
y	average time period measured by the TDR sensor (μs)
z	vertical coordinate; depth (cm); water level in the lysimeter(cm)
α	fitting parameter for van Genuchten (1980) function
γ_d	dry unit weight
Δ S	soil water storage change
θ	volumetric water content
θ_r	residual water content
θ_s	saturated water content
ψ	matric suction
ω	gravimetric water content

INTRODUCTION

One of the most commonly used methods for disposing municipal solid waste (MSW) is to use engineered landfills. According to United States Environmental Protection Agency (EPA), there have been around 1,908 active MSW landfills in the United States in 2009 and about 254 million tons of MSW were generated (US EPA 2017). Landfills are engineered facilities consisting of bottom liner made of compacted clay and geomembrane liner, leachate collection and removal system, gas collection system, and final cover system. When the landfills reach their permitted capacity, they are capped with a final cover system. Final cover reduces infiltration, gas emissions, and odors and minimizes erosion as plants establish and that improves the slope stability and aesthetics.

Based on Resource Conservation Recovery Act (RCRA) Subtitle D (40 CFR 258.60 2009), the final covers of MSW landfills should have low hydraulic conductivity to be as effective as the landfill's bottom liner to reduce infiltration through the waste (40 CFR 258.60 2009). RCRA Subtitle D final cover consists of a two-feet thick compacted soil layer, a geomembrane (GM) layer, an 18-in thick infiltration layer and 6 to 12-in thick vegetative layer. Construction of conventional covers is costly due to the use of GM. The GM layer is prone to damage during the installation as well as during service. In addition, the GM layer prevents plants from establishing deeper and more sustainable root system that protects the plants during extended periods of drought.

ALTERNATIVE FINAL LANDFILL COVERS

Because conventional final covers need more maintenance in the long-term, and are relatively expensive to construct, a majority of states in the U.S. allow alternative covers if they can meet the RCRA subtitle D requirements of equivalent reduction in percolation and erosion. Alternative covers constructed only with natural soils have been approved and been in practice in many states (Albright et al. 2004; Khire 2016; Mijares and Khire 2012).

Numerous studies have been published on the performance of alternative covers demonstrating that the key feature of an alternative cover is its ability to evapotranspire a great portion of precipitation to the atmosphere. Hence, these covers are also referred to as evapotranspirative (ET) covers (Albright et al. 2004). An ET cover may only consist of a compacted storage layer made of native soil(s) having relatively low hydraulic conductivity, and a topsoil layer for plant growth (Khire 2016). The thickness of the storage layer is designed so that the infiltration is either stored in the storage layer or removed via ET. The key difference between a conventional cover and an alternative cover is eliminating the geomembrane in the cover design which results in long-term sustainability. ET covers are made of native soils. An ET cover is relatively easy to maintain and it is around 37% to 75% less costly to construct depending on the availability of suitable soils at the site (Hauser et al. 2001).

For an ET cover to be permitted, it must be equivalent to RCRA Subtitle D cover. The equivalency evaluation is usually carried out using field data and/or water balance numerical modeling. To evaluate the hydraulic performance by using the field data, often lysimeters are constructed, and the water balance parameters: precipitation, surface runoff, soil water storage, evapotranspiration (ET), and percolation through the cover are monitored. ET represents combined evaporation and transpiration because it is not possible to measure these variables separately.

One of the most commonly used water balance simulation models is UNSAT-H (Khire et al. 1997). UNSAT-H is a rigorous and data-intensive model and requires the input of climatic, soil-specific and plant-related parameters to predict ET. There is lack of field data on validation of predicted transpiration by water balance models such as UNSAT-H for humid or sub-humid climates. Hence, when modeling alternative landfill covers, often a conservative approach of ignoring the effect of plants (and transpiration) is adopted (Khire 2016). Ignoring the role of plants in the design and/or in-service evaluation phase of an alternative cover may not be appropriate for humid climates where due to relatively high precipitation, percolation equivalency of the cover may not be met by ignoring the role of plants and removal of water via transpiration.

TRANSPIRATION MEASUREMENT

Literature shows plant transpiration measured by both direct and indirect methods. Using evaporation tanks with cultivated hydrophytes (Sânchez-Carrillo et al. 2001), and continuous measurement of capillary flow porometer of stomatal resistance of leaves (Day 1977) are two of the direct transpiration measurement methods. Some of the most popular indirect methods of plant transpiration measurements are sap flow measurements of plants stems (Nadezhdina et al. 2018; Vogel et al. 2017), and energy budget measurements (Leuning and Foster 1990; Renner et al. 2016). All the indirect methods of transpiration estimation are based on the relationship between planted areas and open water areas which includes numerous variables to monitor and measure. This can be costly and prone to methodological errors (Sânchez-Carrillo et al. 2001). The scale of transpiration measurement in all the mentioned methods may not be representative of a large-scale filed test section. For example, sap flow and porometer measurements are leaf-to-plant estimations of transpiration and may not represent the role of plant transpiration in a large-scale setting. Hence, conducting a field-scale quantification of transpiration for a specific plant is essential. A large-scale study of transpiration will provide more insight into transpiration and evaporation variations based on numerous field-related parameters such as geoclimatic variations and vegetation characteristics. Consequently, understanding the plants' role in water balance performance of an alternative landfill cover will greatly contribute to the design process of an alternative final landfill cover.

USE OF PLANTS ON LANDFILL COVERS

Use of plants on landfill covers has been in practice for a millennia. (Licht et al. 2001; Rock 2003) Since the 1990s, the practice of using plants on land covers has been introduced for the decrease in landfill leachate and leachate treatment (Granley and Truong 2012).

Vetiver grass is considered a simple sustainable, hygienic and low-cost method for landfill leachate chemical treatment (Banerjee et al. 2016; Smeal et al. 2017). However, the effect of vetiver grass on an ET landfill cover water balance has not been evaluated and quantified. Vetiver grass develops a deep root system which grows up to 2.8 m, and at its mature state, the dense plant canopy can be 3 m tall (Truong 2019). Hence, vetiver grass was selected for the field and laboratory studies because of its ability to uptake nutrients and to have a relatively high tolerance to elevated levels of salts, heavy metals and chemicals of leachate (Banerjee et al. 2019; Truong 2019).

Switchgrass is a perennial grass with a dense canopy that can grow up to 1.8 m, and it is a native grass to the vast majority of North America (Hui et al. 2018; USDA, 2018). Switchgrass has been considered a suitable solution for soil erosion control, producing livestock and wildlife habitat aspects of a landfill cover due to its high biomass production, high nutrient uptake and being tolerant to a broad environment condition (Hui et al. 2018; USDA, 2018). Switchgrass was also selected for this research study alongside with vetiver grass. They both have similar plant characteristics while switchgrass is native to North America and vetiver is native to south India.

WATER BALANCE MODELING

One of the most commonly used water balance models is UNSAT-H which is a finite-difference water balance model. It numerically solves a modified form of Richard's equation to calculate the one-dimensional flow of water (or heat) through saturated or unsaturated porous media in both steady and transient states (Fayer 2000). UNSAT-H model has been widely used for evaluating and designing landfill cover systems (Khire 2016; Mijares and Khire 2012; Smesrud et al. 2012). Both evaporation and transpiration are modeled by UNSAT-H. Evaporation is simulated using Fick's law of diffusion (Campbell 1977). And, transpiration is simulated based on the estimates of potential evapotranspiration (PET) which is calculated based on the climatic data (Fayer 2000).

UNSAT-H model and field-data analysis are commonly used for landfill cover systems' performance evaluation with the purpose of percolation equivalency. However, the model's evaporation and transpiration predictions have been only validated for arid and semi-arid climates using plants that are specific to the region. UNSAT-H has a specific built in function for partitioning PET into evaporation and transpiration which was developed based on the Hanford site's vegetation (Duncan et al. 2007; Fayer 2000). The Hanford site's vegetation community was also referred to as shrub-steppe in which cheatgrass was the dominant species. Cheatgrass is an annual grass with shallow roots and its mature height is about 10- 60 cm (USDA, NRCS 2003).

OBJECTIVES

The key objectives of this dissertation were to: (1) compare water balance of ET covers with and without plants and evaluate the effect of plants on overall ET in humid climate; and (2) to validate the numerical model UNSAT-H for water balance predictions of ET covers in humid climate.

METHODOLOGY

In order to fulfill the objectives of this research, instrumented field-scale covers were built at a site located in the southcentral U.S. and instrumented column-scale covers were built in the southeastern U.S. Both sites are in humid climates. For the field-scale experiments, two 11 m long x 11 m wide x 0.9 m thick ET cover test sections were built side by side. A 0.6 m deep pea-gravel layer (lysimeter) was installed beneath each test section to collect percolation. The test sections were instrumented to measure precipitation, soil water contents (soil water storage), and percolation. These test sections were identical except, one test section was planted with vetiver grass and the other test section was bare (control). Water balance parameters of the vegetated and control test sections were evaluated in two phases using two ET estimation methods.

In southeastern U.S., three identical soil columns (25.5 cm diameter) consisting of 76 cm thick compacted sandy silt overlain by 35 cm thick topsoil were instrumented to measure water balance parameters. One of the columns was planted with a vetiver plant, one with a switchgrass plant, and the third column was bare. Data collected over a year was analyzed to assess the ET from the three columns.

ORGANIZATION OF THE DISSERTATION

This dissertation has been written in five chapters. The first chapter is the introduction and objectives. The second chapter is presented as a paper and this paper presents the design, construction, and instrumentation of the field-scale experiment where data was collected over a period of three years. The third chapter presents a paper which includes the design, construction, instrumentation, and water balance data collected over a period of 14-months for three large-scale soil columns. The fourth chapter presents the water balance modeling of the field test sections using the numerical model UNSAT-H. The last chapter summarizes the results and presents the conclusions drawn from the field and large-scale lab experiments and numerical modeling.

PAPER NO. 1: FIELD-SCALE EVALUATION OF VETIVER PLANTS ON EVAPOTRANPIRATION FROM A LANDFILL COVER

ABSTRACT

Due to financial benefits and environmental sustainability offered by using native soil used for constructing alternative final covers, they have been permitted for municipal solid waste landfills since the 1990s. However, often due to a lack of data on the effect of plants on the water balance of the cover, practitioners ignore the effect of plants when alternative covers are designed and permitted. This study focused on evaluating the effect of plants on evapotranspiration (ET) and the water balance of a 90-cm-thick earthen cover. Two 11 m long by 11 m wide by 0.9 m thick test sections were built side by side in the southcentral U.S. where the climate is humid. One test section was planted with vetiver plants and the other test section was maintained bare (control). The test sections were instrumented to measure precipitation, percolation, soil water storage and unsaturated hydraulic characteristics of the cover. ET was estimated from the data. Data collected over three years indicated that there were relatively small differences in ET (less than 2% of the total precipitation). Soil water storage for both bare and vetiver test sections were relatively similar over the 3-year period. Hence, the plants did not alter the water removal ability of the cover significantly.

INTRODUCTION

Landfilling is one of the most commonly used methods for the disposal of MSW. It has been estimated that in 2009, there were around 1,908 active MSW landfills in the United States (US EPA 2017). Landfills are engineered facilities consisting of leachate collection system, bottom liner, gas collection system, and final cover system. When the landfills reach their permitted capacity, they are capped with a final cover system. The key role of the final cover is to prevent infiltration of precipitation and to minimize percolation through the waste layer. The final cover also reduces landfill odors, enhances surface runoff, minimizes erosion once plants establish, and improves the slope stability and aesthetics.

While Resource Conservation Recovery Act (RCRA) Subtitle D regulations mandate final cover that contains a geomembrane (GM), alternative final covers consisting only of natural soils have been approved in many states, including California, Arizona, Colorado, Nevada, Iowa, Nebraska, Michigan and Texas (Albright et al., 2004; Mijares and Khire, 2012; Khire, 2016). For an alternative cover to be permitted, it requires demonstration via field testing and/or numerical modeling that the long-term percolation from the alternative cover is equivalent to RCRA Subtitle D or the "prescriptive" cover. For assessing the hydraulic performance by using the field data, often lysimeters are constructed, and the water balance parameters that include precipitation (P), surface runoff (R), soil water storage (ΔS), and percolation (P_r) through the cover are monitored. Evapotranspiration (ET) is estimated as a water balance error using the water balance equation presented in Equation 1-1:

$$ET = P - P_r - R - \Delta S \quad (1\text{-}1)$$

ET is combined evaporation and transpiration that occurs as plants process water for transport of nutrients and cooling. It is not possible to separately measure evaporation and transpiration accurately at field-scale representative of the scale at which ET covers are built. Water balance models such as UNSAT-H are commonly used to demonstrate percolation equivalency. UNSAT-H is a data-intensive model that is based on fundamental equations that govern the unsaturated flow through soils and evaporation using atmospheric energy. For the model to simulate ET, it requires the input of climatic as well as soil and plant-related parameters. While some of the plant-related input parameters can be measured, there is very little field data on validation of transpiration predicted by water balance models such as UNSAT-H for landfill cover application. Due to the lack of validation or benchmarking studies, practitioners have often resorted to modeling alternative covers by ignoring the effect of plants on the water balance of the cover (Khire 2016). Such an approach is usually considered conservative because for humid climates due to relatively high precipitation, it is unlikely to satisfy the percolation equivalency by ignoring the potential effect of plants on removal of water from the cover via transpiration.

In previous studies, transpiration has been evaluated and measured using both direct and indirect methods. Direct estimation of transpiration included using evaporation pans containing cultivated hydrophytes (Sânchez-Carrillo et al. 2001) and continuous measurement of capillary flow porometer of stomatal resistance of leaves (Day 1977). Some of the most commonly used indirect methods of estimating transpiration are sap flow measurements of plant stems (Nadezhdina et al. 2018; Vogel et al. 2017), and energy budget measurements (Leung and Foster 1990; Renner et al. 2016). All the indirect methods of transpiration estimation are based on the basis of the relationship between planted areas and open water areas which includes numerous variables to monitor and measure which also can be costly and prone to methodological errors (Sânchez-Carrillo et al. 2001). The scale of transpiration measurement in all the mentioned methods may not be representative of a large-scale field test section. For example, sap flow and porometry measurements are leaf-to-plant estimations of transpiration and may not represent the plant transpiration behavior in larger scale. Hence, conducting a field-scale experiment to evaluate the effect of a specific plant is valuable and needed. Because, it provides insight in transpiration and evaporation variations based on numerous field-related parameters such as geoclimatic variations and vegetation characteristics.

Hence, assessment of the effect of plants on the water balance of an ET cover using actual field data will greatly contribute to the alternative cover's design and permitting processes. In addition to the design and permitting aspects of alternative covers, using plants to improve the environment has been in progress for millennia (Licht et al., 2001; Rock, 2003). It has been perceived in the waste industry that the use of plants on ET covers is valuable for leachate management of landfills. Since the 90s, plants have been introduced on landfill covers for the main goal of reduction in leachate generation as well as leachate treatment (Licht et al., 2001; Granley & Truong, 2012; Erdogan & Zaimoglu, 2015).

Vetiver grass has been identified as a plant which can uptake nutrients and heavy metals, and it has been successfully used in Australia, Thailand, and China for MSW landfill leachate treatment since the 1990s (Banerjee et al. 2019; Bwire et al. 2011). Vetiver grass is native to southern India. Vetiver grass can develop a robust root system that helps in the uptake of leachate and improves cover's function regarding erosion and slope stability. Vetiver plant's roots can grow up to 3 m in depth and the grass (plant) can grow up to 3 m in height (Truong 2019). In a majority of the previous studies, vetiver grass is referred to as a simple, hygienic and low-cost method for chemical treatment of wastewater. However, vetiver grass has not been used on permitted ET covers to enhance the water balance performance.

OBJECTIVE

The key objective of this study is to evaluate the effect of vetiver plants on the water balance of an ET cover. For achieving the objective, two 11 m long x 11 m wide x 0.9 thick ET cover test sections located in a humid climate were instrumented. The results presented in this paper are focused on the first three years of data collection.

MATERIALS AND METHODS

Two field-scale test sections, each 0.9-m-thick and lightly compacted were constructed at a landfill located in the southcentral U.S. The location receives about 114 cm of average annual precipitation, and the potential evaporation to precipitation ratio (PET/P) is about 1.4 (Khire 2016). This location is classified humid.

Test Sections

Of the two test sections which were constructed, one test section was “bare” of plants (control) and the other test section was planted with vetiver plants. Vetiver plants were spaced about 45 cm. The plants were about 30 cm tall when planted and they grew to 150 cm after one year and to full mature height of 3 m and full mature canopy in about one and half years. The control test section started out bare but had a relatively small number of weeds by the end of the first year and the weeds remained throughout the 3-year monitoring period. The weeds had relatively little foliage compared to the vetiver test section. The soil used for constructing the 90-cm-thick cover was a silty clay (USCS Classification CL) mixed with topsoil. Table 1-1 shows the physical properties of the 90-cm thick storage layer representing the covers. The soil was very lightly compacted using a track dozer to a unit weight of ~15 kN/m^3. Light compaction ensured conditions favorable to promote plant growth. A 0.6 m thick pea gravel drainage layer underlain by a GM liner (lysimeter) was placed below the soil cover to collect and measure percolation. The GM was sloped at 12% towards a sump where percolation was drained once the lysimeter approached its capacity of 17,200 L (17.2 m^3). A 60-cm-tall berm was constructed around the perimeter of each of the test sections to divert surface flow from outside the test section away and to prevent runoff from the test area to be shed. Hence, all potential runoff infiltrated through the test sections. Figure 1-1 illustrates the configuration of the test sections and relative locations of the sensor nests and instrumentation.

Table 1-1: Geotechnical properties of the storage layer

Property	**Storage Layer**
USCS Classification	CL
D_{10} (mm)	0.003
D_{50} (mm)	0.074
D_{60} (mm)	0.15
C_u	50
C_c	2
Liquid Limit (LL)	30
Plasticity Index (PI)	10
G_s	2.53

Hydraulic Conductivity (cm/s) (Lab)	~5×10^{-5} - 1×10^{-4}
Hydraulic Conductivity (cm/s) (Field Data Analysis)	~ 0.5×10^{-4} - 4×10^{-4}

Hydraulic conductivity of the storage layer was estimated by two methods: applying unit gradient method to field data; and by conducting laboratory rigid wall permeameter tests. For the unit gradient method, saturated hydraulic conductivities of the control and vetiver covers were estimated using measured percolation when the test sections were nearly saturated. This method is presented by Mijares et al. (2011). The estimated saturated hydraulic conductivities for the control and vetiver cover using the unit gradient method are 0.5×10^{-4} cm/s and 4×10^{-4} cm/s, respectively. Results of rigid wall permeameter tests (ASTM D5856 – 15) for three dry unit weights showed that the estimated saturated hydraulic conductivity of loosely compacted soil was in the range of 5×10^{-5} cm/s to 1×10^{-4} cm/s (Figure 1-2).

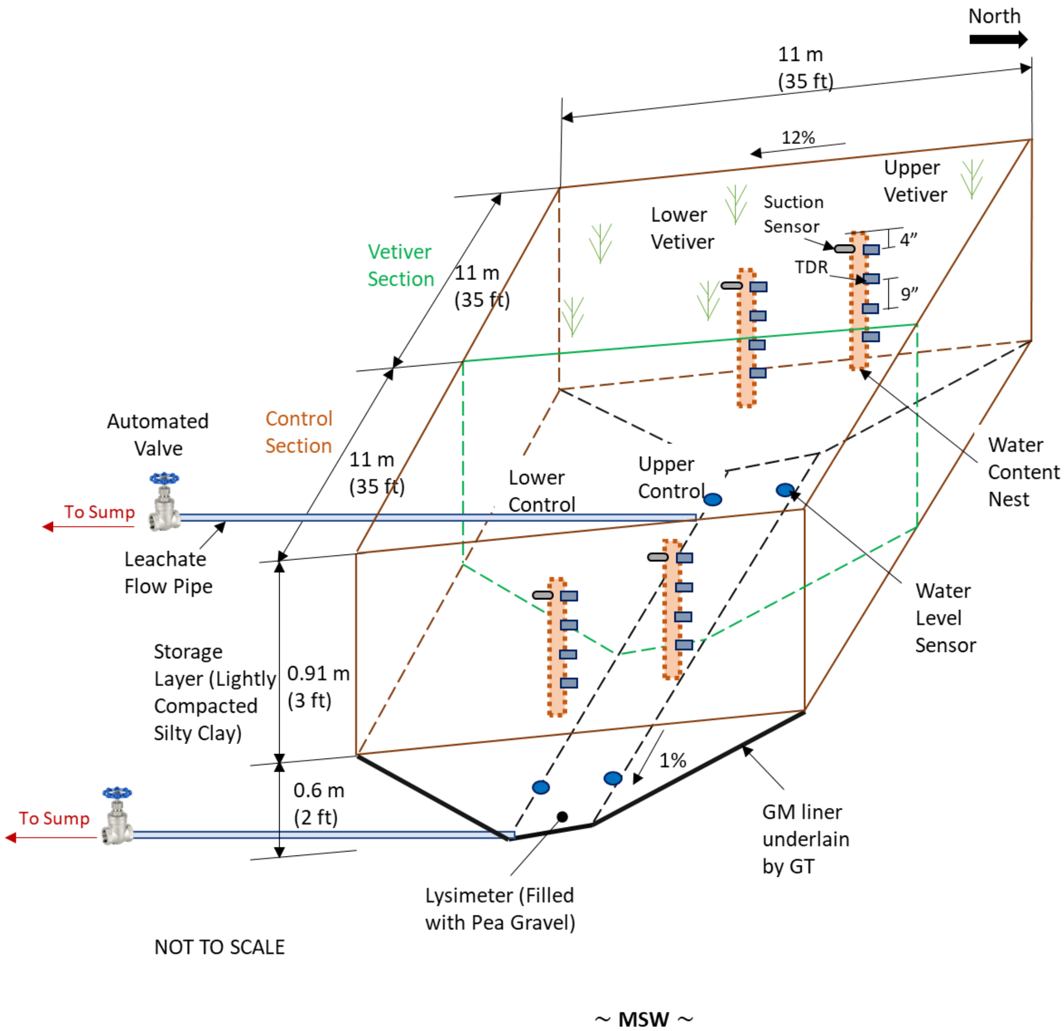

Figure 1-1: Schematic of field test sections: control and vetiver.

These conductivities are relatively high for a final cover. However, in this project, the key goal of this project was to compare the water balance of covers with and without plants and evaluate the effect of plants on overall ET.

Lysimeter

Each lysimeter below the two test sections is constructed using a trapezoidal excavation with the average depth of 0.6 m. Figure 1-1 shows the geometry and dimensions of the lysimeters. Each lysimeter is lined with a geomembrane underlain by a geotextile layer. Thus, the lysimeters' lower boundaries are impermeable in order to collect percolation. The excavation was filled with pea gravel with an average hydraulic conductivity of 1 cm/s and porosity of 0.3. The volume of the lysimeters was designed such that it could store percolation collected during a period of one typical month. Two water level sensors were placed at the bottom of each lysimeter (Fig. 1-1). The datalogger monitors lysimeter water levels continuously and logs data hourly. When the water level reaches a pre-specified threshold, the lysimeter is automatically drained. The drainage occurs via actuator valves that are opened using a relay that is turned on by the datalogger. The drained leachate is directed to a sump. The sump is pumped and emptied each time it is full by the site staff. By having a lysimeter, percolation through the test sections can be measured directly. The water level measured by the level sensor was converted to percolation using lysimeter bathymetry.

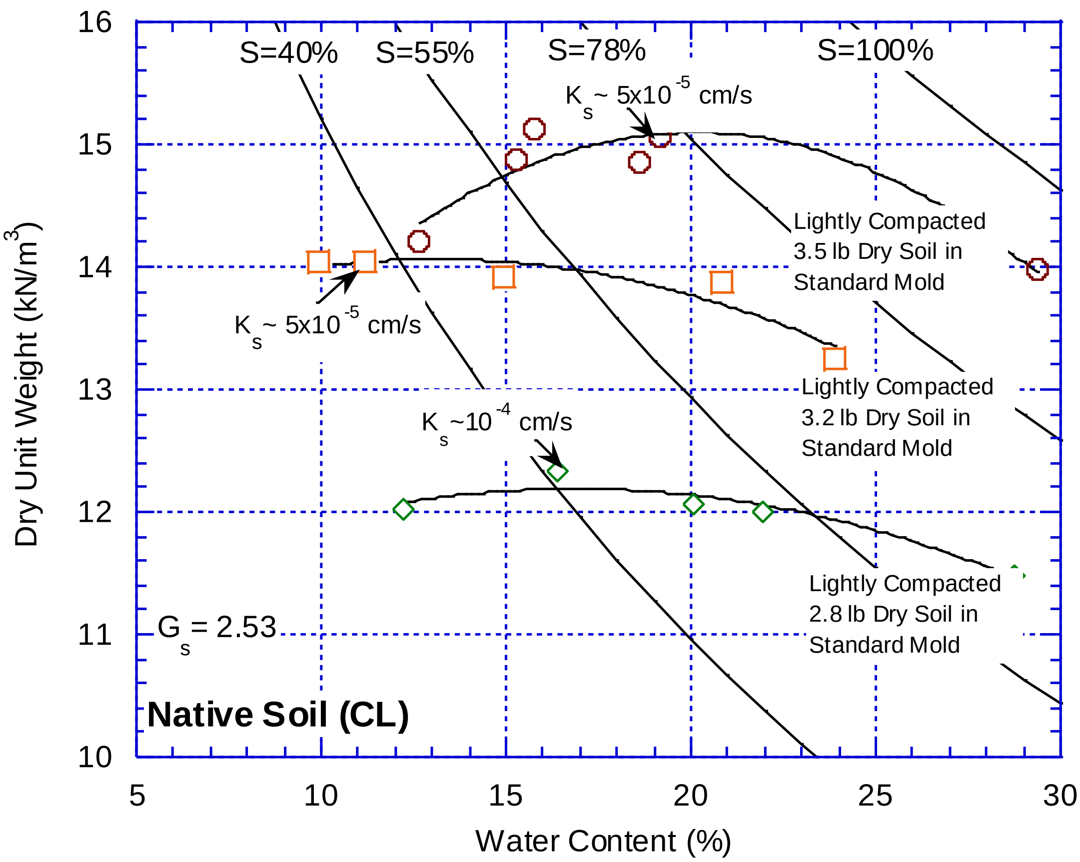

Figure 1-2: Compaction properties and hydraulic conductivities of the cover

Monitoring and Data Collection System

Sensors were installed to continuously monitor the hydraulic performance of the test sections and to record field data. Instrumentation at the site included: water content sensors, matric suction sensors, temperature, and water level sensors. Each of the two test sections has two sensor nests: one upslope and one downslope of the ET cover as shown in Figure 1-1. A weather station was installed to measure hourly precipitation, air temperature, relative humidity, and solar radiation. Figure 1-3 shows the comparison between on-site precipitation and precipitation measured at a National Oceanic and Atmospheric Administration (NOAA) station located about 16 km from the site. All sensors are connected to a measurement and data logging system consisting of Campbell Scientific CR1000 datalogger. The data logger is programmed to take readings hourly. Collected field data are transmitted offsite for data analysis using a wireless data modem. The datalogger was also programmed to drain the lysimeters when they reached a certain volume automatically or in manual mode.

Water Content Sensors

For measuring volumetric water contents, time-domain reflectometer-based (TDR) sensors (Model CS655) manufactured by Campbell Scientific Inc. were used. The CS655 TDR sensor has two stainless steel rods, each rod is 12 cm long and has a diameter of 3.2 mm, and the sensor measures volumetric water content, dielectric permittivity, electrical conductivity and temperature of soils (Campbell Scientific Inc. 2011). The TDR sensor calibration curve was developed in the lab using the time period and soil temperature. Equation 1-2 presents the calibration equation that converts temperature, x (℃) and average time period, y (μs) measured by the TDR sensor to the volumetric water content, θ of the storage layer. Each of the two test sections has two water content sensor nests and each nest contains four water content sensors and one suction sensor. Figure 1-4a shows a typical sensor nest containing the water content sensors installed at 10, 33, 56 and 79-cm depths from the surface.

$$\theta = 1.063\, y^2 - 0.013xy - 2.556y + 0.016x + 1.6 \qquad (1\text{-}2)$$

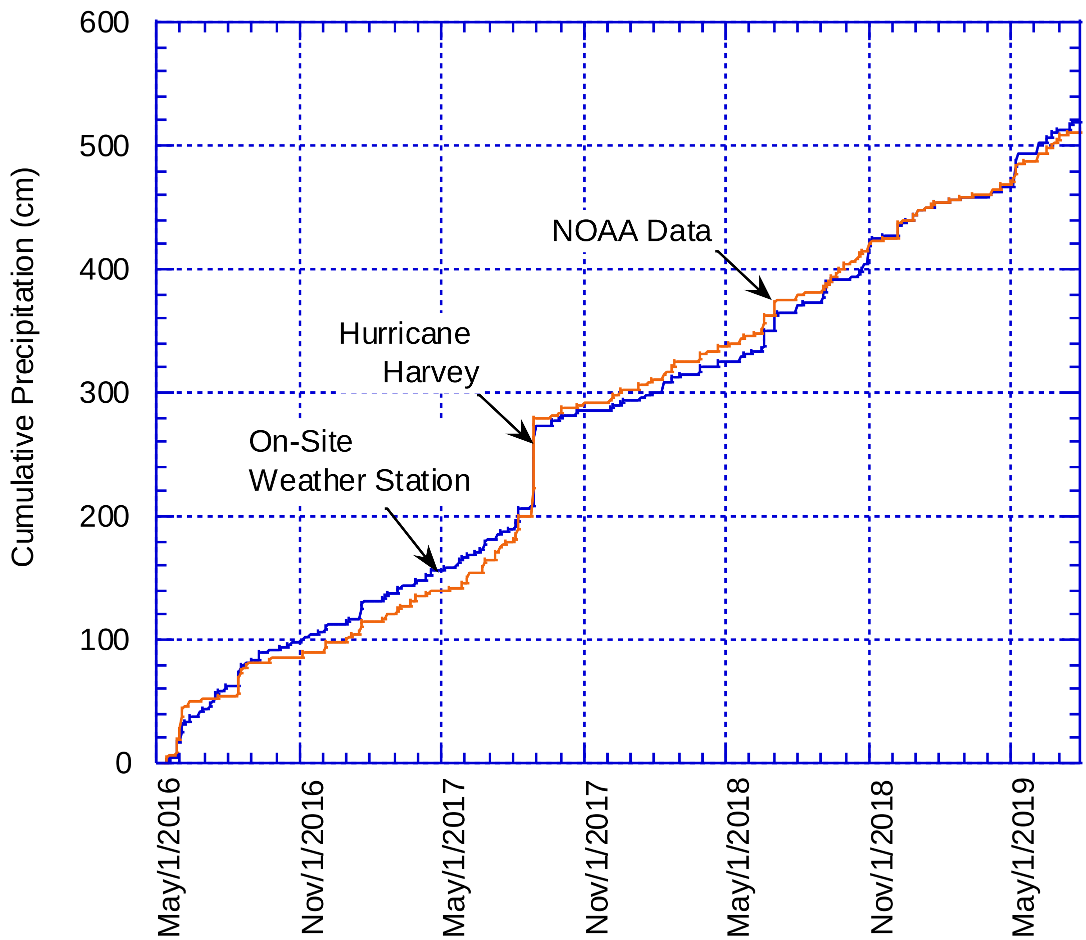

Figure 1-3: On-site and NOAA recorded precipitation

Soil Suction Sensors

Capacitance-based soil suction sensors were installed in each test section to provide data to generate the soil-water characteristic curve (SWCC) for the soil used to construction the test sections. The sensor is manufactured by Decagon Devices Inc. (Model MPS-6). It consists of a porous ceramic disc (diameter of 3.2 cm) attached to the head of the sensor. The MPS-6 sensor measures the dielectric permittivity of the solid matrix (porous ceramic disc) to determine its water potential (Decagon Devices Inc. 2017). Soil water potential measurements using this sensor ranges from -9 kPa to -10,000 kPa (Decagon Devices Inc., 2017). One such sensor was installed in each water content sensor nests at a depth of 10 cm from the surface. Figure 1-4b shows the installation of one of the soil suction sensors alongside with water content sensor. The suctions when paired with water contents provide the field SWCC which is required as an input for water balance modeling (Mijares and Khire 2012).

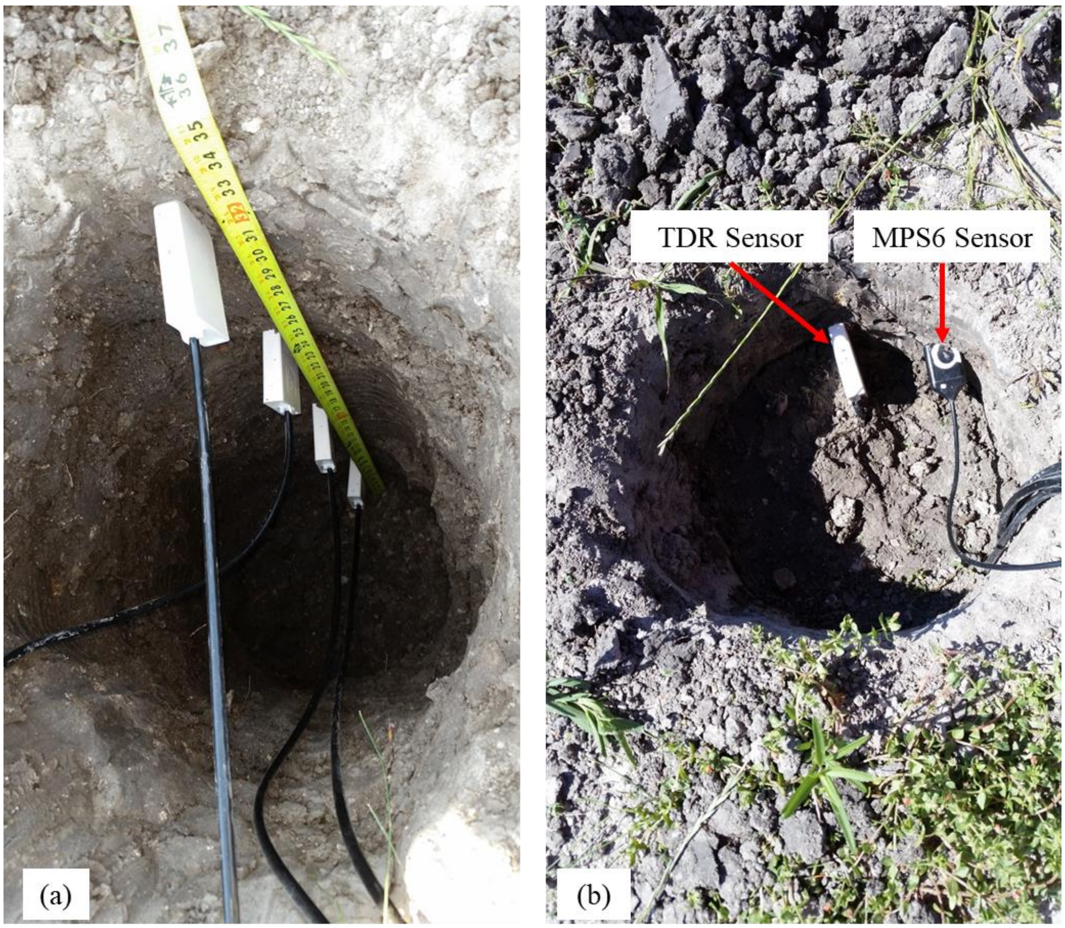

Figure 1-4: (a) Nest of water content sensors installed at 10, 33, 56, and 79-cm depths; and (b) water content and soil suction sensor installed at 10-cm depth.

Water Level Sensors and Percolation Measurement

Percolation collected by the lysimeter was measured using two water level sensors placed at the bottom of the lysimeters (Figure 1-1). The water level sensors are Levelgage manufactured by Keller America Inc. To estimate percolation from the ponded water level in the lysimeters, a calibration curve was developed using water level and areal contours (bathymetry) of the bottom of the lysimeter (Figure 1-5).

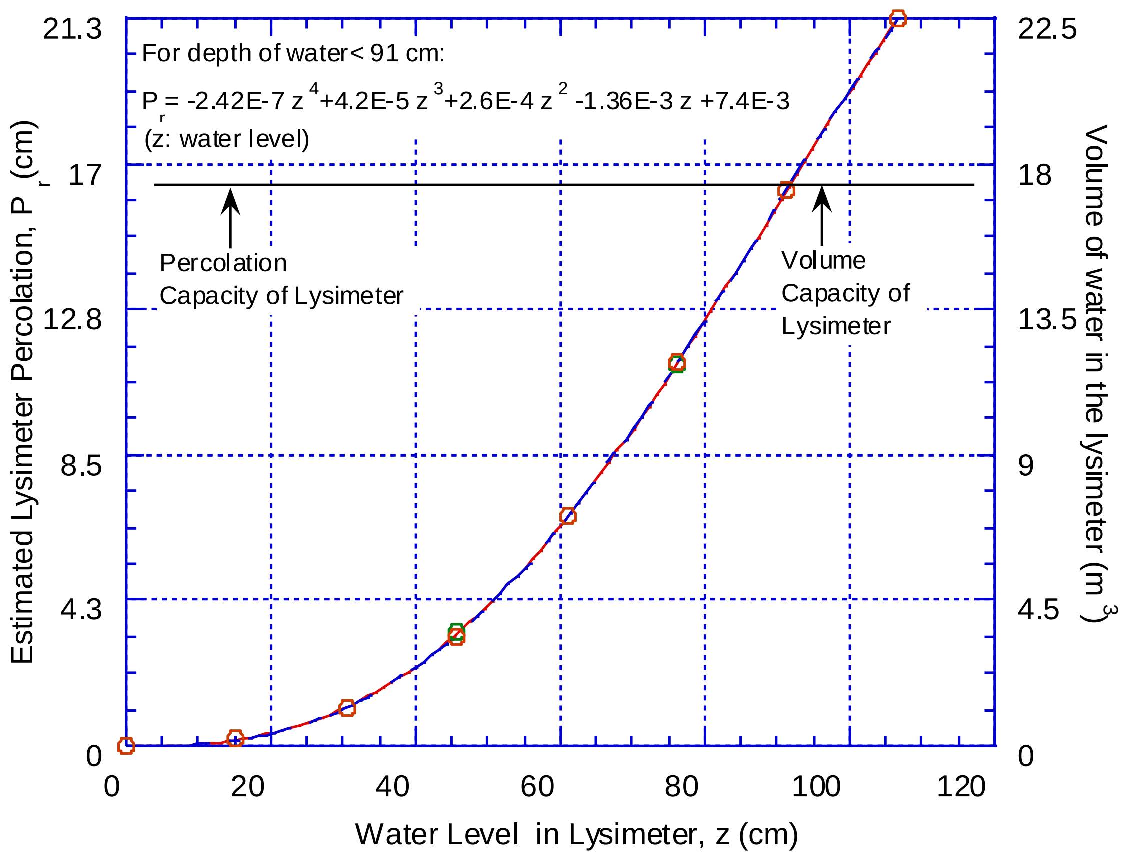

Figure 1-5: Calibration curve for estimating percolation from water level readings.

For developing the calibration curve, the volume of water as a function of water level was calculated. The calibration curve indicates that the lysimeter could measure a maximum percolation of 16.5 cm before it had to be drained. The 16.5 cm percolation corresponds to a volume of water equal to 17,200 L (17.2 m^3). Each lysimeter has a drain that is opened when the lysimeter approaches its capacity with an automated actuator valve controlled by the datalogger. The datalogger program records water levels hourly. The measured water level was input to the equation presented in Figure 1-5 to estimate percolation.

RESULTS AND DISCUSSION

Weather Data

Daily mean and standard deviations of air temperature, relative humidity, solar radiation, and total precipitation and total solar radiation recorded by the on-site weather station are summarized in Table 2-2. In addition, cumulative precipitation and total solar radiation received at the site are also presented.

During the 3-year period from May 2016 to July 2019, 519 cm of precipitation (average 156 cm/year) was recorded which is significantly greater than the 30-year normal precipitation of 127 cm a year. Table 1-2 shows that during the data collection period (May 2016- July 2019) the test sections have received higher precipitation than the 30-mean average. Thus, the three years represent relatively wet years for the location. In Figure 1-6, average daily air temperature as an indicator of seasonal variations is shown and compared to the 30-year mean, high and low temperatures for the site. Figure 1-6 shows that during the growing season for the location (March 1st to November 30th), the air temperature has been slightly higher than the 30-year mean temperature.

Table 1-2: Field climatic data and 30-year average from NOAA.

	Field Daily Means ± Standard Deviations			Field Totals		30-Year Normal	
	Air Temp (°C)	Relative Humidity (%)	Solar Radiation (MJ/m2)	Solar Radiation (MJ/m2)	Total Precipitation (cm)	Annual Precipitation (cm)	Daily Mean Temp (°C)
May 2016-Dec 2016	23.5 ± 5.7	76.5 ± 11.8	12.2 ± 5.2	2,935	113.4		
Jan 2017-Dec 2017	21.1 ± 6.2	73.4 ± 13.8	12.2 ± 5.3	4,452	180.6		
Jan 2018-Dec 2018	20.2 ± 7.6	74.4 ± 13.9	11.6 ± 5.7	4,249	150.2	127	21
Jan 2019-Jul 2019	19.9 ± 7.2	74.3 ± 13.8	11.7 ± 5.7	2473	75.5		

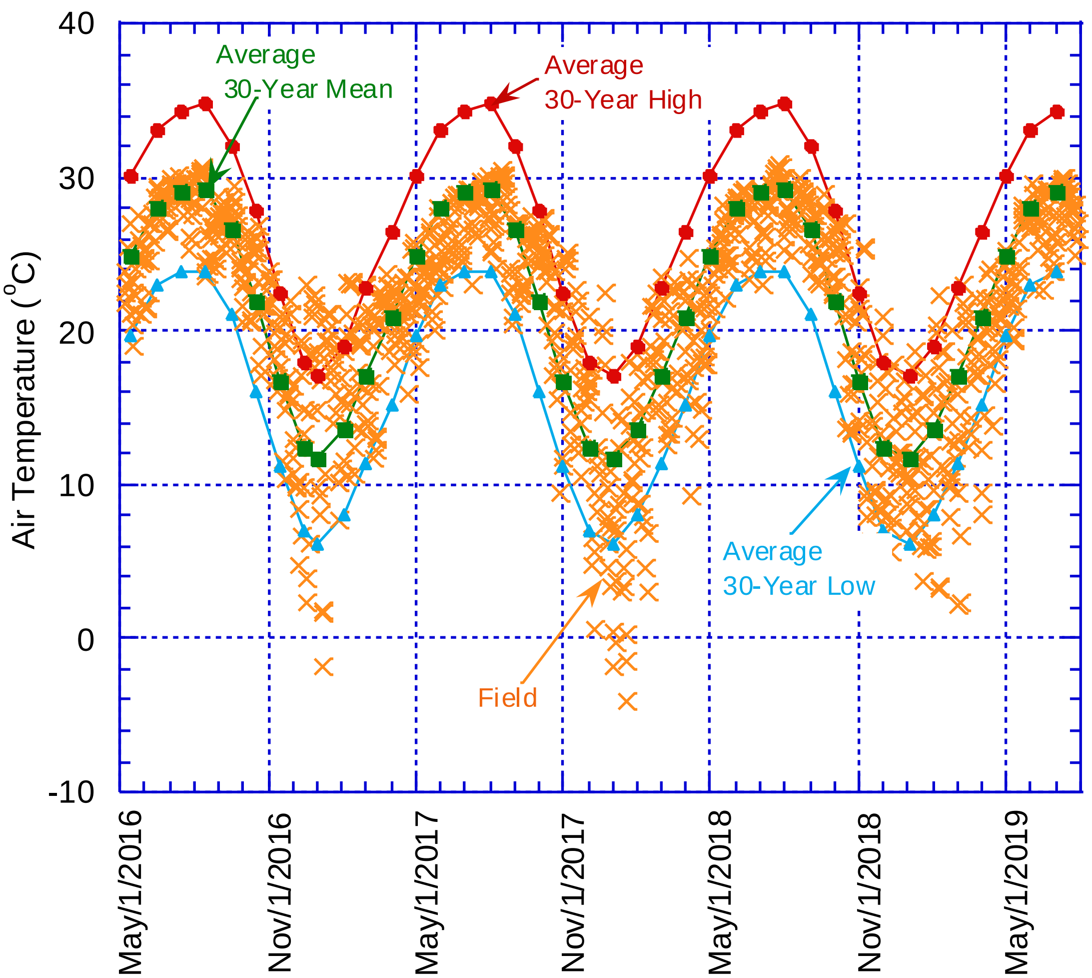

Figure 1-6: Field air temperatures and 30-year normals.

Soil Temperatures

Figure 1-7 shows the temperature measured by the TDR sensors for the control lower nest at various depths and the air temperature. The temperature changes mimic seasonal variations. The temperature trends have the same trend as the air temperature. All other three nests (control upper, vetiver lower and vetiver upper) show similar temperatures as shown in Figure 1-7.

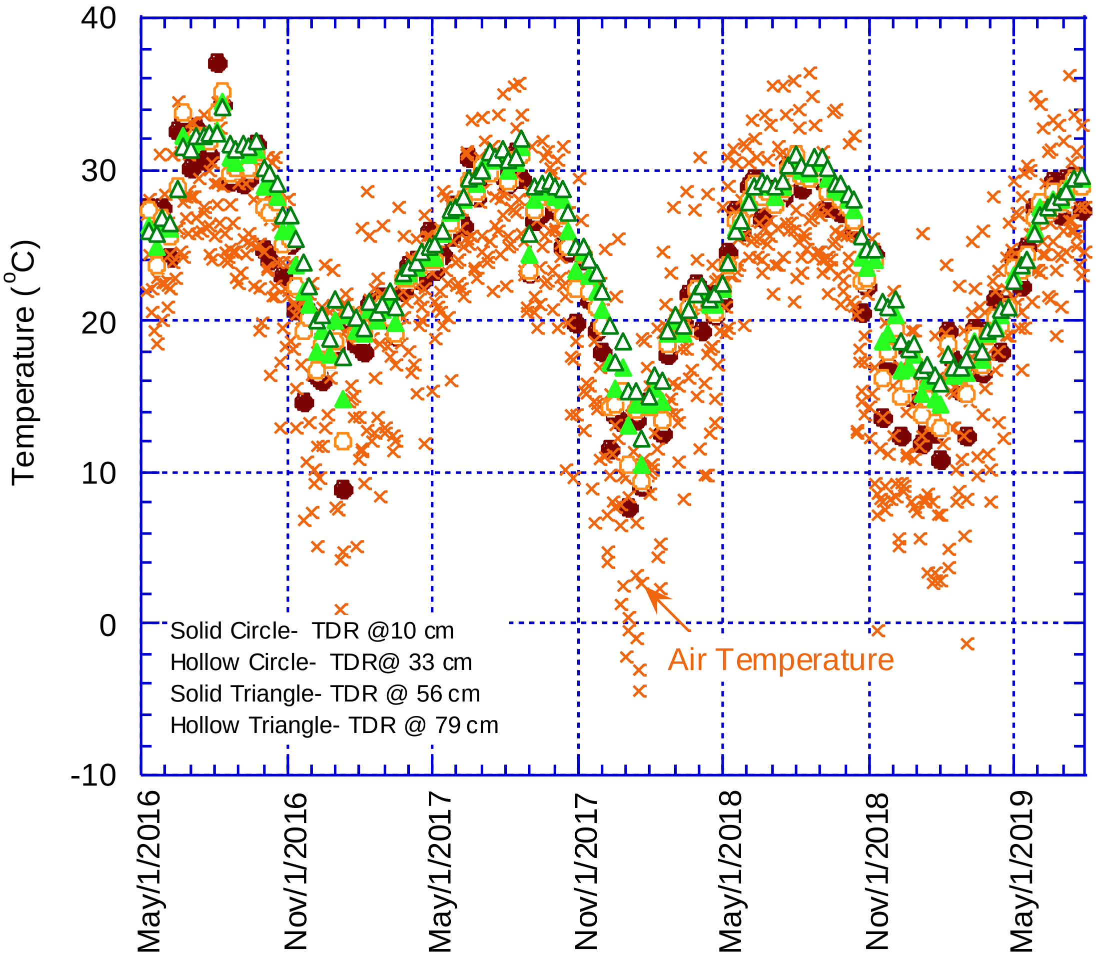

Figure 1-7: Soil temperatures at various depths for the control test section.

Unsaturated Properties

Using the water content and matric suction sensor readings, unsaturated properties were estimated using the van Genuchten equation (1980). van Genuchten equation (1980) is presented in Eq. 1-3.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{1 + (a \cdot \psi)^n} \right\}^m \tag{1-3}$$

where θ_s is the saturated volumetric water content, θ_r is the residual water content, and ψ is suction. α, n and m ($m= 1- n^{-1}$) are fitting parameters. The α relates to the air-entry value of the soil and n and m relate to the slope at the inflection point of SWCC. Figure 1-8 demonstrates the fitting parameters of Equation 1-3 using the field data.

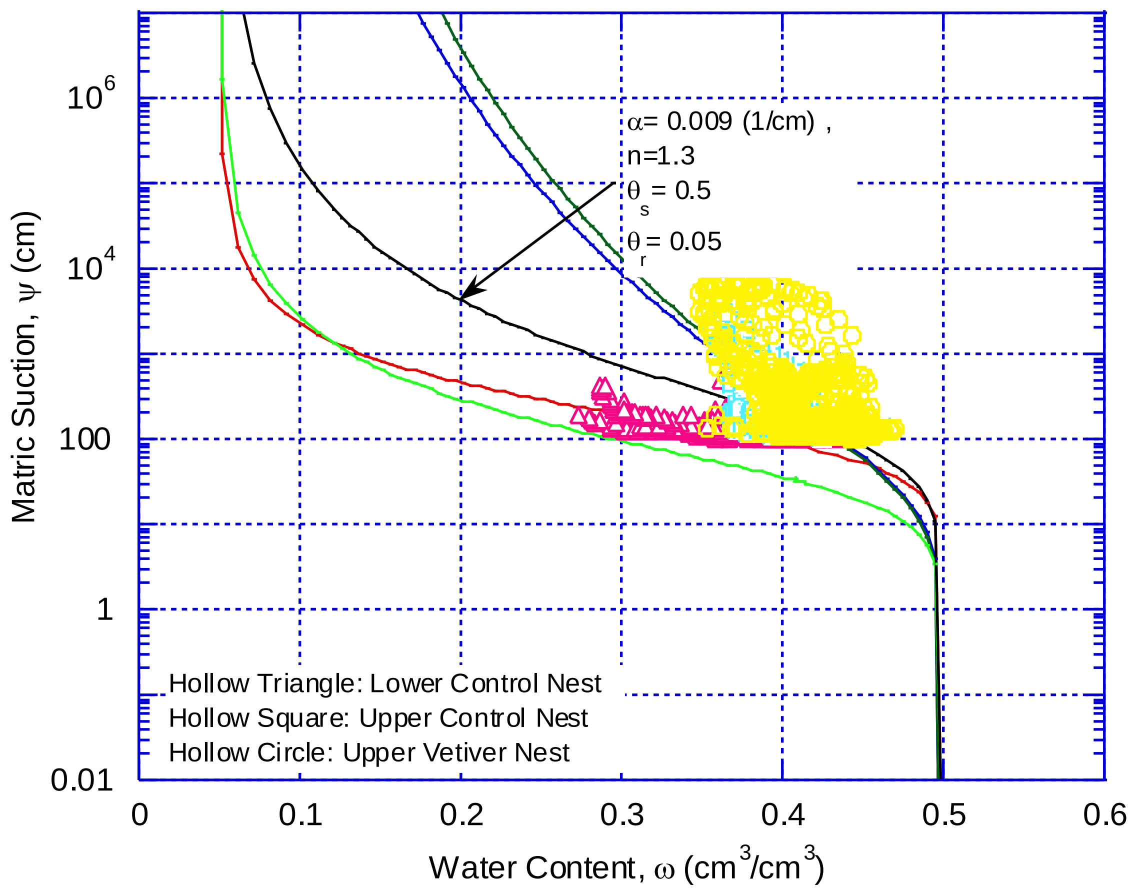

Figure 1-8: SWCC of the storage layer.

Hydraulic conductivity of the storage layer was estimated by two methods; applying unit gradient method on field data, and by conducting rigid wall permeameter tests. Using unit gradient method saturated hydraulic conductivities of the control and vetiver covers were estimated using the percolation measurements when the cover was saturated (Mijares et al. 2011). The estimated saturated hydraulic conductivities for the control and vetiver covers are 0.5×10^{-4} cm/s and 4×10^{-4} cm/s, respectively. Results of rigid wall permeameter test (per ASTM D5856 – 15) on three different dry unit weights showed that the estimated saturated hydraulic conductivity of loosely compacted soil was in the range of 5×10^{-5} cm/s to 1×10^{-4} cm/s (Figure1-2). These conductivities are relatively high for a final cover. However, in this project, the key goal was to evaluate the water balance parameters of the test sections. The fitting parameters of the soil-water characteristic curve (SWCC) of the test sections were estimated using the field data (using co-located readings of water content and matric suction sensors measured in the field). Hydraulic properties of each test section are presented in Table 1-3.

Table 1-3: Hydraulic properties of the storage layer.

Section	**Material**	**θ_s (cm^3/cm^3)**	**θ_r (cm^3/cm^3)**	**α (1/cm)**	**n**	**K_{sat} (Using IPM) (cm/s)**
Control	Loose silty clay	0.5	0.05	0.009	1.3	0.5×10^{-4}
Vetiver	Loose silty clay	0.5	0.05	0.009	1.3	1.4×10^{-4}

ET

Estimation of ET for each test section is divided into two phases: (1) by incorporating measured precipitation, percolation, and changes in soil water storage into the water balance equation (Equation 1-1) for the period May 2016 to May 2017 (Phase 1); and (2) estimating water loss from lysimeter and storage layer while lysimeters of both test sections were allowed to fill up by closing the actuator valves for the period from October 2017 to July 2019 (Phase 2).

Phase 1: Using Direct Percolation Measurements: Using the lysimeter characteristics and the water level sensor readings, percolation for each test section was estimated during Phase 1. Figs. 1-9 and 1-10 show the cumulative precipitation, percolation, evapotranspiration (ET) and soil water storage (SWS) for control and vetiver test sections, respectively.

Over the first-year monitoring period, the vetiver plants grew from 30 cm to about 150 cm. When matured or fully grown, the height is approximately 3 m. Figure 1-11 shows the cumulative precipitation and soil water storages (SWS) for the control and vetiver test sections. SWS was estimated by integrating water contents measured by four TDR sensors in each nest over the entire depth of the cover. The thickness of the storage layer for both test sections is about 90-cm. The porosity (θ_s) of the storage layer is around 0.5. Hence, Figure 1-11 shows that both test sections have approached 95% degree of saturation on occasions during wet periods (July-Aug. and Sept.). For a majority of the monitoring period, the test sections were at a degree of saturation of about 70% to 80%.

Total precipitation during the one-year period (Phase 1) was approximately 157 cm. The SWS changes were almost the same for both (control and vetiver) upper and lower nests. During October, both upper nests show a major drop due to a relatively small amount of precipitation and relatively high ET. Usually, the infiltration is greater at the bottom of the slope due to the re-infiltration of runoff shed by the upper or upgradient portion of the slope (Mijares and Khire 2012). Hence, soil water storages for the top nests are lower than those for the bottom nests. Nevertheless, the changes in the SWS for both test sections over the 1-year period were about the same. Both test sections had almost the same percolation. ET was estimated by subtracting the change in soil water storage and total percolation from total precipitation received during the 1-year period as per Equation 1-1.

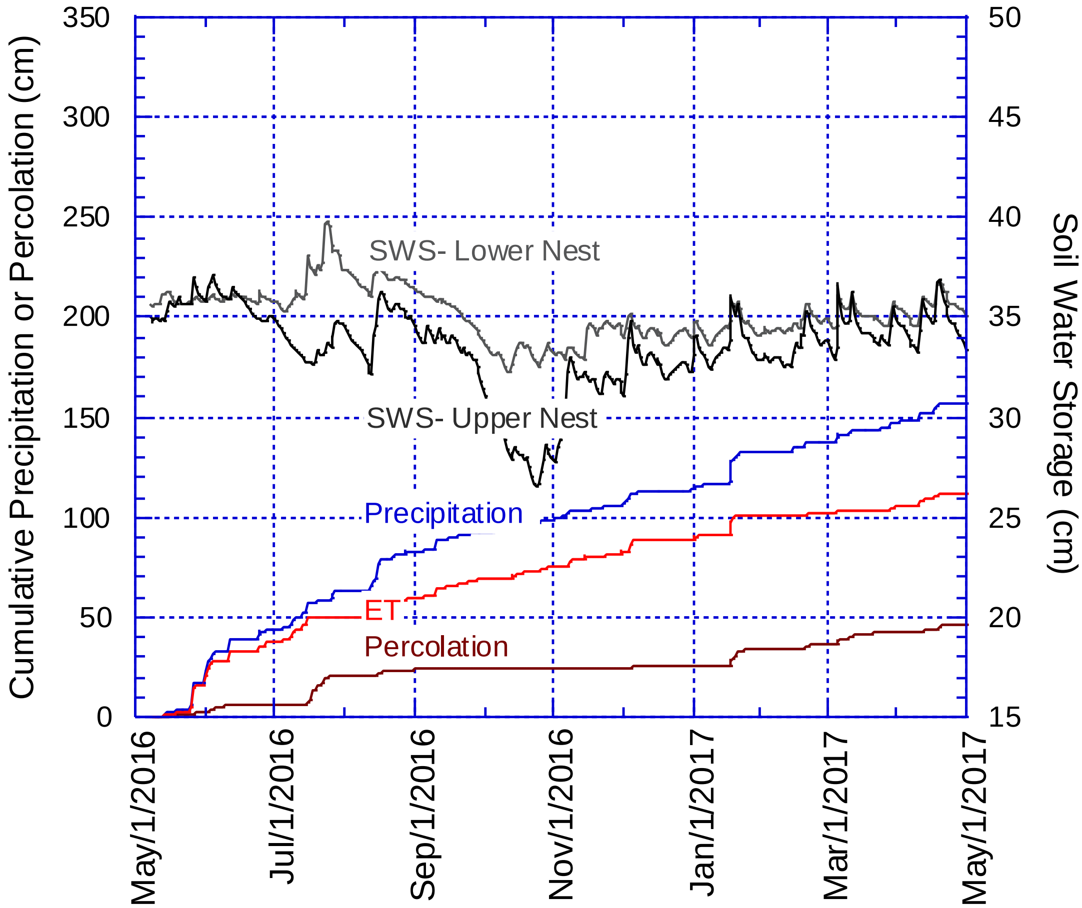

Figure 1-9: Measured water balance for control or “bare” test section (Phase 1).

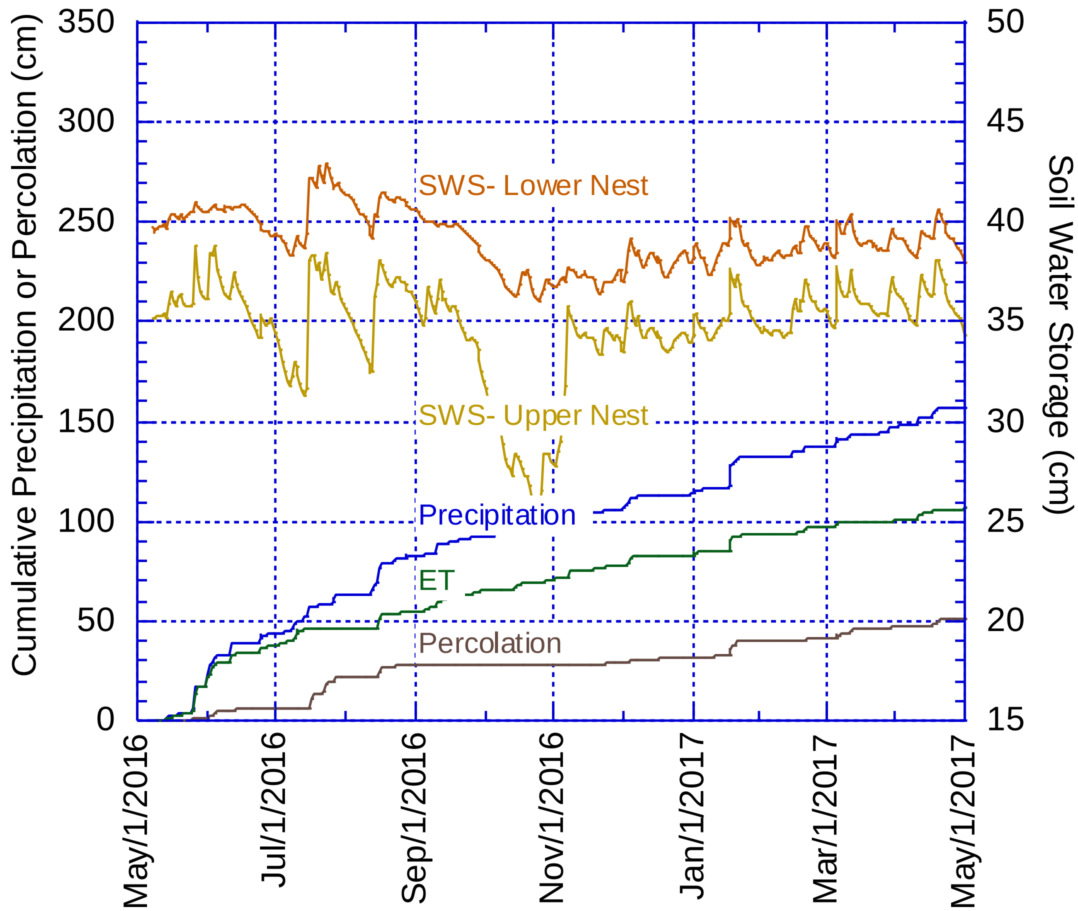

Figure 1-10: Measured water balance for vetiver test section (Phase 1).

Estimated percolation for two test sections over the 1-year data monitoring period is shown in Figure 1-12. Vetiver section percolation is higher by 2% of the total precipitation than the control section percolation for the same time period.

Figure 1-13 shows the estimated ET for control and vetiver test sections. Figure 1-13 indicates there is very little difference between the ET for control vs. vetiver. Thus, during the first year of the project, the combined evaporation and transpiration from the plants is about the same as the evaporation from the control test section. Thus, effect of vegetation on ET and the overall water balance during the first year was negligible.

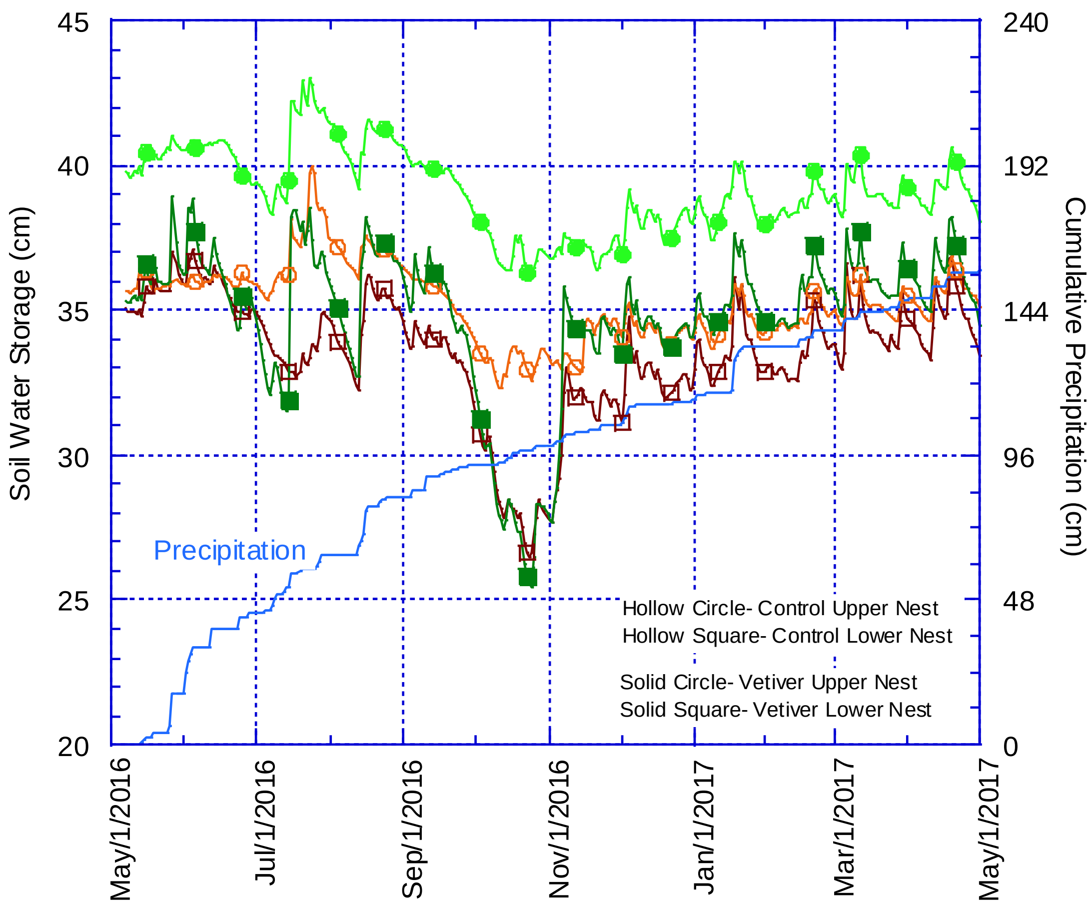

Figure 1-11: Soil water storages for control and vetiver test sections (Phase 1).

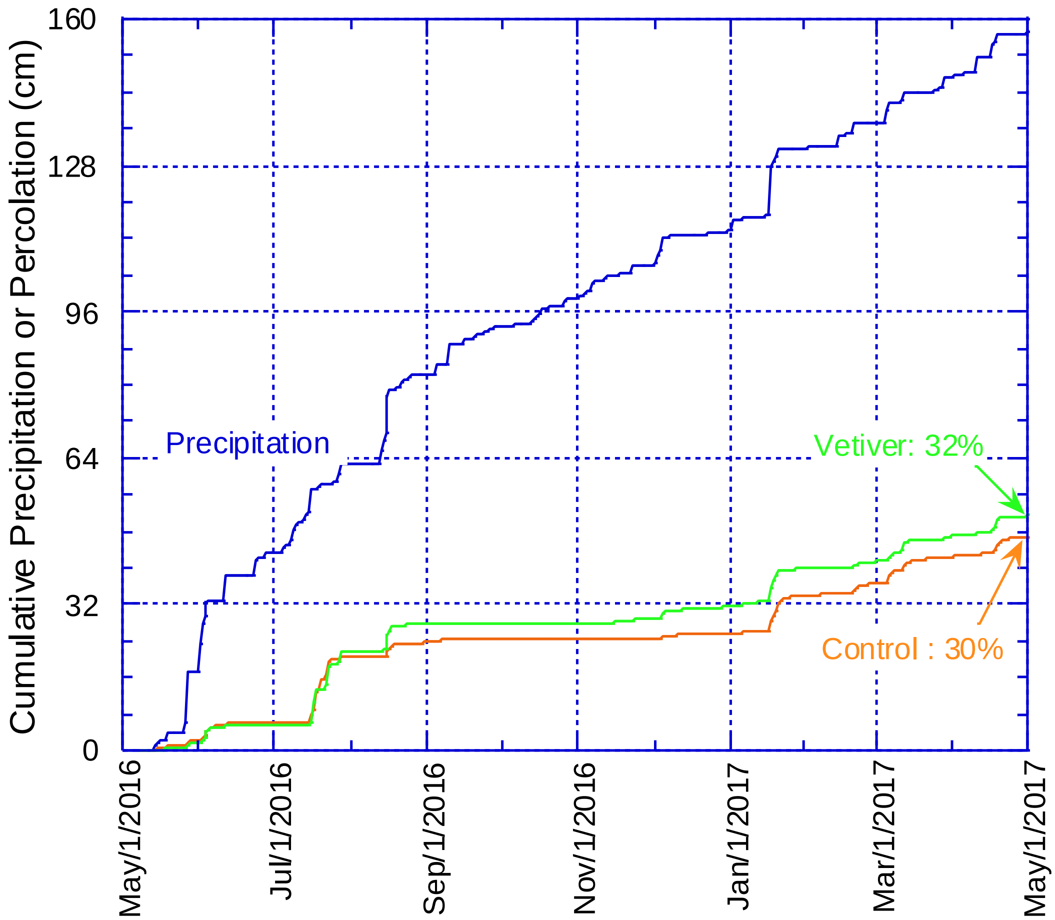

Figure 1-12: Measured percolation for vetiver and control test sections.

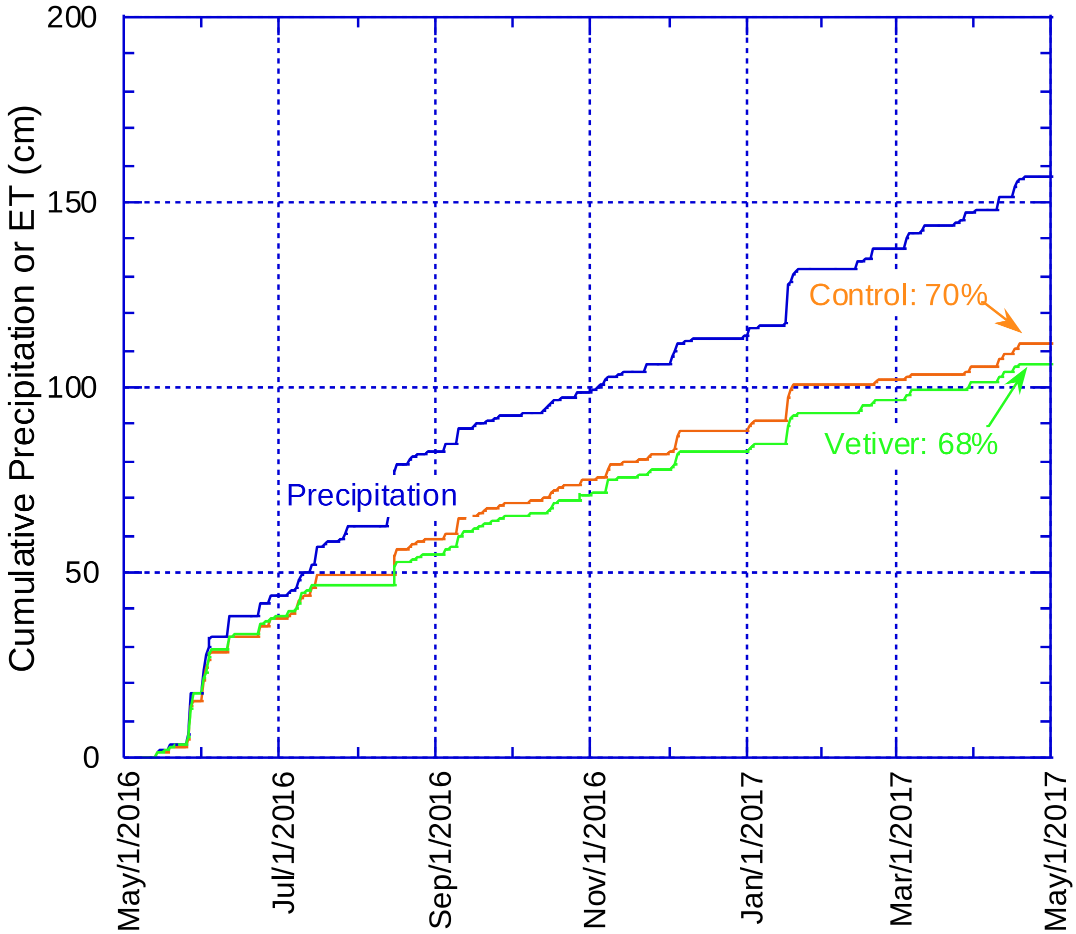

Figure 1-13: Estimated ET for control and vetiver test sections (Phase 1).

Table 1-4 shows the monthly averages of estimated ET and estimated percolation for the 1-year period from May 2016 to April 2017. The 12-month average of ET rates for control and vetiver test sections are 0.31 cm/day and 0.30 cm/day, respectively. Monthly ET rates of both test sections are illustrated in Figure 1-14 for the period May 2016 to August 2017. The figure shows that ET rates of vetiver section increases by the beginning of the new growing season starting in February 2017. ET rates of the vetiver section was higher than bare section by around 31% in February 2017 and around 13% to 8% from March 2017 until August 2017.

Table 1-4: Control and vetiver test section monthly ET rates for the period May 2016 to August 2017.

Month	**Estimated ET (cm/day)**	
	Control	Vetiver
May-16	0.57	0.58
Jun-16	0.76	0.79
Jul-16	0.14	0.05
Aug-16	0.54	0.45
Sep-16	0.42	0.44
Oct-16	0.27	0.29
Nov-16	0.16	0.12
Dec-16	0.21	0.16
Jan-17	0.29	0.30
Feb-17	0.07	0.10
Mar-17	0.11	0.13
Apr-17	0.19	0.21
12-Month Average (cm/day)	**0.31**	**0.30**
16-Month Average (cm/day)	**0.31**	**0.31**

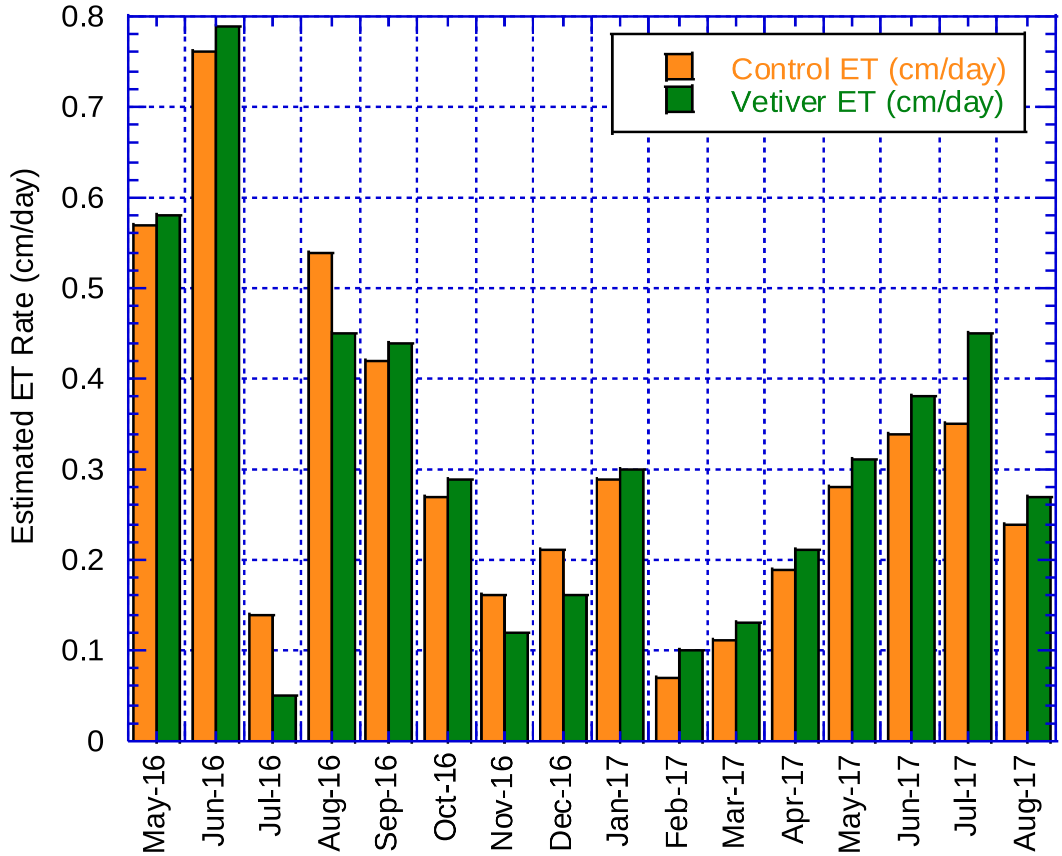

Figure 1-14: Control and vetiver test sections' monthly ET rates from May 2016 to August 2017.

Phase 2: Water Removal from the Storage Layer and the Lysimeter:

During the period from October 2017 to July 2019, the lysimeter valves of both test sections were closed. Hence, lysimeters filled up beyond their design capacity and level sensor readings could not be used to accurately measure percolation. During this phase, whenever there was a period when there was no precipitation, any water level drop in the lysimeter is assumed to be due to water removal by evaporation and/or water uptake by the plants. In addition, using the measured water contents, soil water storage of each nest was estimated, and any decrease in the SWS of the storage layer was assumed to be due to ET.

To estimate water removal, change (decrease) in lysimeter water level and soil water storage were analyzed for specific “water removal” events. These events were selected such that: (1) both SWS and water levels of the lysimeter were declining over the duration of the event for both vetiver and control sections; and (2) there was no precipitation during the time period to ensure that water removal is solely due to ET. Figure 1-15 illustrates how water removal was estimated for the control test section. The subscripts B and E in the schematic represent the beginning and ending value, respectively for the time period. ET_c represents estimated evaporation for the control test section for the time period corresponding to the selected event. CB 10, CB 33, CB56 and CB 79 are water content sensors located in the test section at 10 cm, 33 cm, 56 cm, and 79 cm depths, respectively.

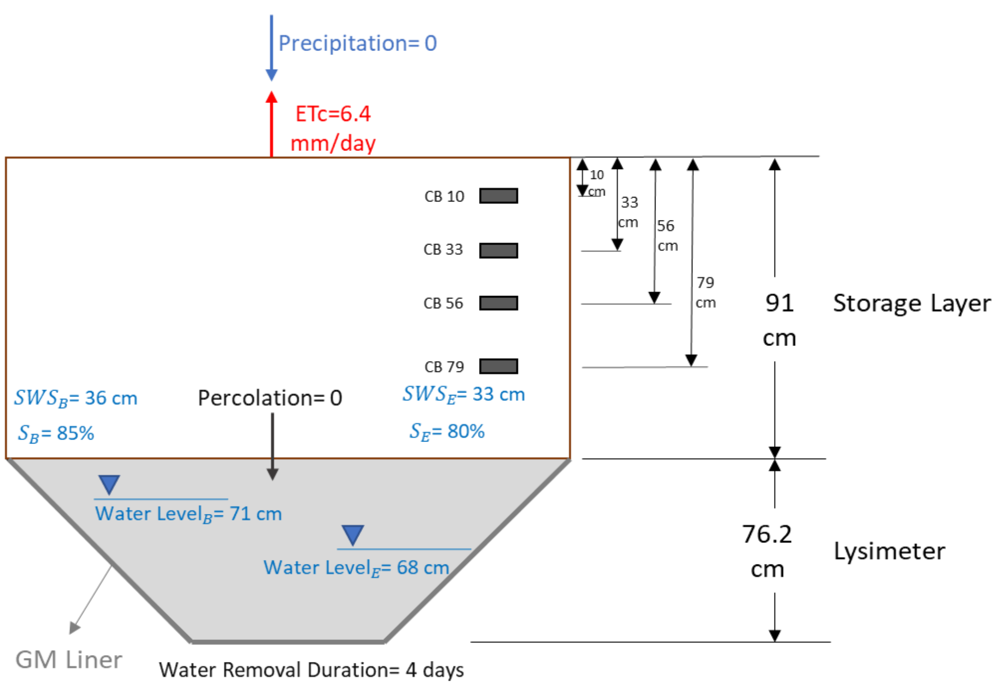

Figure 1-15: Water removal schematic.

During Phase 2, 22 “water removal” events were identified and analyzed for both control and vetiver test sections. The estimated water removal is assumed to be the ET from the test section for the event.

Figure 1-16 illustrates the ET rates estimated from the data analyzed during Phase 2 by using SWS of lower nest and upper nest for each test section. The ET removal rates also included decrease in lysimeter level during the time period specified for the event. The figure shows that there is a slight difference between estimated ET of control and vetiver test sections. During the growing season (March 1st to November 30th) ET from bare is slightly higher than ET for vetiver.

The average estimated ET using SWS measured by the lower sensor nest for bare and vetiver test sections is 3.4 mm/day and 2.9 mm/day, respectively. The average estimated ET using SWS measured by the upper sensor nest is 2.6 mm/day and 1.7 mm/day for bare and vetiver test sections, respectively. At the beginning of Phase 2, vetiver plants were fully mature to their normal height and canopy coverage. Moreover, the vetiver canopy had gotten relatively large such that greater than 90% of the surface was covered with the vetiver plant foliage. Phase 2 also represents a period when the site received much higher precipitation than the normal which may have helped in the rapid growth of vetiver plants.

Figure 1-17 illustrates the measured soil water storage for all four sensor nests. SWS for all four nests during this time period followed a similar pattern and there has been no significant change in SWS over the data monitoring period. This shows that water storage and removal pattern was not visually altered by vetiver plants. This shows, when fully matured, vetiver plants did not draw more water from the storage compared to control.

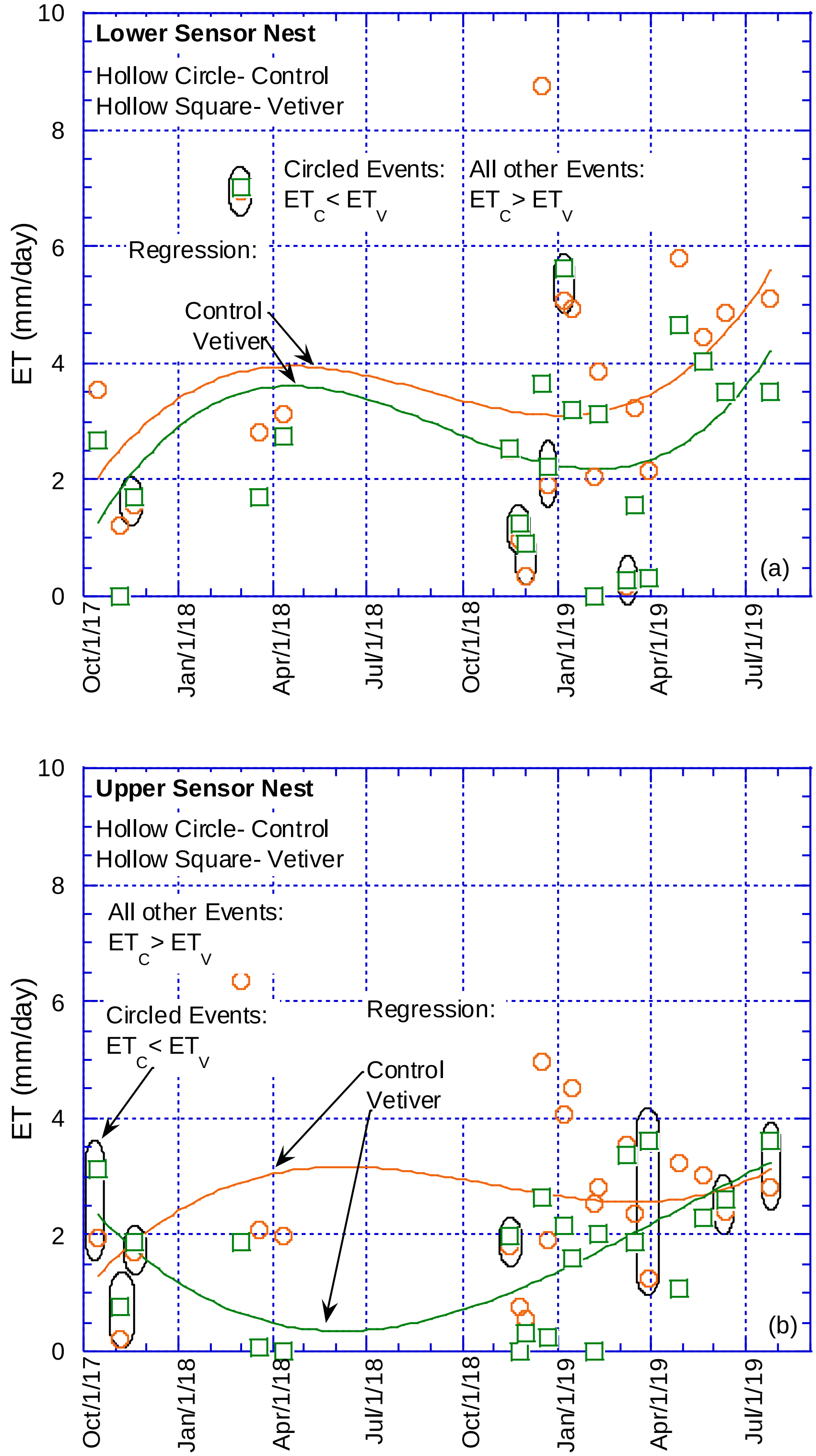

Figure 1-16: Estimated ET for control and vetiver test sections during Phase 2 using SWS of (a) lower sensor nest; and (b) upper sensor nest.

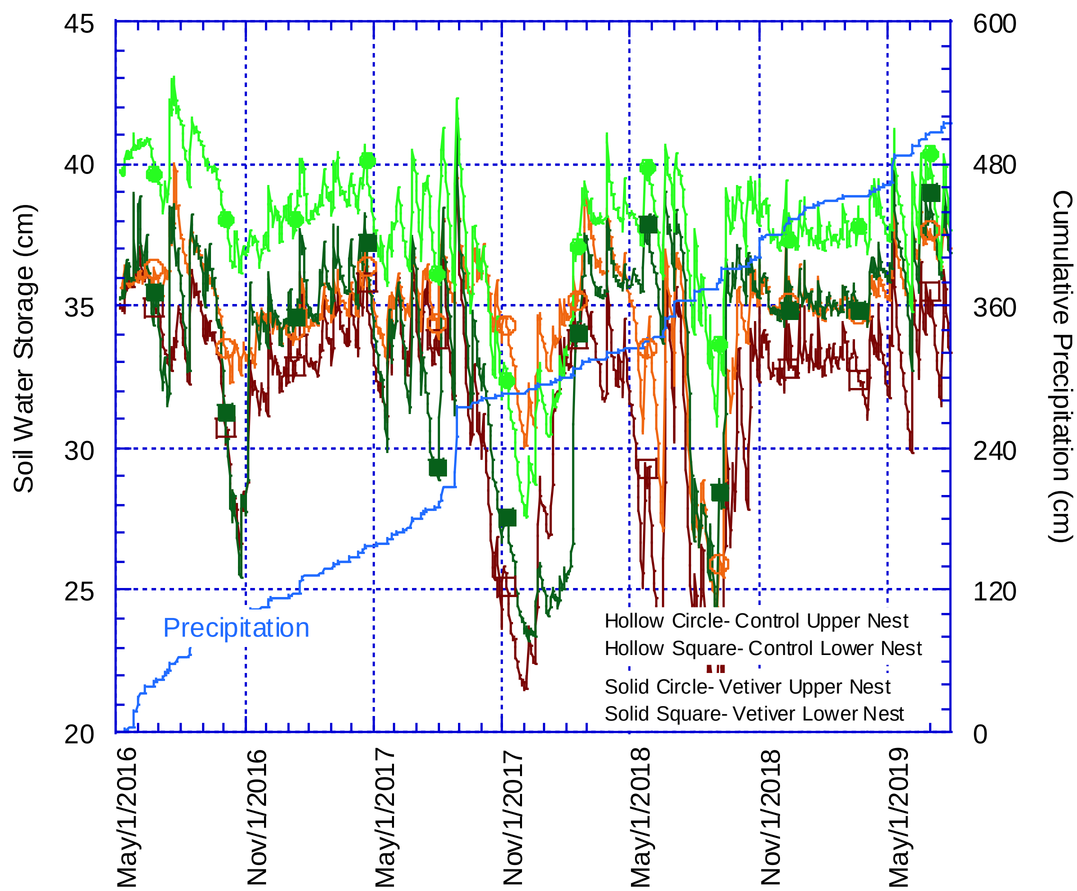

Figure 1-17: SWS of control and vetiver test sections.

SUMMARY AND CONCLUSIONS

This paper presents a field-scale study to evaluate the effect of vetiver plants on the overall water balance of a 90-cm-thick earthen cover test section. Two field-scale test sections of a soil cover are built and instrumented. One of the test sections is planted with vetiver and the other test section is control that is almost bare. Climatic and water balance data has been collected from these test sections in two phases: during Phase 1 all water balance parameters were measured, and during Phase 2 the lysimeters were allowed to fill up, and water removal was estimated using the changes in soil water storage and lysimeter water levels for specific time periods when there was no precipitation.

During both phases, the estimated ET for both test sections is about the same. ET from vetiver is slightly less than from control for a majority of the time period over the three-year duration of the project. It shows that plants did not enhance ET and decrease percolation compared to the control test section. The plants reached fully matured height and canopy coverage within the first one and half years of the monitoring period which was relatively wet period for the site. The data indicate that vetiver plants did not enhance ET from soil cover in the humid climatic location. A possible reason why vetiver did not enhance ET may be due to the relatively big canopy. The canopy reduces solar radiation landing on the surface and that cuts down the rate of evaporation. The transpiration from the plants may be about the same or little less than possible evaporation if the surface was fully exposed.

Hence, a suggested future study may include the effect of plants with a thinner canopy to allow evaporation to continue to occur at the maximum possible rate while plants can remove water from the cover via transpiration. While this study shows vetiver, plants did not enhance ET or water removal from the cover, using plants on landfill covers offers other significant benefits such as improved slope stability, aesthetics, carbon sequestration, and wildlife habitat.

REFERENCES

40 CFR 258.60. (2009). “Title 40: Protection of Environment-PART 258—Criteria For Municipal Solid Waste Landfills.” <https://www.ecfr.gov/cgi-bin/text-idx?SID=558a9db9fee0e89333a2588d0fba87c4&mc=true&node=sp40.27.258.d&rgn=div6> (Oct. 7, 2018).

Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P., Lyles, B. F., and Rock, S. A. (2004). “Field Water Balance of Landfill Final Covers.” *Journal of Environment Quality*, 33(6), 2317.

Apiwantragoon, P., Benson, C. H., and Albright, W. H. (2015). “Field hydrology of water balance covers for waste containment.” *Journal of Geotechnical and Geoenvironmental Engineering*, 141(2).

Banerjee, R., Goswami, P., Lavania, S., Mukherjee, A., and Lavania, U. C. (2019). “Vetiver grass is a potential candidate for phytoremediation of iron ore mine spoil dumps.” *Ecological Engineering*, Elsevier, 132(January), 120–136.

Banerjee, R., Goswami, P., Pathak, K., and Mukherjee, A. (2016). “Vetiver grass: An environment clean-up tool for heavy metal contaminated iron ore mine-soil.” *Ecological Engineering*, Elsevier B.V., 90, 25–34.

Benson, C. H., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. H. (2007). “Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils.” *Journal of Geotechnical and Geoenvironmental Engineering*, 133(4), 349–359.

Bréda, N. J. J. (2003). “Ground-based measurements of leaf area index: A review of methods, instruments and current controversies.” *Journal of Experimental Botany*, 54(392), 2403–2417.

Bwire, K. M., Njau, K. N., and Minja, R. J. A. (2011). “Use of vetiver grass constructed wetland for treatment of leachate.” *Water science and technology : a journal of the International Association on Water Pollution Research*, 63(5), 924–30.

Campbell Scientific Inc. (2011). *Instruction Manual, CS650 and CS655 Water Content Reflectometers,*. Logan , Utah.

Day, W. (1977). “A direct reading continuous flow porometer.” *Agricultural Meteorology*, 18, 81–89.

Decagon Devices Inc. (2017). *Dielectric Water Potential Sensors*.

Duncan, J. P., Burk, K. W., Chamness, M. A., Fowler, R. A., Fritz, B. G., Hendrickson, P. L., Kennedy, E. P., Last, G. V, Poston, T. M., Sackschewsky, M. R., Scott, M. J., Snyder, S. F., Sweeney, M. D., and Thorne, P. D. (2007). *Hanford Site National Environmental Policy Act (NEPA) Characterization*.

Erdogan, R., and Zaimoglu, Z. (2015). “The Characteristics of Phytoremediation of Soil and Leachate Polluted by Landfills.” *Advances in Bioremediation of Wastewater and Polluted Soil*, InTech.

Fayer, M. J. (2000). *UNSAT-H Version 3.0: Unsaturated Soil Water and Heat Flow Model. Theory , User Manual , and Examples*. *Model Manual*.

Granley, B. A., and Truong, P. N. (2012). "A Changing Industry: On-site Phytoremediation of Landfill Leachate Using Trees and Grasses-Case Studies." Global Waste Management Symposium, 5.

Hauser, V. L., Weand, B. L., and Gill, M. D. (2001). "Natural Covers for Landfills and Buried Waste." *Journal of Environmental Engineering*, American Society of Civil Engineers, 127(9), 768–775.

Hui, D., Yu, C.-L., Deng, Q., Dzantor, E. K., Zhou, S., Dennis, S., Sauve, R., Johnson, T. L., Fay, P. A., Shen, W., and Luo, Y. (2018). "Effects of precipitation changes on switchgrass photosynthesis, growth, and biomass: A mesocosm experiment." *PloS one*, Public Library of Science, 13(2), e0192555.

Khire, M. V. (2016). "Geoclimatic Design of Water Balance Covers for Municipal Solid Waste Landfills in Texas." *UNCC-CEE-14-100, Lone Star Chapter of the Solid Waste Association of North America, Aug*, 334.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (1997). "Water Balance Modeling of Final Earthen Covers." *Journal of Geotechnical and Geoenvironmental Engineering*, 123(8), 744–754.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (2000). "Capillary Barriers: Design Variables and Water Balance." *Journal of Geotechnical and Geoenvironmental Engineering*, 126(8), 695–708.

Kiniry, J. R., Burson, B. L., Evers, G. W., Williams, J. R., Sanchez, H., Wade, C., Featherston, J. W., and Greenwade, J. (2007). "Coastal bermudagrass, bahiagrass, and native range simulation at diverse sites in Texas." *Agronomy Journal*, 99(2), 450–461.

Leuning, R., and Foster, I. (1990). "Estimation of transpiration by single trees: comparison of a ventilated chamber, leaf energy budgets and a combination equation." *Agricultural and Forest Meteorology*, 51(1), 63–86.

Licht, B. L., Aitchison, E., Schnabel, W., English, M., and Kaempf, M. (2001). "Landfill Caping with Woodland Ecosystems." *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 5(October), 175–184.

Meerdink, J., Benson, C., and Khire, M. (1996). "Unsaturated Hydraulic Conductivity of Two Compacted Barrier Soils." *Journal of Geotechnical Engineering*, (J. Meerdink, ed.), 122(7), 565–576.

Mijares, R. G., and Khire, M. V. (2012). "Field Data and Numerical Modeling of Water Balance of Lysimeter versus Actual Earthen Cap." *Journal of Geotechnical and Geoenvironmental Engineering*, 138(8), 889–897.

Mijares, R. G., Khire, M. V, and Johnson, T. (2011). "Field-Scale Evaluation of Lysimeters Versus Actual Earthen Covers." *Geotechnical Testing Journal*, 35(1).

Nadezhdina, N., Al-Okaishi, A., and Madera, P. (2018). "Sap Flow Measurements in a

Socotra Dragon’s Blood Tree (Dracaena cinnabari) in its Area of Origin.”

Renner, M., Hassler, S. K., Blume, T., Weiler, M., Hildebrandt, A., and Guderle, M. (2016). “Dominant controls of transpiration along a hillslope transect inferred from ecohydrological measurements and thermodynamic limits.” 2063–2083.

Rock, S. A. (2003). “Vegetative Covers for Waste Containment.” *Phytoremediation. Advances in Biochemical Engineering/Biotechnology*, Springer, Berlin, Heidelberg, 78(1), 157–170.

Sânchez-Carrillo, S., Âlvarez-Cobelas, M., Benitez, M., and Angeler, D. G. (2001). "A simple method for estimating water loss by transpiration in wetlands*". Hydrological Sciences~Journal-des Sciences Hydrologiques*.

Smeal, C., Hackett, M., and Truong, P. (2017). “Vetiver System for Industrial Wastewater Treatment in Queensland , Australia.” (September), 1–13.

Smesrud, J. K., Benson, C. H., Albright, W. H., Richards, J. H., Wright, S., Israel, T., and Goodrich, K. (2012). “Using pilot test data to refine an alternative cover design in Northern California.” *International Journal of Phytoremediation*, 14(SUPPL.), 76–93.

Truong, P. (2019). “Vetiver system for environmental protection.” *Vetican Consulting, Brisbane.*

United States Department of Agriculture (USDA). (2018). “Switchgrass Fact Sheet.” <https://plants.usda.gov/core/profile?symbol=pavi2> (Jan. 10, 2017).

US EPA. (2017). “Municipal Solid Waste Landfills.” <https://www.epa.gov/landfills/municipal-solid-waste-landfills> (Dec. 5, 2018).

USDA, NRCS, N. P. D. (2003). *Cheatgrass Fact Sheet*.

Vogel, T., Votrubova, J., Dohnal, M., and Dusek, J. (2017). “A Simple Representation of Plant Water Storage Effects in Coupled Soil Water Flow and Transpiration Stream Modeling.” *Vadose Zone Journal*, GeoScienceWorld, 16(5), 0.

PAPER NO. 2: EXPERIMENTAL STUDY ON EFFECTIVENESS OF PLANTS ON WATER BALANCE IMPROVEMENT OF COMPACTED SANDY SILT COLUMNS

ABSTRACT

Three identical large-scale soil columns, one without vegetation, one planted with vetiver grass, and one planted with switchgrass were instrumented to evaluate the effect of plants on water balance. This study was carried out in the southeastern U.S. where the climate is humid. Each column consisted of 35 cm thick topsoil underlain by 76 cm thick compacted sandy silt. Each column simulates an evapotranspirative (ET) cover. The key objective was to measure the water balance and to evaluate the effect of plants on hydrological performance of the soil columns where the storage layer was compacted to achieve relatively low hydraulic conductivity. Data collected over a period of one-year shows that ET from vetiver and switchgrass columns was 9% and 2% higher than the control column, respectively. However, the increase in ET occurred during a relatively short period of time. It was during summer when there was 1-month drought. This shows that plants can enhance ET in humid climate when plants are under stress due to drought.

INTRODUCTION

In the U.S. the primary method to manage municipal solid waste (MSW) is landfilling. In 2009, it was estimated that there were around 1,908 active landfills in the U.S (US EPA 2017). Landfills are engineered facilities with components that include bottom liner, leachate collection system and final cover. The final cover is a designed component of the landfill which is mandated to cover the landfill when it reaches its capacity (US EPA 2017). Landfill cover reduces odors, minimizes erosion after plants establish, and improves the slope stability and aesthetics. However, the most important role of a landfill cover is to minimize percolation through the waste as it reduces leachate generation during the post-closure care period.

Resource Conservation Recovery Act (RCRA) Subtitle D regulations require a final cover that contains a geomembrane. However, alternative final covers consisting only of natural soils have been approved in many states across the U.S. (Albright et al., 2004; Mijares and Khire, 2012; Khire, 2016). However, due to the cost and maintenance of RCRA covers, alternative landfill covers have been favored by the industry. For an alternative cover to be permitted, it must be shown that hydrological performance of the alternative cover is equivalent to the RCRA cover via numerical simulations and/or field data analysis.

In order to estimate field water balance parameters of a landfill cover, often lysimeter is used in which surface runoff (R), precipitation (P), soil water storage (ΔS), and percolation (P_r) through the cover are monitored. Water balance of a lysimeter can be expressed using the following equation:

$$ET = P - P_r - R - \Delta S \tag{2-1}$$

ET is the sum of transpiration and evaporation which happen simultaneously in a vegetated cover. In field-scale practices using the water balance equation (Equation 2-1), transpiration and evaporation cannot be measured or estimated separately and are lumped together. Evaporation is the process of water removal from the ground surface, and transpiration happens as plants process water for photosynthesis- related process. For proving the percolation equivalency of an alternative landfill cover, usually water balance simulations are implemented. One of the most commonly used water balance models is UNSAT-H. The model requires climatic as well as transpiration parameters. Transpiration input parameters can be measured. However, there is very little field-scale or laboratory-scale research on validation of transpiration predicted by water balance models for landfill cover applications. Because there is such a deficiency of verification studies, practitioners often choose the conservative scenario of modeling alternative landfill covers by ignoring transpiration (Khire 2016). However, ignoring transpiration in the design/numerical modeling of alternative covers may not be appropriate in humid climates. In such climates, precipitation is relatively high which makes it unlikely to satisfy the percolation equivalency by eliminating the effect of plants on water removal (if present) from the cover via transpiration. It is also unknow if plants could reduce evaporation due to plant canopy but compensate the loss via transpiration.

There have been numerous studies on direct and indirect methods of measuring transpiration. Using evaporation tanks with cultivated hydrophytes (Sânchez-Carrillo et al. 2001) and continuous measurement of capillary flow porometer of stomatal resistance of leaves (Day 1977) are couple of mostly used direct methods. Some of the examples of indirect transpiration measurement methods are sap flow measurements of plants' stems (Nadezhdina et al. 2018; Vogel et al. 2017), and energy budget measurements (Leung and Foster 1990; Renner et al. 2016) which are all based on the relationship between planted areas and open water areas which require estimation and measurement of numerous variables which can be costly and the results can be more prone to methodological errors (Sânchez-Carrillo et al. 2001). There is lack of research on evaluation of transpiration in a bigger scale and its role in the water balance equation (Equation 3-1). Large-scale experiments on effect of plants on the water balance of covers will provide insight into other parameters influencing the hydrologic behavior of a landfill cover. In other words, the goal is not just to answer how much does a specific plant transpire as an individual canopy, the answer to these question can be found in the literature (Bréda 2003; Hui et al. 2018). However, the main goal of this research is to study hydrological behavior of soil columns when they have vegetation which is perceived to enhance water balance performance of a compacted soil system such as an alternative landfill cover in field-scale or a compacted soil column as a laboratory-scale soil-plant system. Two plants that are perceived to be beneficial for landfill cover water balance behavior were selected: vetiver grass and switchgrass.

Quantifying the effect of plants on the water balance using large-scale laboratory data will contribute to design process of alternative landfill covers. Besides using plants on alternative covers due to permitting aspects, plants have been used for a millennia on landfill covers for improving the environment (Licht et al. 2001; Rock 2003; Smesrud et al. 2012). Using plants on landfill covers in general has been perceived in the industry to improve leachate management of a landfill. Since the1990s, plants have been introduced on landfill covers for the main goal of reduction in leachate generation as well as leachate treatment (Licht et al., 2001; Granley & Truong, 2012; Erdogan & Zaimoglu, 2015).

Vetiver grass has been identified as a plant which can uptake nutrients and heavy metals, and it has been successfully used in Australia, Thailand, and China for MSW landfill leachate treatment since the 1990s (Banerjee et al. 2019; Bwire et al. 2011). Vetiver grass is native to southern India. Vetiver grass can develop a robust root system which helps in the uptake of leachate and improves cover’s function for erosion and slope stability. Vetiver plant's roots can grow up to 3 m in depth and the grass (plant) can grow up to 3 m in height (Truong 2019) . In a majority of the previous studies, vetiver grass is referred to as a simple, hygienic and low-cost method for chemical treatment of wastewater. However, vetiver grass has not been evaluated for ET covers to enhance ET.

Switchgrass- *Panicum virgatum (L.)* is a perennial grass that grows up to 1.8 m in height and is native to vast geoclimatic regions from southern Canada to the U.S. and Mexico (Hui et al. 2018; USDA, 2018). Switchgrass characteristics such as production of relatively high volume biomass, high nutrient uptake and being tolerant to a broad environmental condition makes it a suitable choice for erosion control, producing livestock, and wildlife habitat aspects of a landfill cover (Hui et al. 2018; USDA, 2018). Hence, switchgrass was one of the plants selected in this study. The other plant selected was vetiver to allow direct comparison with the component of this study carried out in the field at another site in the southcentral U.S.

In addition, the two plant species (vetiver and switchgrass) were selected for the purpose of comparing two relatively similar plants in biomass production and environmental tolerance with the difference that switchgrass is a native U.S. grass, whereas, vetiver is not native to the climate of North America.

In order to fulfil the research objectives, three plexiglass columns containing compacted sandy silt storage layer and a topsoil layer were built and instrumented. Column 1 is bare (control), Column 2 is planted with a vetiver plant and Column 3 is planted with a switchgrass plant.

MATERIALS AND METHODS

The three columns are made of plexiglass and are 1.4 m tall and 25 cm in diameter. Each column contains the following layers from top down:

- 35 thick topsoil layer;
- 76 cm thick compacted sandy silt (storage layer); and
- Geonet and geotextile drainage layer to collect and drain percolation.

COLUMN DESIGN AND CONSTRUCTION

Design of Columns

For designing the columns, a native soil (sandy silt) was sourced from Landis, NC, located about 50 km from UNC Charlotte main campus. The following properties of this soil were measured:

- USCS classification was carried out and the soil was classified as SM (sandy silt).
- Proctor compaction tests were carried out at two compaction efforts: standard effort and ~96% of the standard effort. Proctor compaction curves are presented in Figure 2-1.
- Saturated hydraulic conductivity of the soil was measured using flexible wall permeameter (per ASTM D5084) at various molding water contents (Figure 2-1). The average saturated hydraulic conductivity of the soil was 2×10^{-6} cm/s.

The unsaturated hydraulic properties of the sandy silt which was selected to construct the storage layer of the soil cover simulated in the columns were estimated using the instantaneous profile method (IPM). In this method, a cylindrical sample of the soil at the target unit weight was compacted. The sample was then saturated by inflow of water from the lower boundary and it was subjected to air drying only from the top boundary by running fan that constantly moved air across the surface of the sample. This process has been successfully tested by (Meerdink et al. 1996) and used by Khire (2016) and Mijares and Khire (2012) for landfill cover projects. Saturated hydraulic conductivity of the soil for samples with two different dry density and optimum water content were estimated using IPM. First sample compacted with dry density of 15.5 kN/m^3 and water content of 15.5%. The second sample was compacted with dry density of 14.3 kN/m^3 and water content of 12%. The soil compacted at higher compaction effort was used for constructing the lower half part of the column and the soil compacted at lower compaction effort was used for constructing the upper half of the column. Measured saturated and unsaturated hydraulic properties of the storage layer soil and the topsoil are summarized in Table 2-1.

Meteorological data consisting of air temperature, solar radiation, precipitation, wind speed, wind direction and relative humidity were measured from a weather station installed next to the three columns. UNSAT-H model was used to simulate the columns containing sandy silt storage layer ranging in thickness from 60 cm to 83 cm. The hydraulic properties measured for the soil and climatic data were input to the model. Plants were not simulated in these runs as there was no plant data available. Based on the results of these simulations, the cover design was selected with 76 cm thick compacted sandy silt storage layer. The design goal was that the average annual percolation to be around 20% of the precipitation (~ 21 cm). This amount of percolation is higher than what ET covers are required to be designed for. However, the main goal of the study was to evaluate the effect of plants on ET from columns. Consequently, it was hypothesized that breakthrough (collect enough percolation from the columns) would occur during early stages of the experiment and as the plants matured, the magnitude of percolation would decline as the plants removed more water via transpiration.

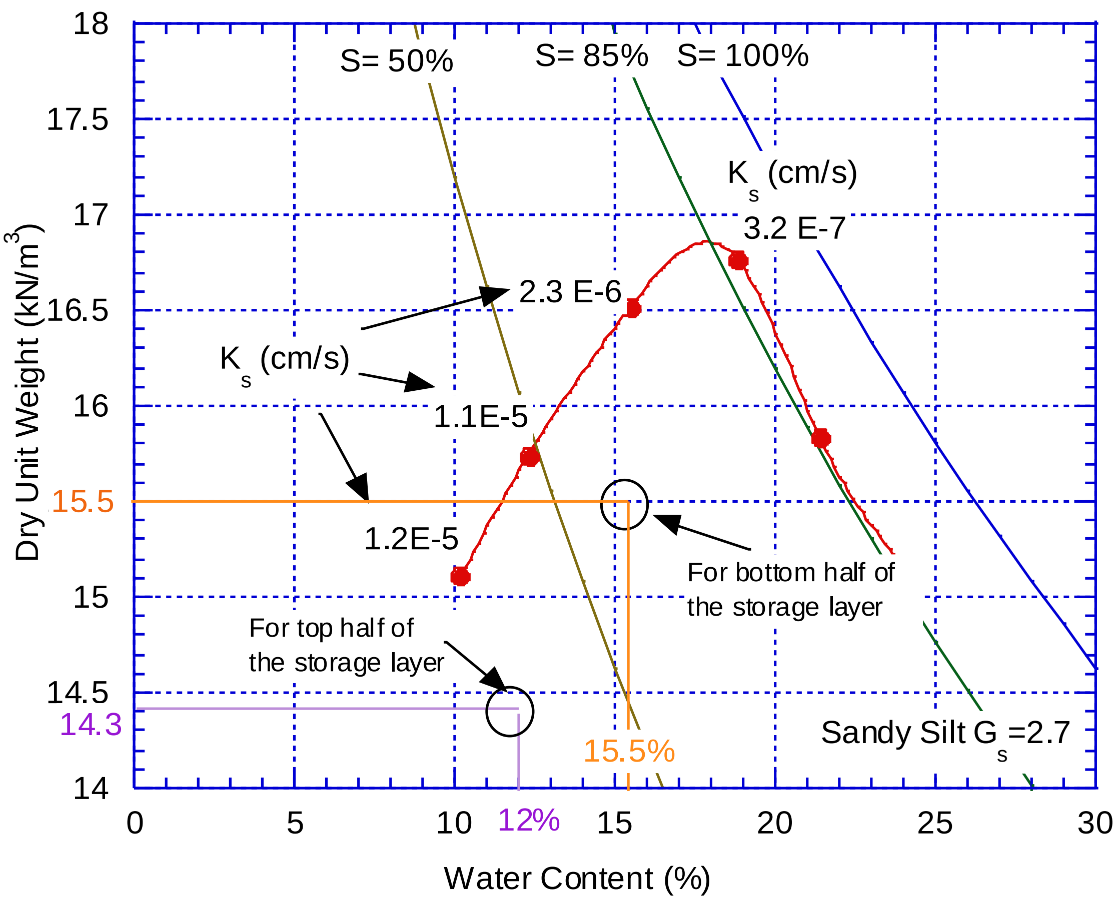

Figure 2-1: Compaction tests, unit weights and estimated hydraulic conductivities.

Table 2-1: Geotechnical properties of the storage layer.

	Storage Layer
USCS Classification	SM
D_{10} (mm)	0.002
D_{50} (mm)	0.013
D_{60} (mm)	0.148
C_u	74
C_c	1

Liquid Limit- LL (%)	43
Plasticity Index- PI (%)	1
G_s	2.7
Hydraulic Conductivity (cm/s) (Laboratory- Rigid Wall Permeameter)	~ 2×10^{-6}
Hydraulic Conductivity (cm/s) (Laboratory- IPM)	~ 4×10^{-6} to 6×10^{-6}
As-built Hydraulic Conductivity (cm/s) (Ponding Test)	~ 2×10^{-6}

Column Setup

The large-scale column experiment comprised of three transparent acrylic cylinders having 25 cm internal diameter and 1.4 m height. Each cylinder was filled with two layers of compacted sandy silt having total thickness of 76 cm (moisture storage layer) overlain by loosely placed topsoil layer having total thickness of 35 cm. For constructing the storage layer, approximately 59 kg of dry sandy silt was compacted in two layers each having different compaction specifications: bottom 38 cm of the storage layer was compacted to achieve dry unit weight of 15.5 (kN/m^3) with molding water content (gravimetric) of 15.5%, and top 38 cm of the storage layer was compacted to achieve dry unit weight of 14.3 (kN/m^3) and molding water content of 12%. The upper portion of the storage layer had lower dry unit weight to allow plant roots to enter the storage layer with less difficulty as the plants matured.

To make sure that all three columns had identical hydraulic characteristics and the storage layer of all three columns was relatively homogenous, the storage layer of all columns was compacted in 7.6-cm thick lifts which were compacted with the same effort all at the same time by the same two lab personnel. In order to minimize occurrence of preferential flow paths, annular rings made of duct tape were glued to the internal walls of the plexi-glass cylinders at 0.4 m depth from the surface of the storage layer. To collect percolation at the bottom, an outlet was installed in the baseplate of the column. Percolation was collected in a graduated beaker placed under the column and recorded daily. A geocomposite (geonet and geotextile) layer was placed at the bottom of each columns immediately below the storage layer to collect percolation. A schematic of the column setup is shown in Figure 2-2. All three columns are identical in design, construction and instrumentation with the difference that one is planted with a vetiver plant, one is planted with a switchgrass plant and the third column is control that is left bare After the storage layer was constructed, ponding tests were conducted on each column to estimate the as-built saturated hydraulic conductivity at the start of the test (Table 2-1). The as-built hydraulic conductivity of the columns was 2×10^{-6} cm/s.

The vetiver and switchgrass plants were about 16 cm and 58.5 cm tall, respectively, at the time of plantation. Perimeter of all columns were covered with fiber glass insulation and a plastic liner to reduce the effect of variations in air temperature on the soil temperature. Figure 2-3 shows the experimental setup after the construction and instrumentation was complete.

INSTRUMENTATION AND DATA COLLECTION SYSTEM

Sensors were installed to monitor the hydrological performance of all three columns. Instrumentation included volumetric water content sensors and soil matric suction sensors. Each column has pairs of water content and matric suction sensors at three depths within the storage layer (Figure 2-2). A weather station was installed near the experiment setup to measure precipitation, air temperature, relative humidity, wind speed, wind direction, and solar radiation on hourly interval. Figure 2-4 shows precipitation recorded on-site recorded vs. recorded by a National Oceanic and Atmospheric Administration (NOAA) station located about 20 km from the site. All sensors are connected to a measurement and logging system consisting of Campbell Scientific CR1000 datalogger. The datalogger is programmed to take hourly reading of all sensors. The data was collected on weekly basis for a period that exceeded one year after the experiment began.

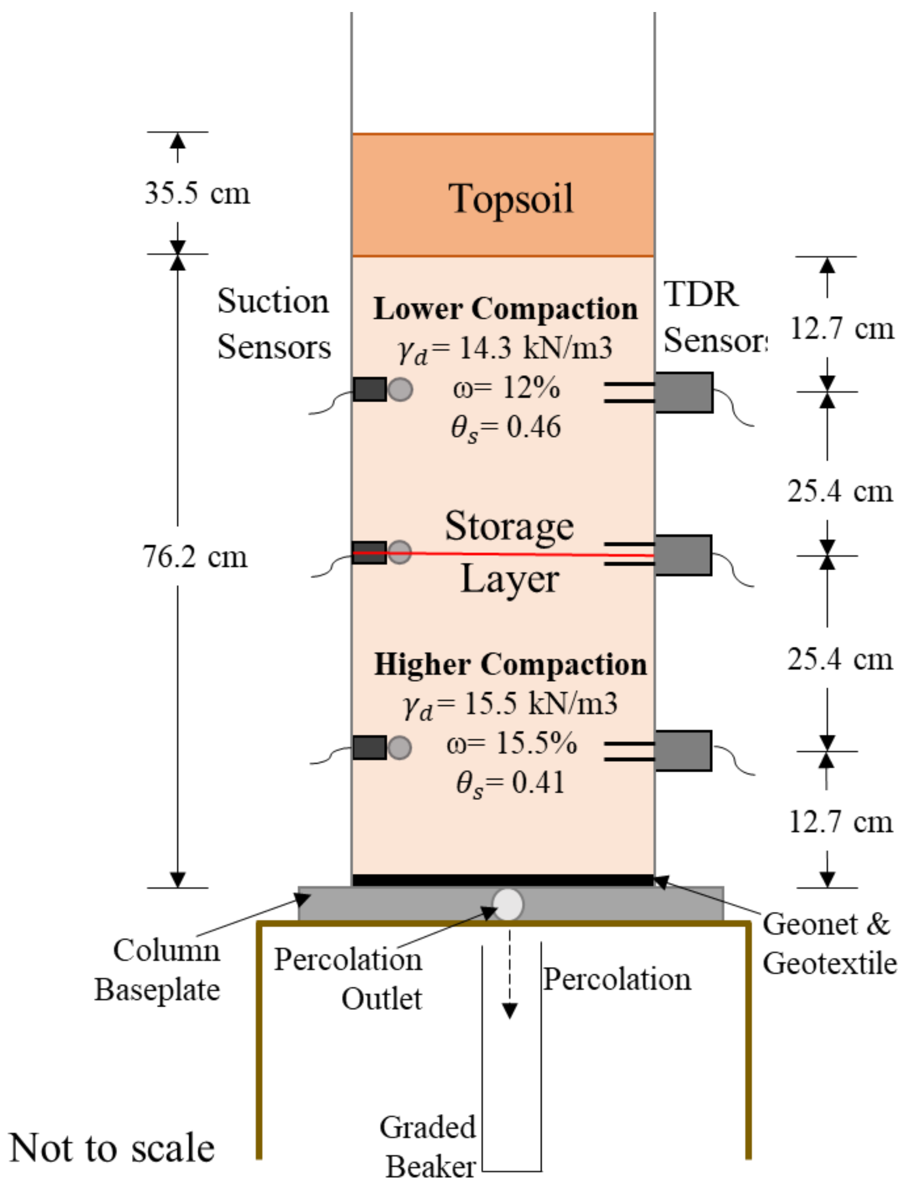

Figure 2-2: Schematic of soil layers and instrumentation for each column.

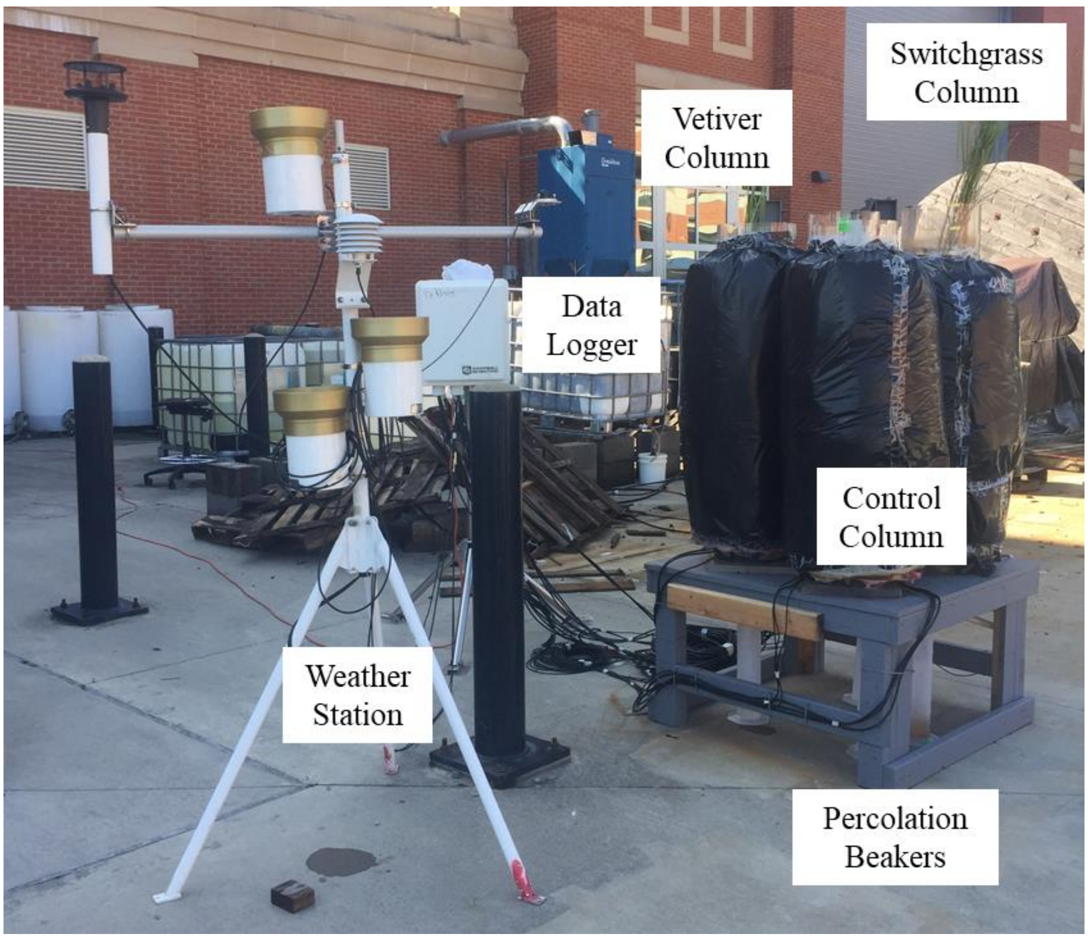

Figure 2-3: Experimental setup and configuration while tests in progress.

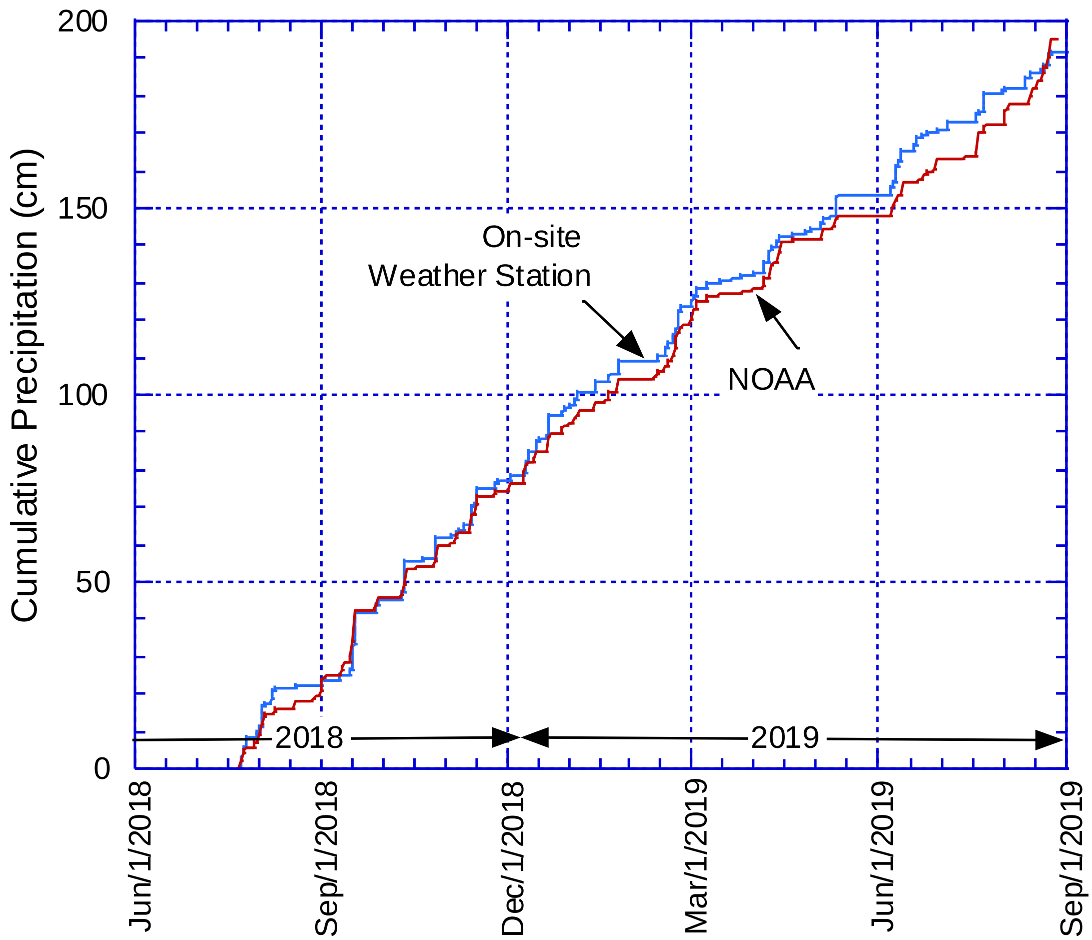

Figure 2-4: On-site and NOAA recorded precipitation.

Water Content Sensors

For measuring volumetric water contents, CS655 sensors manufactured by Campbell Scientific Inc. were used. The CS655 sensors work on the principle of time domain reflectometry (TDR). The TDR sensor has two stainless steel rods, each rod is 12 cm long and has a diameter of 3.2 mm. The sensor measures volumetric water content, electrical conductivity, dielectric permittivity, and temperature of soils (Campbell

Scientific Inc., 2011). The TDR sensor calibration curve was developed by carrying out experiment on the sandy silt in the lab and correlating time period and soil temperature to the volumetric water content via the calibration equation. Equation 2-2 is the calibration equation that converts temperature, x (℃) and average time period, y (μs) measured by the TDR sensor to the volumetric water content θ of the storage layer.

$$\theta = 0.1124y^2+0.0027xy+0.2981y+0.0041x-0.4761 \tag{2-2}$$

Each column has three water content sensors in the storage layer as shown in Figure 2-2. Figure 2-5a shows photos of installation of TDR sensors in one of the columns (before wrapping the column with insulation). The water content sensors were installed at 12.7 cm, 38 cm and 63.5 cm depths from the surface of the storage layer. The TDR sensor head dimensions are 85 mm× 63 mm ×18 mm, and the length of the sensor rod is 12 cm. Placing the entire TDR sensor (head and rods) inside the column was avoided as the whole sensor would take considerable space, and it would interfere with the natural flow path of water within the column. Consequently, holes having the same size as the diameter of the TDR rods were drilled in the acrylic column wall at the specified locations where the sensor rods would be inserted. TDR sensor rods were gently pushed through the drilled holes with the sensor head left column (Figure 2-5a). Silicone caulking was used to seal the hole after the sensor was fully inserted.

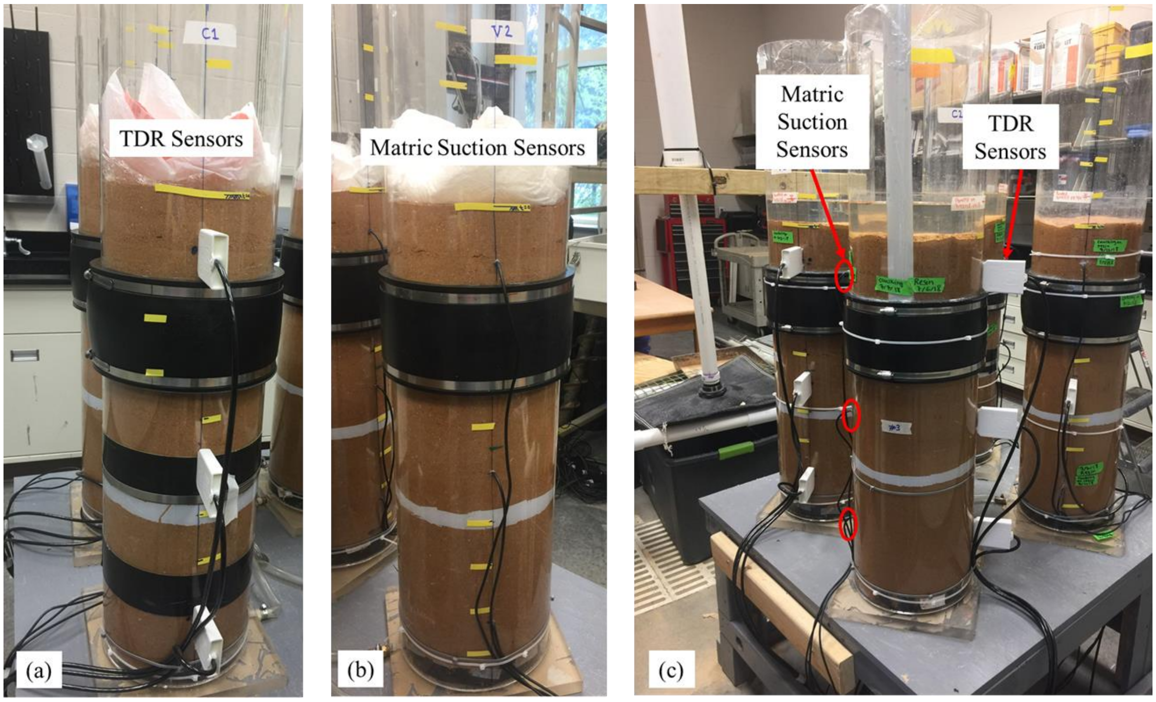

Figure 2-5: Instrumentation of the soil columns: (a) TDR sensors, and (b) matric suction sensors installed at 12.7, 38 and 63.5-cm from the surface of the storage layer, (c) perspective view of all instrumented columns during ponding test.

Water Potential Sensors

Capacitance-based water potential sensors were installed in each column to measure matric suction of the storage layer. The sensor is manufactured by Decagon Devices Inc. (Model MPS-6). It consists of a porous ceramic disc having diameter of 3.2 cm attached to the head of the sensor. The MPS-6 sensor measures the dielectric permittivity of the solid matrix (porous ceramic disc) to determine its water potential (Decagon Devices Inc., 2017). Soil water potential measurements using this sensor ranges from -9 kPa to -100 kPa. It also measures suctions less than -100 kPa but the accuracy of those measurements has been gone through a limited validation (Decagon Devices Inc., 2017). Three water potential sensors for each column were installed in the storage layer at the same depths where the TDR sensors were installed (Figure 2-6). The MPS-6 sensor head and porous disc are relatively small compared to the diameter of the column. Hence, the whole MPS6 suction sensor was placed vertically in the storage layer when the specific lift of the storage layer was being compacted (Figure 2-6).

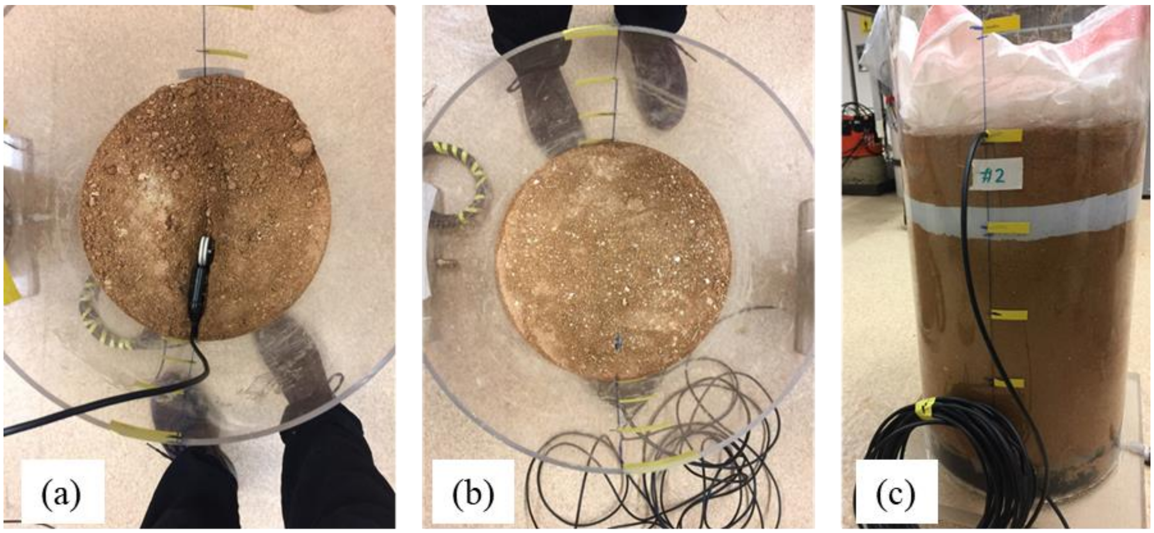

Figure 2-6: (a) Matric suction sensor installation at depth of 38-cm from the storage layer surface, (b) matric suction sensor covered with compacted soil, and (c) matric suction sensor cable inserted in the wall of the cylinder.

RESULTS AND DISCUSSION

The columns were filled, planted, and instrumented in late July 2017. The data from this experiment was collected for a period of little over one year. The data and results are presented in this section.

Weather Data

Mean monthly measured weather data that includes precipitation, air temperature, wind speed, solar radiation and relative humidity obtained from the weather station during the one-year monitoring period compared to 30-year mean obtained from NOAA is presented in Table 2-2. Daily averages of measured weather parameters and standard deviations and annual normal precipitation and mean temperatures are presented in Table 2-3. Total annual precipitation for the one-year duration was 180 cm while the 30-year average was 105 cm. Thus, it was a relatively wet year. Table 2-2 and Figure 2-7 show the seasonal variation. The growing season (Jul 2018- Nov 2018 and Mar 2019- July 2019) was warmer than the 30-year average. During the one-year period, the growing season received more precipitation than the 30-year average (Figure 2-8).

Plant Growth

Height of the plant canopy for both vetiver and switchgrass were measured weekly during growing season and bi-weekly during colder months. At the time of planting, vetiver and switchgrass plants were about 16 cm and 58 cm tall, respectively. Vetiver height increased rapidly and after one year it reached about 152 cm (about 50% of its expected fully-grown height).

Switchgrass height grew to 116 cm but most of the increase was in the last four months of the monitoring period. 116 cm represents about 76% of its expected fully-grown height. Figure 2-9 shows measured monthly mean height of the plants. Switchgrass has shown a slower canopy growth in comparison with vetiver. However, switchgrass canopy has been denser than vetiver canopy at the end of the one-year monitoring period.

Table 2-2: On-site Monthly Climatic measurements and 30-year normal.

	Monthly Averages - Field Measurements					**30-year Normal**	
Month	Precip-itation (cm)	Air Temp (°C)	Wind Speed (m/s)	Total Solar Radiation (MJ/m^2)	Relative Humidity (%)	Precip-itation (cm)	Mean Air Temp (°C)
Jul-18	10.2	24.9	0.7	14.0	73.5	9.35	20.06
Aug-18	13.5	25.3	0.7	39.2	72.2	10.72	19.56
Sep-18	21.7	24.5	0.7	28.0	77.1	8.23	15.78
Oct-18	16.3	16.8	0.7	26.1	73.7	8.64	9.33
Nov-18	15.2	8.4	0.8	13.7	74.5	7.98	4.00
Dec-18	20.3	6.7	0.7	8.8	74.8	8.26	-0.06
Jan-19	11.9	5.9	0.8	13.1	62.8	8.66	-1.33
Feb-19	15.4	9.0	0.8	16.2	66.5	8.43	0.39
Mar-19	7.9	9.9	0.9	180.3	57.2	10.19	4.06
Apr-19	11.8	17.0	0.9	394.3	62.9	7.72	8.28
May-19	9.5	23.1	0.8	532.5	64.9	8.08	13.22
Jun-19	16.9	24.2	0.8	526.6	66.3	9.50	18.06
Jul-19	10.3	26.7	0.7	524.8	65.9	9.35	20.06
Total	**108.9**					**115.1**	

Table 2-3: Daily means ± standard deviation and 30-year normal.

	Field Daily Means ± Standard Deviations			**Field Total Values**		**30-Year Normal**	
	Air Temp (°C)	Relative Humidity (%)	Wind Speed (m/s)	Solar Radiation (MJ/m2)	Precip-itation (cm)	Precip-itation (cm)	Mean Temp (°C)
Jul 2018-Jul 2019	17.4±8.7	68.7±15.4	0.77 ± 0.27	2765	180	105	15.5

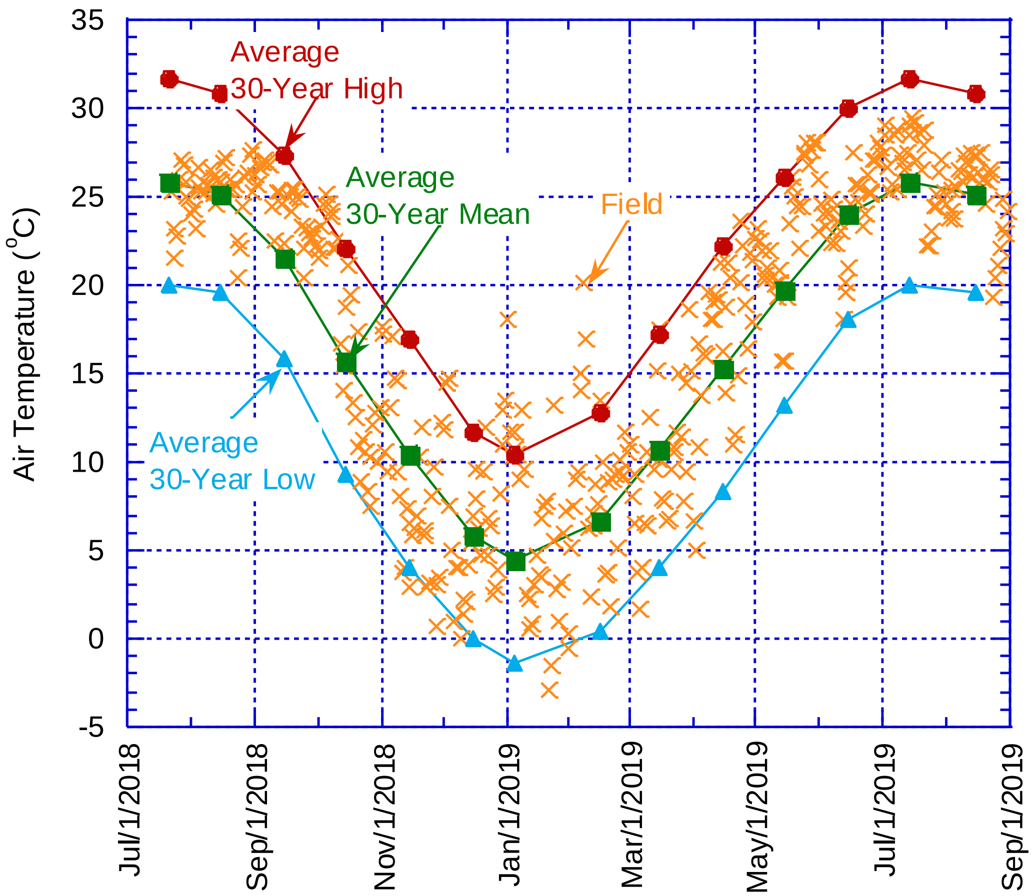

Figure 2-7: Measured air temperatures and 30-year normal.

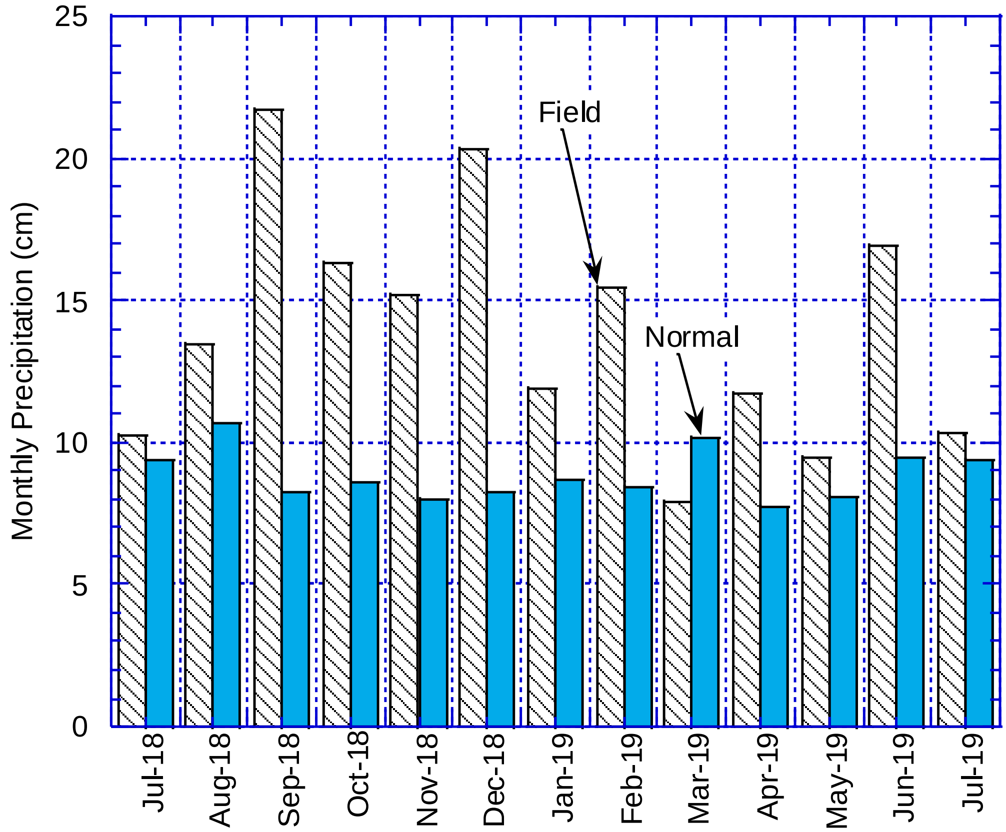

Figure 2-8: Monthly normal and field precipitation.

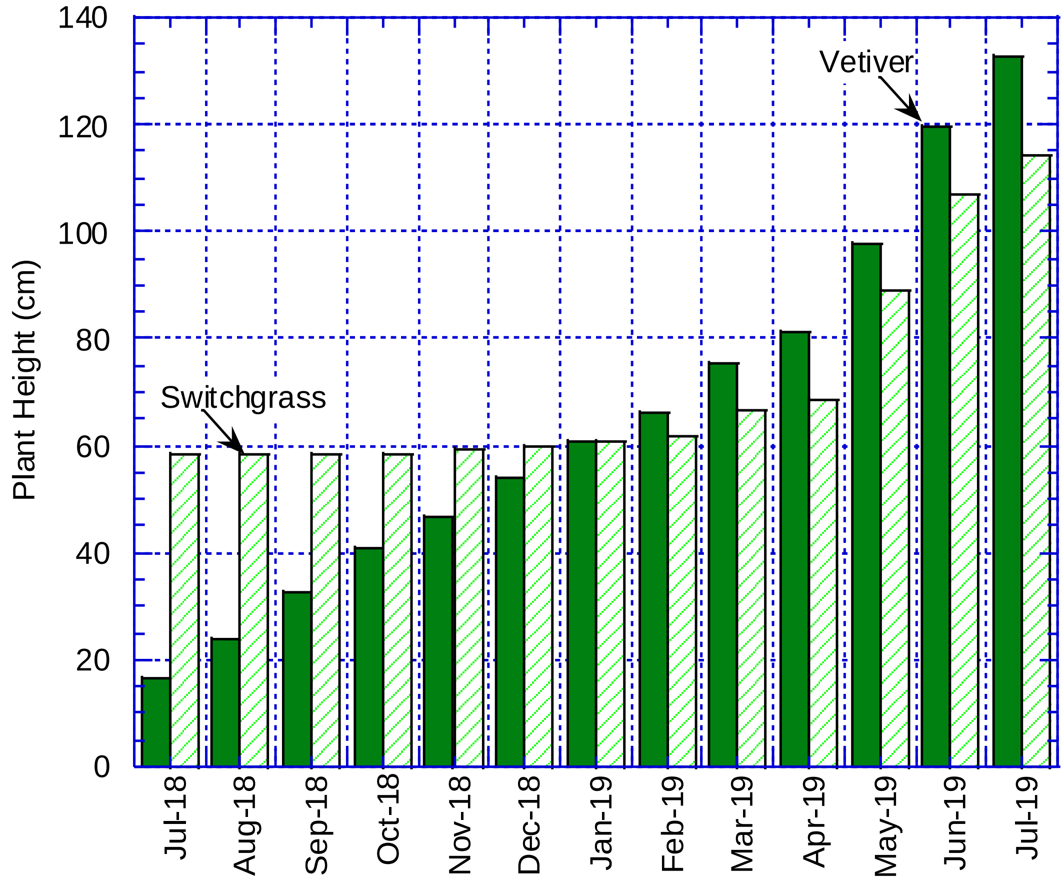

Figure 2-9: Vetiver and switchgrass monthly average height.

Unsaturated Hydraulic Properties of the Storage Layer

Using the water content and matric suction sensor measurements, SWCCs were fitted using van Genuchten (1980) function. The van Genuchten function is presented in Eq. 2-3.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{1 + (a \cdot \psi)^n} \right\}^m \qquad (2\text{-}3)$$

where θ_s is the saturated volumetric water content, θ_r is the residual water content, and ψ is suction. α, n and m ($m = 1 - n^{-1}$) are fitting parameters related to the air-entry value of the soil, slope at the inflection point of SWCC, respectively.

The unsaturated hydraulic conductivity function can be predicted using the saturated hydraulic conductivities and van Genuchten fitting parameters. Equation 2-4 presents the van Genuchten-Mualem model (van Genuchten 1980; Mualem 1976) for predicting unsaturated conductivities as a function of matric suction:

$$\frac{K_\psi}{K_s} = \frac{\{1-(a\cdot\psi)^{n-1}\cdot[1+(a\cdot\psi)^n]^{-m}\}^2}{[1+(a\cdot\psi)^n]^{m/2}} \tag{2-4}$$

where K_s is the saturated hydraulic conductivity, and K_ψ is the corresponding hydraulic conductivity for matric suction ψ. Figures 2-10 and 2-11 show the fitted unsaturated parameters for the sandy silt used to construct the storage layer in all three columns.

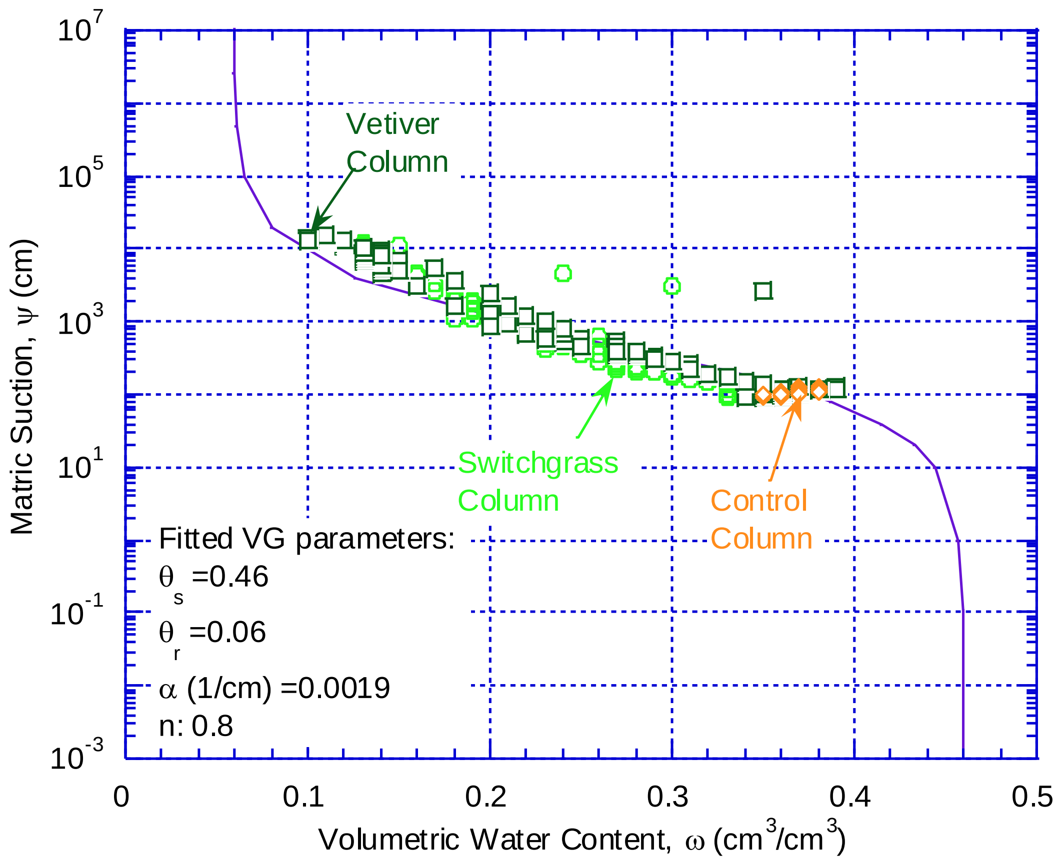

Figure 2-10: SWCC of the storage layer.

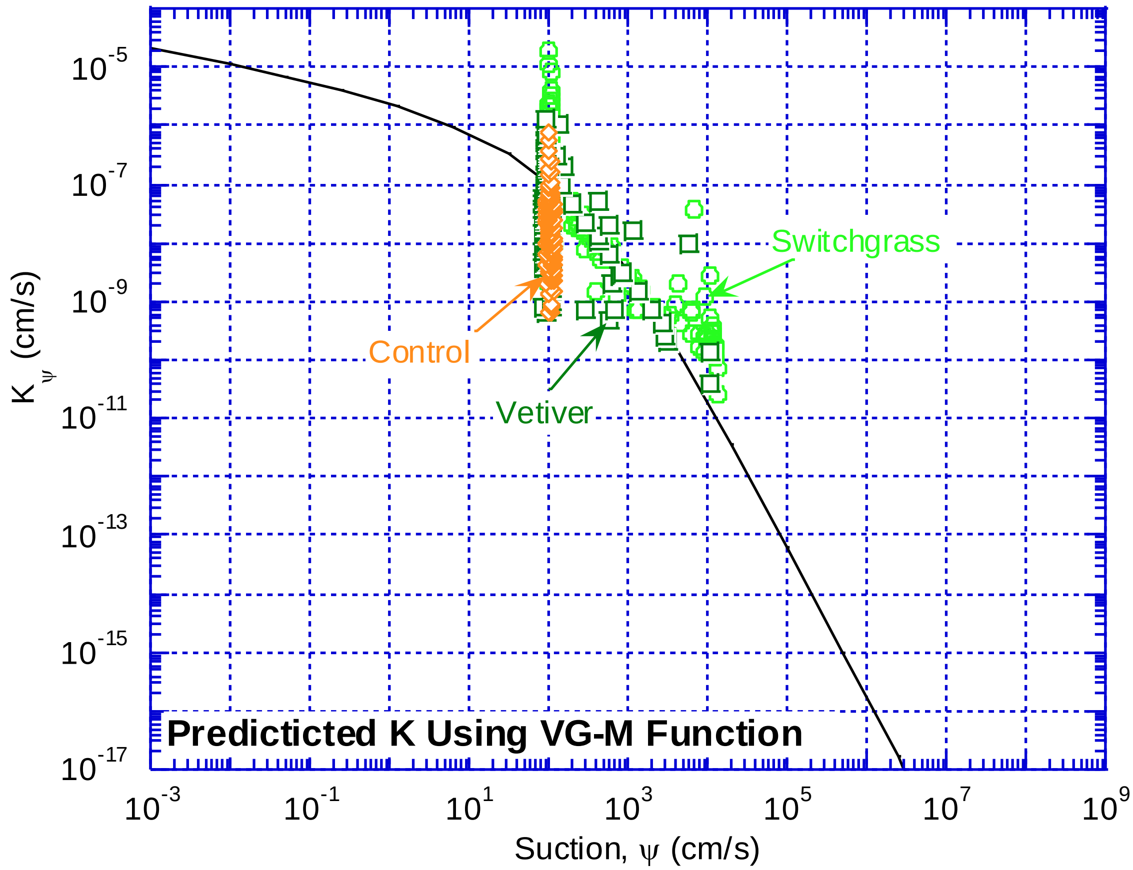

Figure 2-11: Predicted K_ψ using van Genuchten-Mualem function

Measured Water Contents and Suctions

Measured volumetric water contents and matric suctions are presented in Figs. 2-12 to 2-17. Figs. 2-12 to 2-14 illustrate the water content measurement for switchgrass, vetiver and bare column, respectively. From the beginning of the experiment in July 2018 until mid-May 2018, the soil water contents for all three columns show relatively small changes. The sandy silt layer mostly maintained its degree of saturation to 77% to 80%. However, from 13 May to 7 June 2019, due to drought, a sharp decrease in water contents of all three water content sensors of switchgrass and vetiver columns was observed. The water contents in these columns containing plants reached the residual water content of 0.06. However, water contents of the sandy silt layer of the bare column showed very little or no change during this drought period (Fig .2-14). A slight decrease was observed in the uppermost water content sensor that is closest to the topsoil layer. This major observed difference between the bare and the planted columns indicates that the plants were responsible for removal of water from the compacted sandy silt layer during this 25-day period.

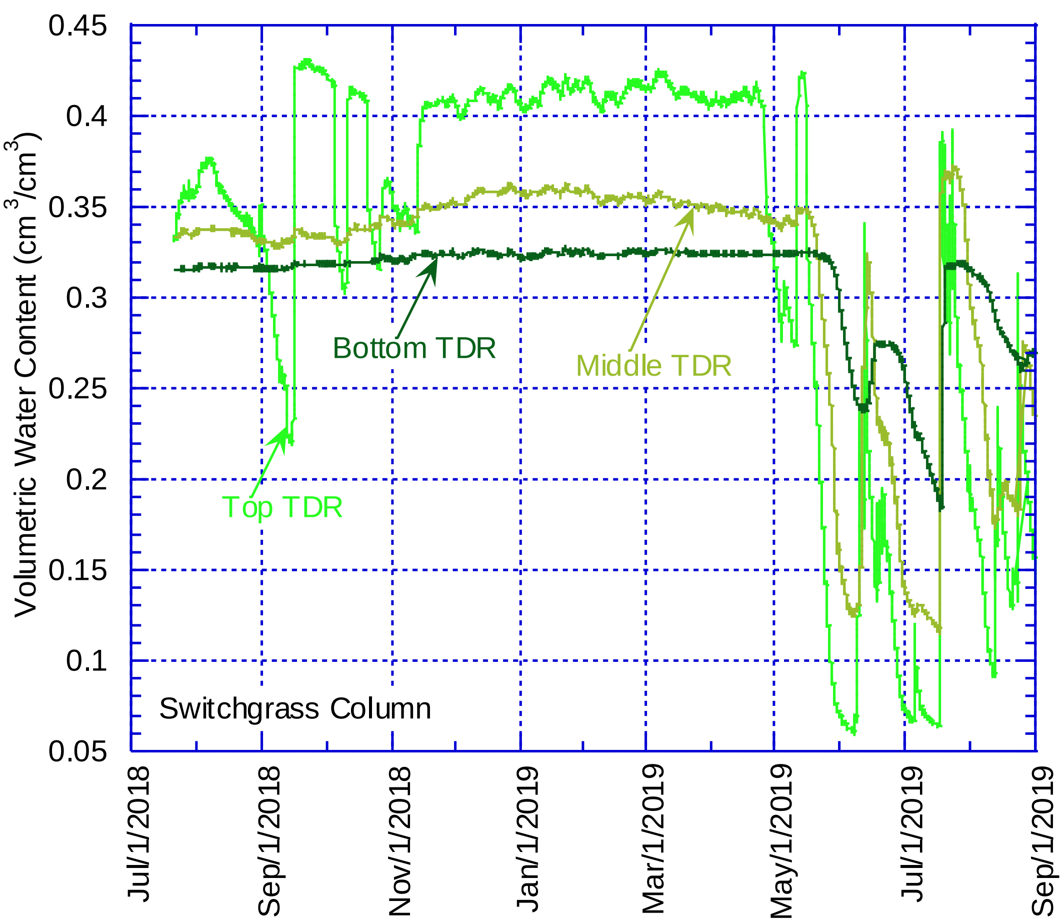

Figure 2-12: Switchgrass column volumetric water content measurements.

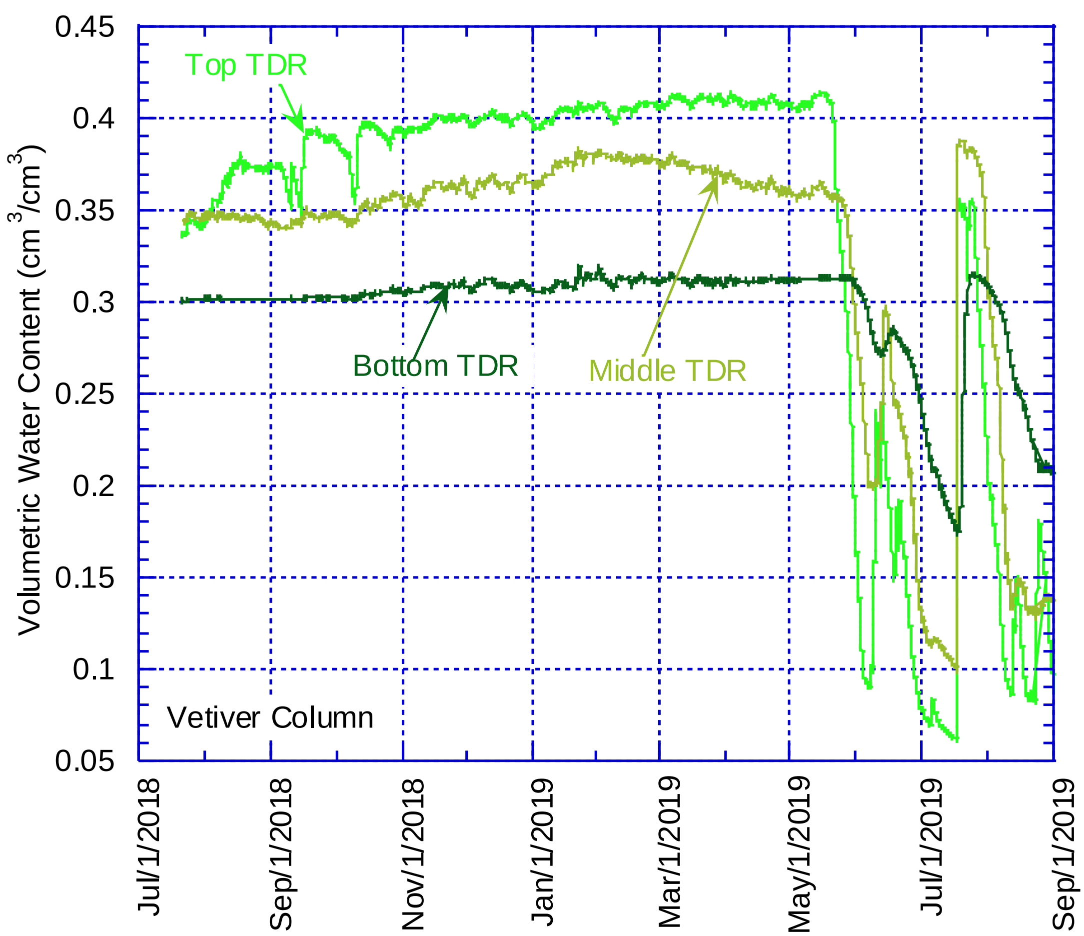

Figure 2-13: Vetiver column volumetric water content measurements.

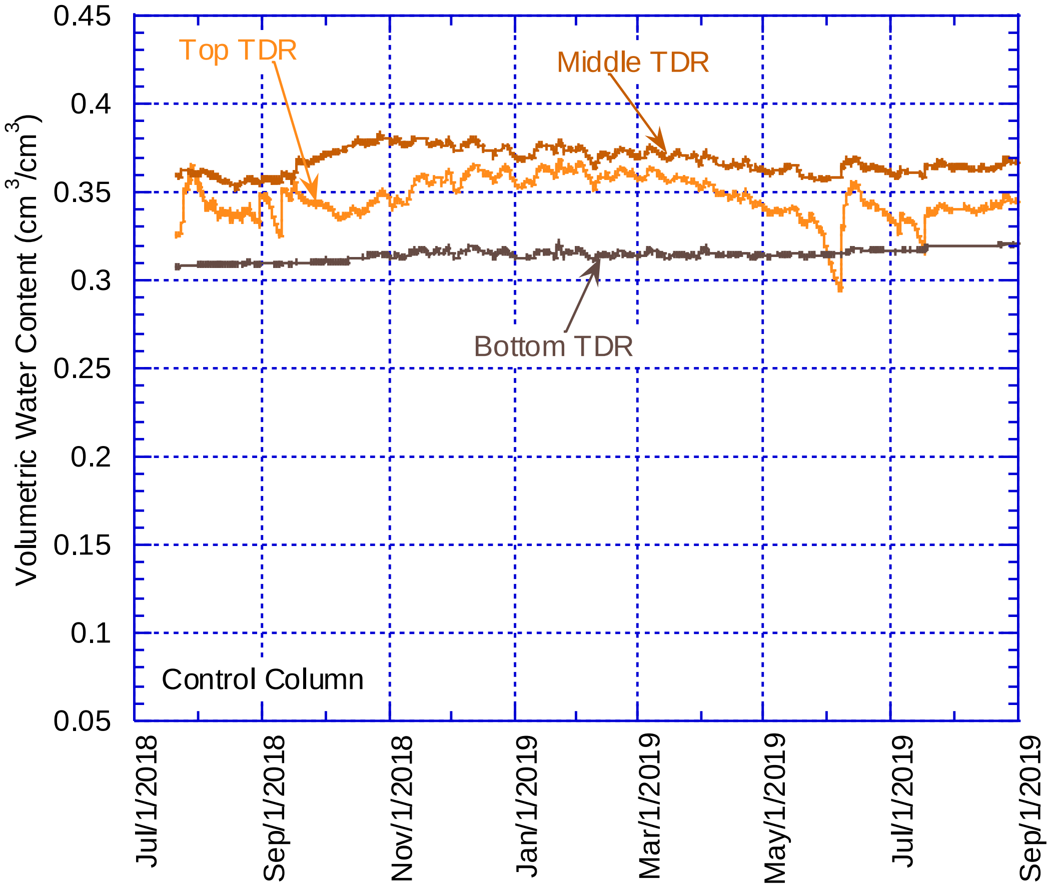

Figure 2-14: Control column volumetric water content measurements.

Figures 2-15 to 2-17 show the matric suction measured by the sensors for the three columns. The suction readings were consistent with the TDR readings and indicated relatively high suctions for the switchgrass and vetiver columns when the water contents dropped during the drought. The suction values in the bare column did not increase during that period as the water contents were relatively high (Fig. 2-17). Thus, the suction readings confirm that the water removal via ET from the bare column fell behind the ET from planted columns during the period of drought.

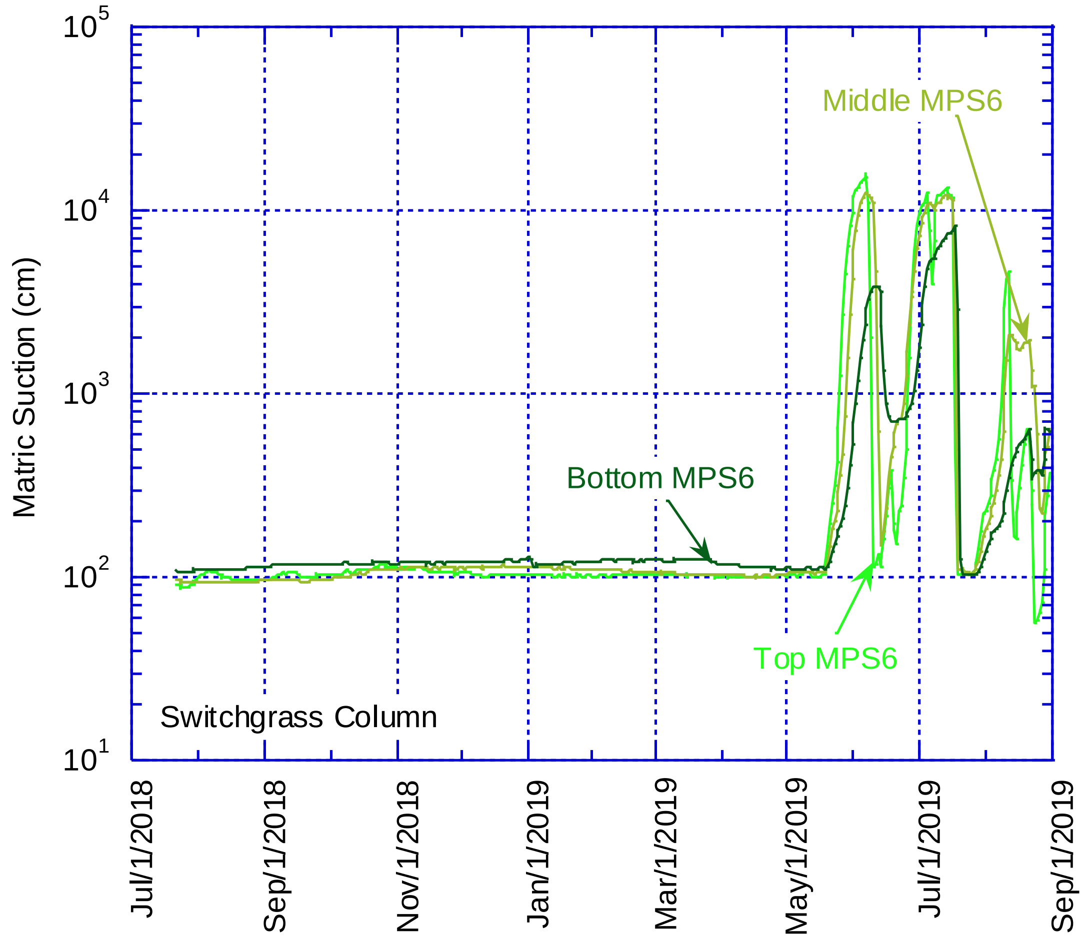

Figure 2-15: Switchgrass matric suction measurements.

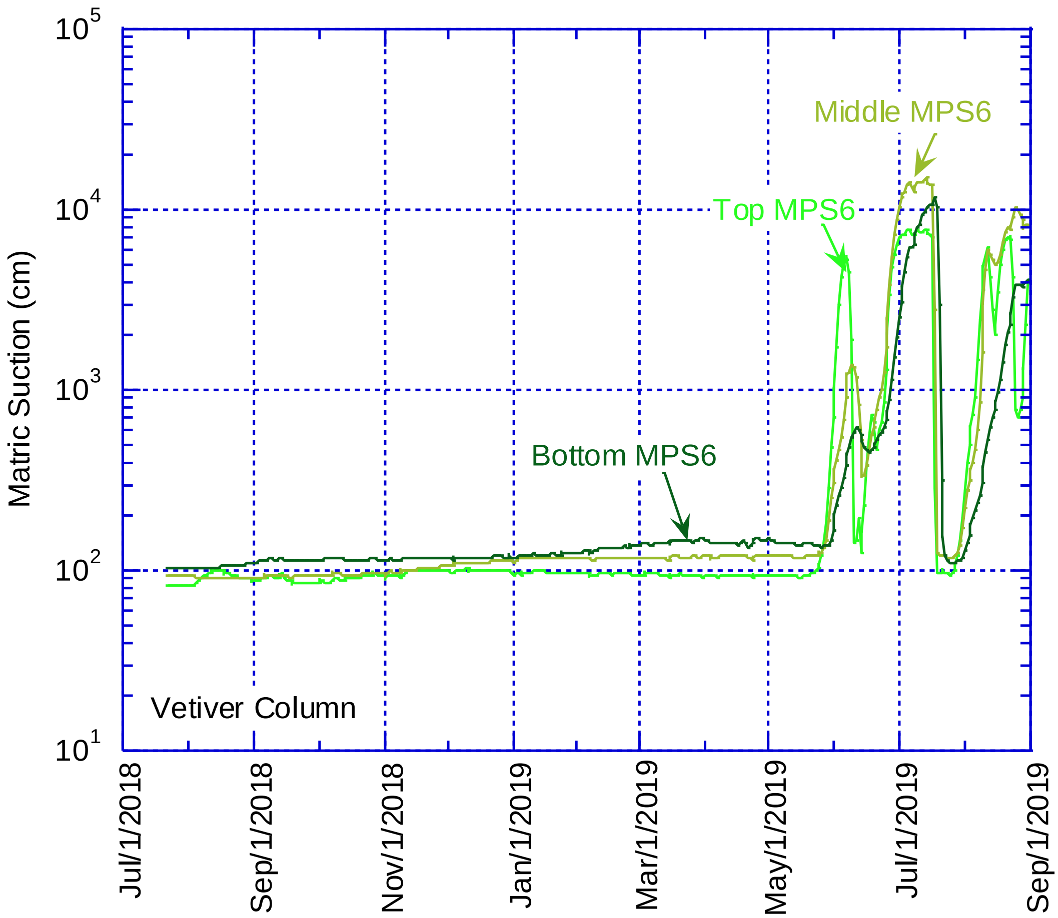

Figure 2-16: Vetiver column matric suction measurements.

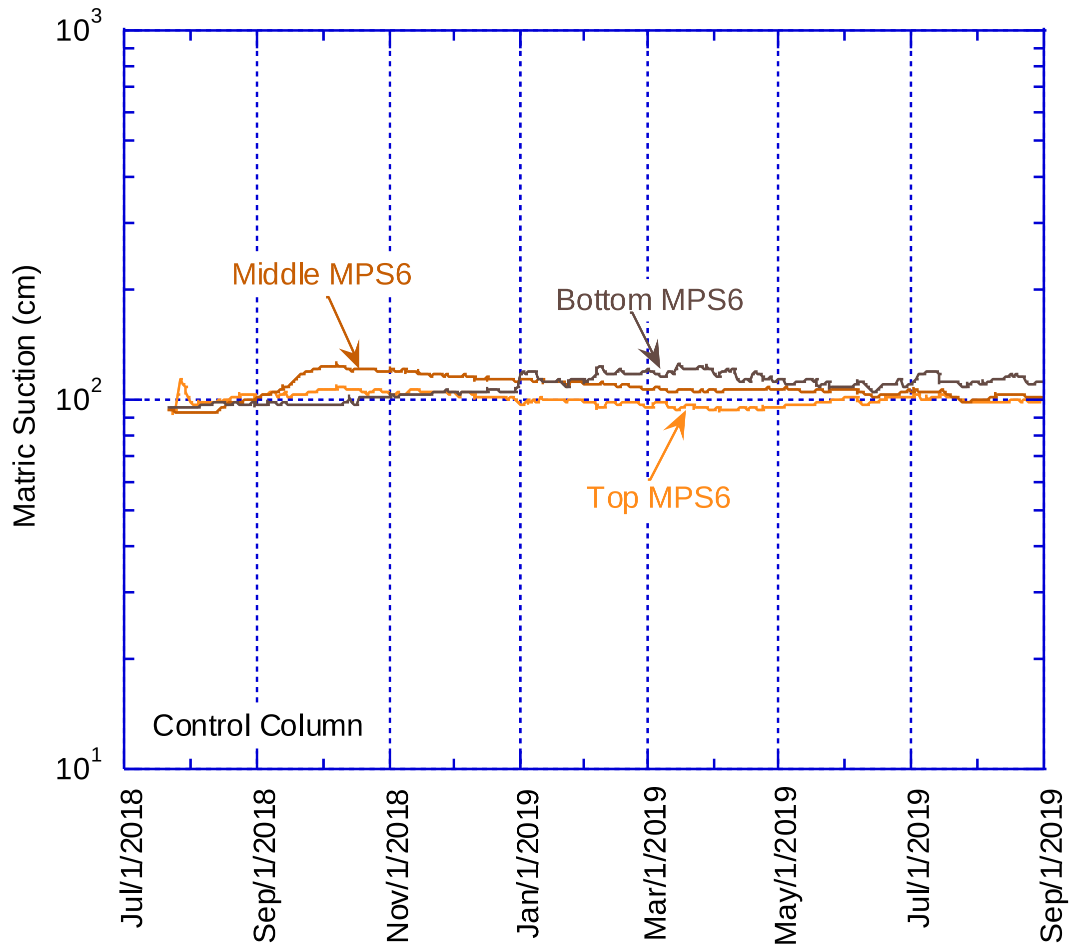

Figure 2-17: Control column matric suction measurements.

Water Balance Evaluation

Percolation was measured manually from graduate cylinders used to collect percolation. Soil water storage (SWS) of compacted sandy silt layer of each column was estimated by integrating water contents measured by three TDR sensors over the entire depth of the layer. Total water applied during the experiment was obtained from the precipitation gauge and 23 cm irrigation applied to the columns during the drought in late summer of 2019 to keep the plants alive. Water balance equation 2-1 was used to estimate ET.

Figure 2-18 shows the SWS for the three columns. The porosity θ_s of the storage layer is around 0.46. During the first 10 months of the study period (July 2018 to May 2019), SWS of all three columns remained about the same and in the range of 25 cm to 27 cm which corresponds to about 72% to 78% degree of saturation. During late May 2019, due to drought, SWS of both vetiver and switchgrass columns decreased to 11 cm and 15 cm (degrees of saturation ~ 31% and 43%), respectively. During this period, percolation from both vetiver and switchgrass columns was zero. Hence, the decrease in SWS observed for both planted columns can be attributed to water uptake by the plants. During this period, the SWS drop pattern of both planted columns was about the same but the reduction in SWS from the vetiver column was greater. Another major reduction in SWS of vetiver and switchgrass columns was observed starting early June 2019. Hence, 23 cm of irrigation was applied on July 17, 2019 to all three columns to keep the plants alive.

During this period when vetiver and switchgrass showed major drop in SWS, the control showed no reduction in the SWS. The degree of saturation of the control column storage layer stayed about 72% to 78%. This indicates that during the drought, plants used the water from the storage layer. It may show that if excess water is available, water uptake is masked by evaporation from the soil. However, during drought when water is in demand, plants use the water that is stored in the storage when evaporation at the surface may not be able to draw water from deeper depths under the action of capillarity.

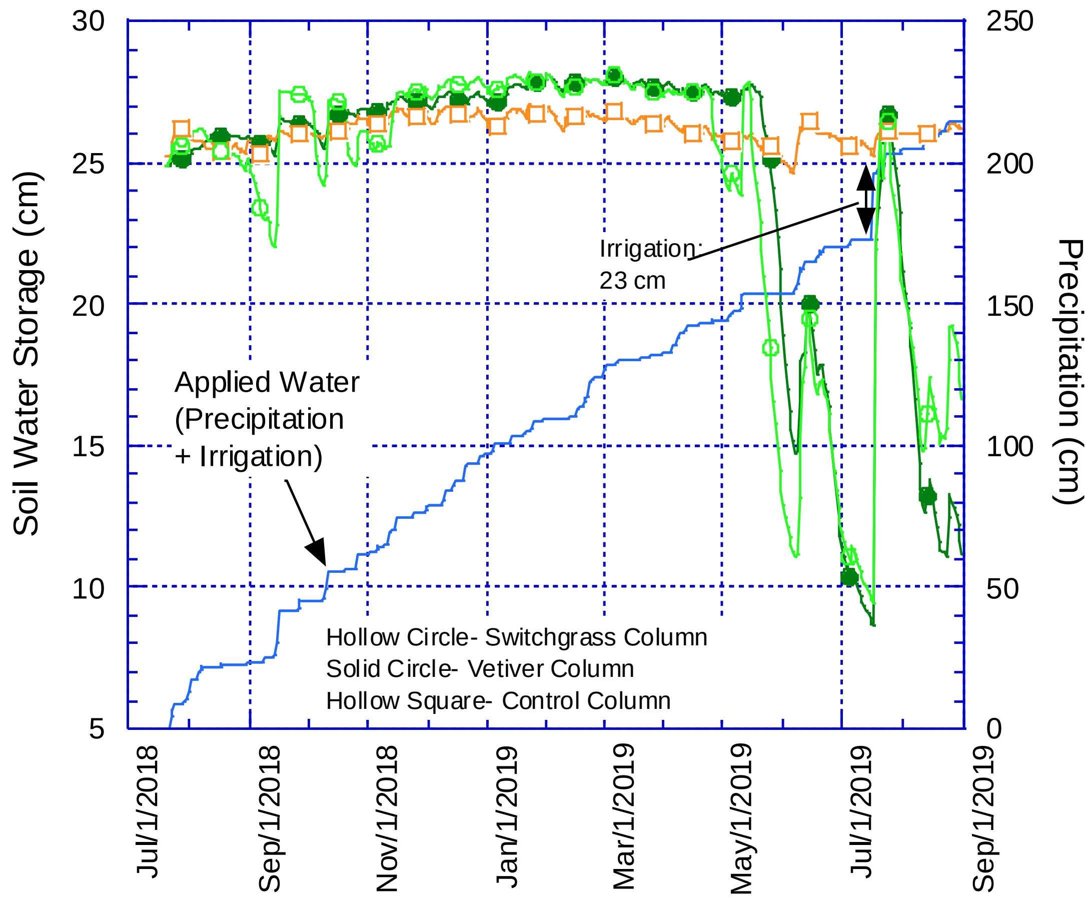

Figure 2-18: Soil water storages for control, vetiver and switchgrass columns.

Figure 2-19 shows the measured percolation and Fig. 2-20 shows the estimated ET for all three columns. Percolation for control, switchgrass and vetiver columns were 45.5, 51, and 42.2 cm respectively. ET (for vegetated columns) or evaporation (of the control column) was estimated by subtracting the change in soil water storage and total percolation from total water applied during the 14-month period (Equation 2-1). Estimated ET or E for control, switchgrass and vetiver columns are 167.9, 171.5, and 185.7 cm respectively. This data shows that when plants are under stress due to drought, plants uptake water from the storage layer. Hence, ET from both vetiver and switchgrass columns significantly increased in comparison to the bare column during the period when drought occurred.

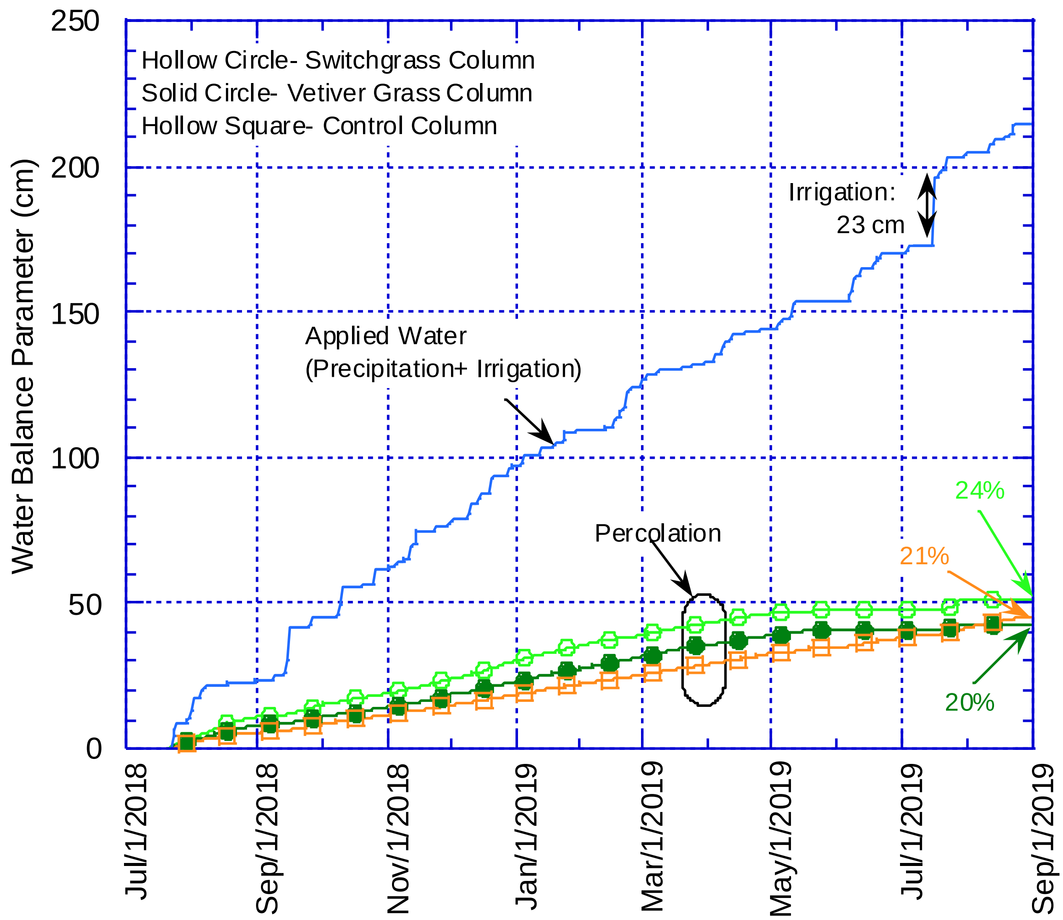

Figure 2-19: Percolation of control, vetiver and switchgrass columns.

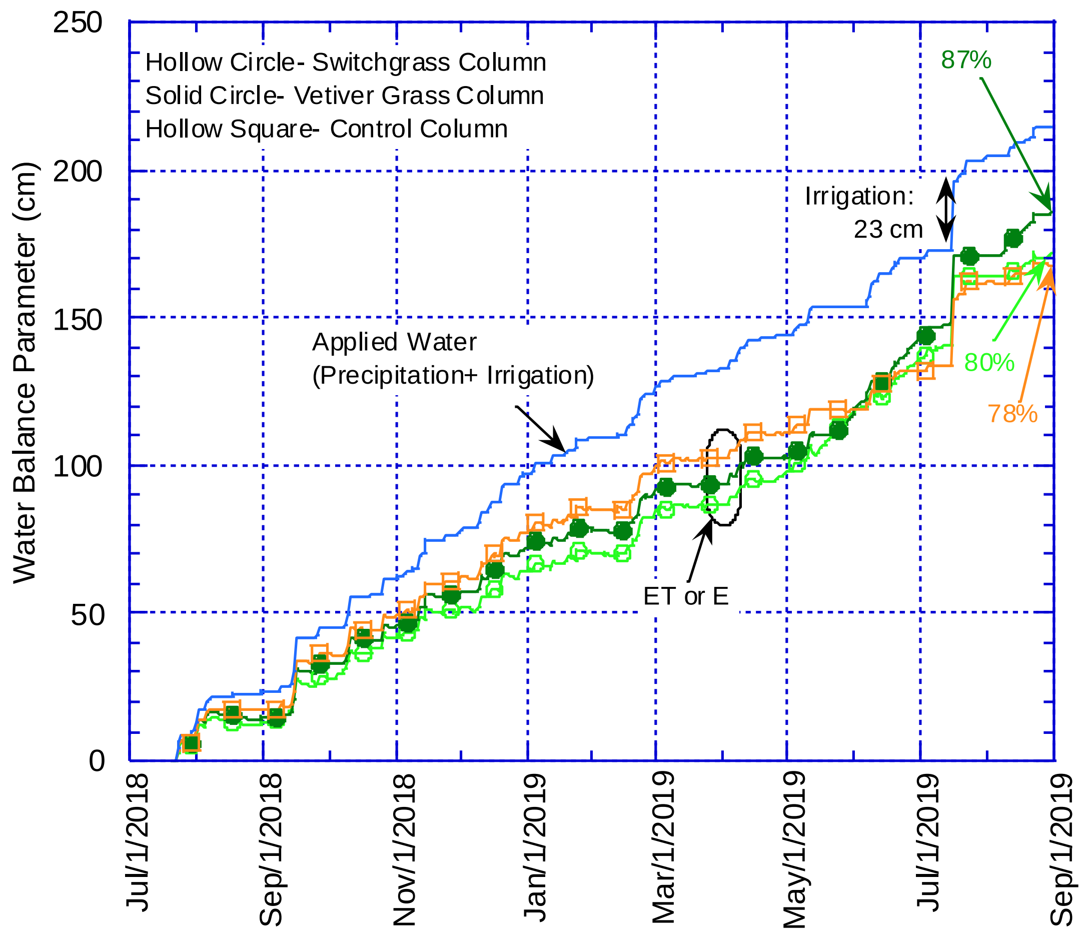

Figure 2-20: Estimated ET of control, vetiver and switchgrass columns.

Figure 2-21 and 2-22 present monthly percolation and ET for all three columns, respectively. Figure 2-21 shows that for July to March, control column has the lowest percolation. On the other hand, starting with the growing season in March 2019, percolation from both vegetated columns dropped significantly due to drought that began in late May 2019 and water uptake from the storage layer by both plants during the growing season. Monthly estimated ET of vetiver and switchgrass columns and evaporation of control column is presented in Figure 2-22. Figure 2-22 shows that monthly ET of all three columns is about the same until April 2019. However, after April 2019, the ET from vetiver and switchgrass columns exceeds evaporation from the control column. In April 2019, the vetiver and switchgrass were about 50% and 75% of their mature height. In mid-July, all columns were irrigated with 23-cm of water to keep the plants alive.

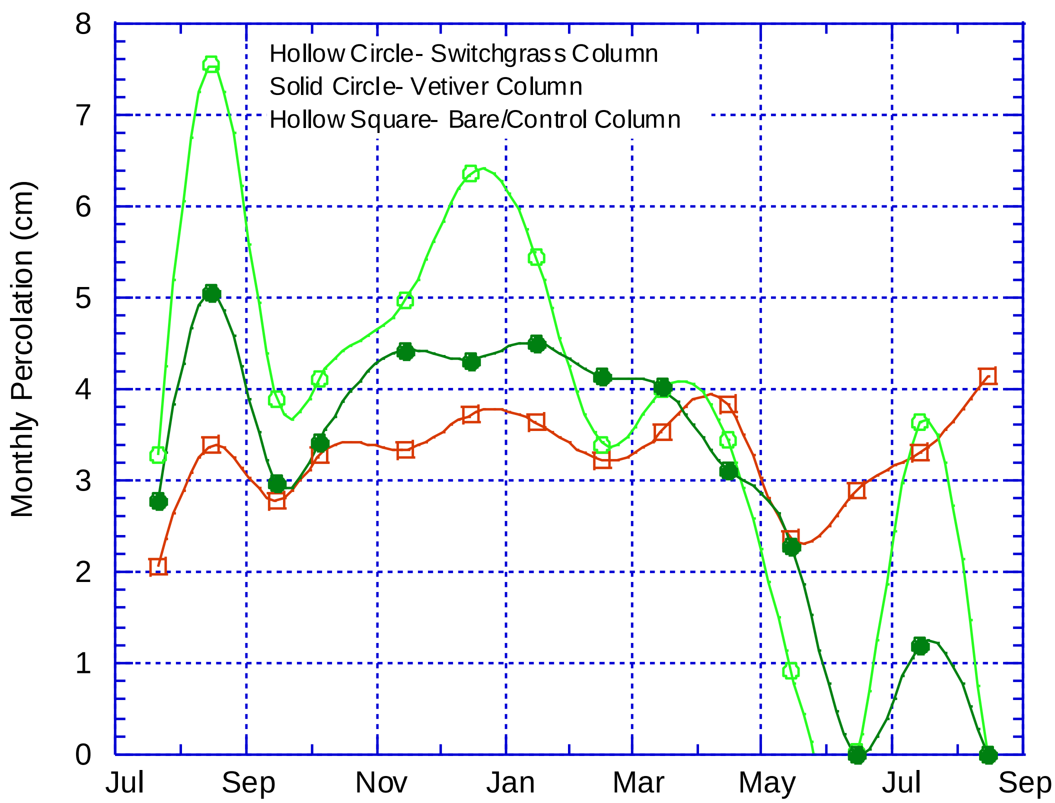

Figure 2-21: Monthly percolation of Vetiver, Switchgrass and control columns.

In order to further investigate the effect of plants on the water balance of the columns, ET, evaporation and percolation are presented in Table 2- 4 for two time periods: (a) the entire 14-month testing period; and (b) only the 5-month growing season from May to Sep. 2019. During the 14-month testing period, there was very little difference between the percolation from control and the vegetated columns. However, ET from vetiver was slightly higher than control and switchgrass columns. However, if only the growing season is considered, percolation from control was 11% to 13% higher compared to switchgrass and vetiver columns, respectively. Similarly, during the growing season, ET from control was 24% and 37% less compared to switchgrass and vetiver columns.

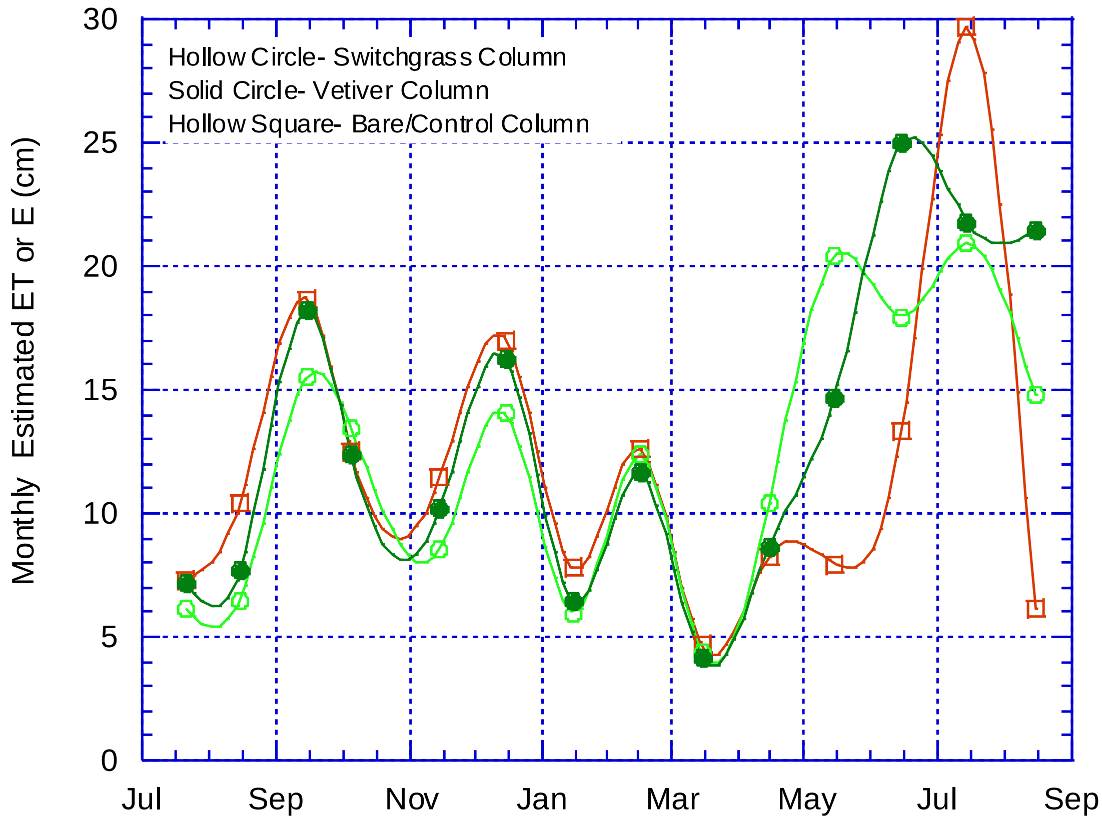

Figure 2-22: Monthly estimated ET from vetiver, switchgrass columns and evaporation from control column.

The noticeable difference in water balance between the two time periods presented in Table 2-4 maybe due to: (1) the plants were not fully established earlier in the monitoring period; (2) plants grew during the latter part of the monitoring period and established the root mass needed for water uptake; and (3) the drought in the later part of the monitoring period stressed the plants and the plants depleted the soil water storage during the drought.

Table 2-4: Water balance of three columns split in two time frames.

	Column	E or ET (cm)	Perc-olation (cm)	Applied Water (cm)	E or ET (% of Applied Water)	Perc-olation (% of Applied Water)
July 2018- Sep 2019	Switchgrass	171.5	51.0	214.3	80%	24%
	Vetiver	185.7	42.2		87%	20%
	Control	167.8	45.5		78%	21%
May 2019-Sep 2019	Switchgrass	73.7	4.5	70.1	105%	6.5%
	Vetiver	83.0	3.3		118%	4.7%
	Control	57.0	12.7		81%	18.1%

ET and Percolation Rates

Monthly ET rates from the planted columns and monthly evaporation rates of the control column alongside with monthly percolation rates of all three columns were calculated. The data are summarized in Table 2-5 and plotted in Figures 2-23 and 2-24. The 14-month average ET and percolation rates are presented in Table 2-6. Until April 2019, control column evaporation rate was higher than the planted columns. As the growing season approaches and both vetiver and switchgrass plants get more mature and established, estimated ET rates of both planted columns start to exceed evaporation rate of control column from April 2019 and after. On 17 July 2019, 23 cm of irrigation was applied to all three columns. The irrigation water caused a sudden jump in evaporation rate of the control column because it was around 70% saturated at the time of the irrigation, as a result the water was ponded on the control column and a major part of it was evaporated. However, since at the time of the irrigation, both planted columns were relatively dry (volumetric water content was ~ 0.06), the irrigated water, saturated the planted columns' storage layer. Hence in July 2019, ET of planted columns decreased, and percolation was observed after a one-month long no percolation period.

Table 2-5: Monthly percolation and ET rates for switchgrass, vetiver grass and control columns.

Month	Applied Water (cm/day)	**ET (cm/day)**			**Percolation (ml/day)**		
		Switchgrass	Vetiver	Control	Switchgrass	Vetiver	Control
Jul-18	0.85	0.51	0.60	0.61	131.61	123.29	91.63
Aug-18	0.45	0.22	0.26	0.35	121.28	89.97	59.98
Sep-18	0.72	0.52	0.61	0.62	62.64	52.65	49.31
Oct-18	0.54	0.45	0.41	0.42	65.97	60.64	57.98
Nov-18	0.50	0.29	0.34	0.38	79.97	78.64	59.31
Dec-18	0.68	0.47	0.54	0.57	101.96	76.64	65.97
Jan-19	0.40	0.20	0.21	0.26	87.30	79.97	64.64
Feb-19	0.52	0.41	0.39	0.42	54.64	73.31	57.31
Mar-19	0.26	0.15	0.14	0.15	63.97	71.31	62.64
Apr-19	0.39	0.35	0.29	0.27	55.31	55.31	67.97
May-19	0.32	0.68	0.49	0.27	14.66	40.65	41.98
Jun-19	0.56	0.60	0.83	0.45	0.67	0.00	51.31
Jul-19	1.11	0.70	0.73	0.99	58.64	21.33	58.64
Aug-19	0.35	0.49	0.72	0.20	0.00	0.00	73.31

Table 2-6: ET and percolation averages for switchgrass, vetiver and control columns over the 14-month monitoring period.

ET (cm/day)			**Percolation (ml/day)**		
Switchgrass	Vetiver	Control	Switchgrass	Vetiver	Control
0.42	0.46	0.41	60.27	55.13	59.34

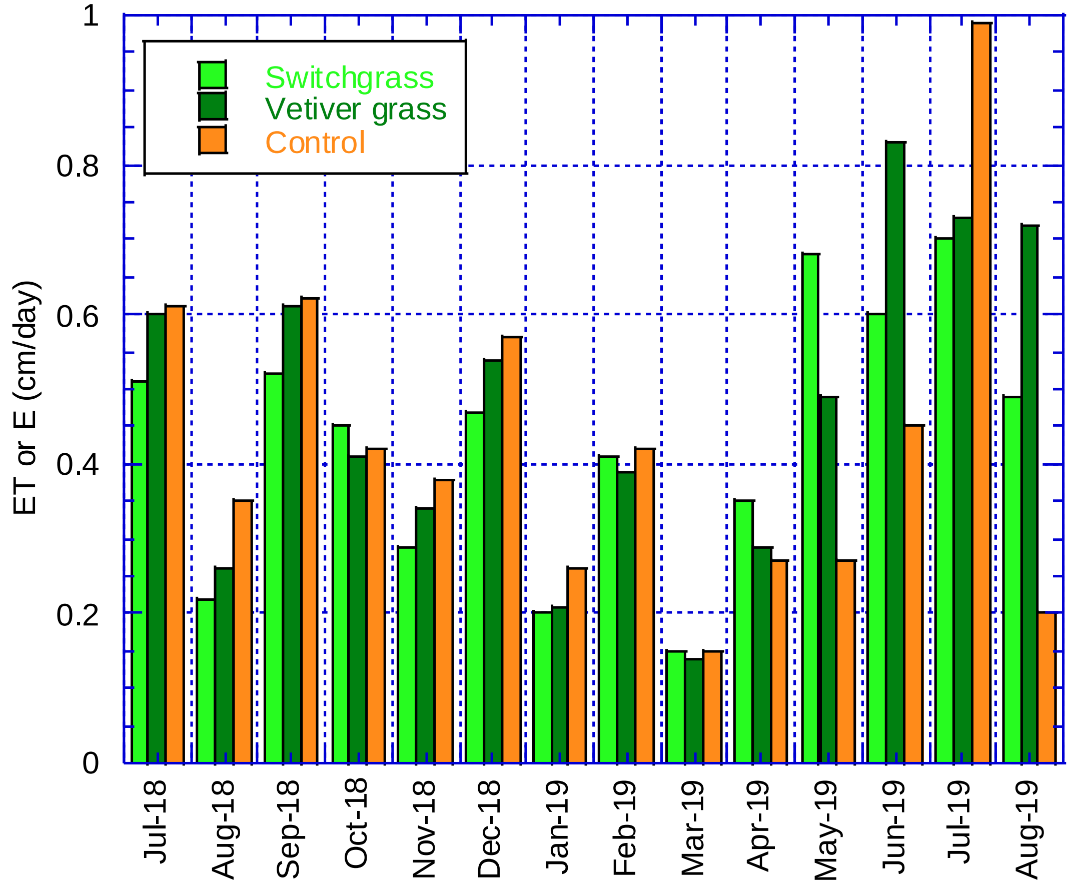

Figure 2-23: Monthly ET rates of switchgrass, vetiver grass and control columns.

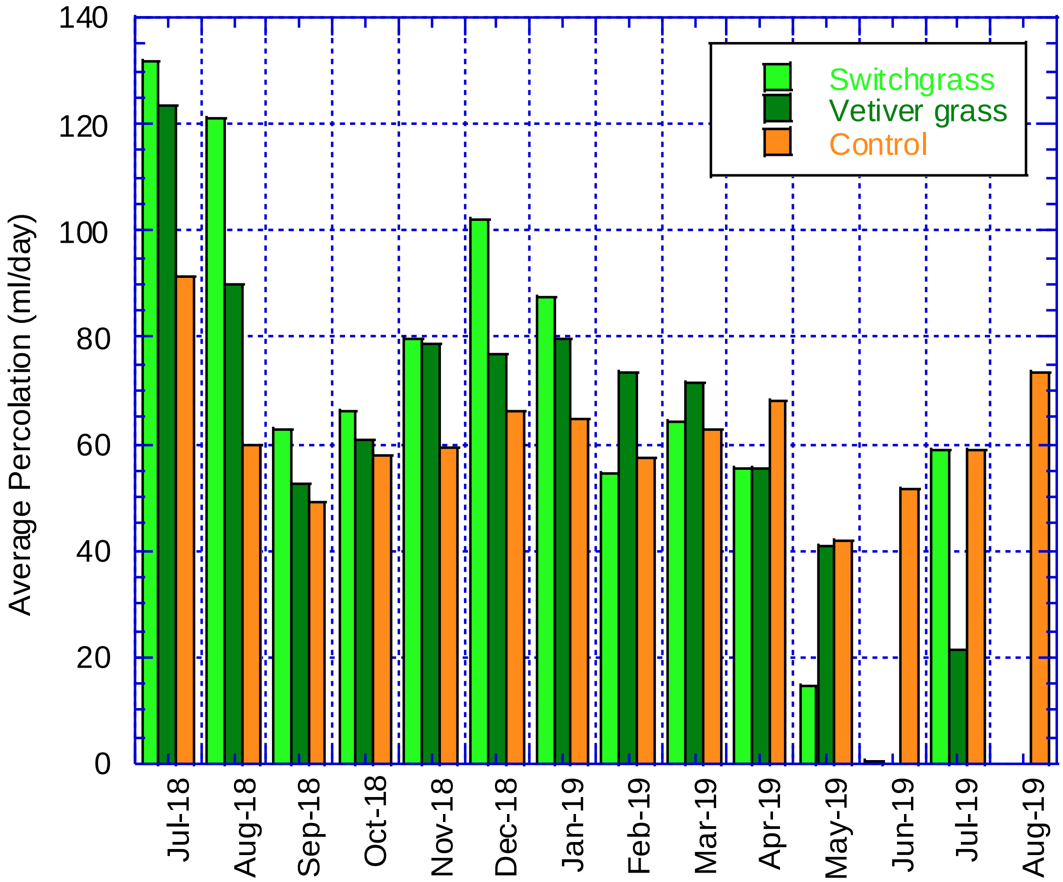

Figure 2-24: Monthly average percolation for switchgrass, vetiver grass and control columns.

SUMMARY AND CONCLUSIONS

This paper presents a large-scale column study to evaluate the effect of plants on the water balance of 1.4 m thick two-layered soil columns which were designed to replicate an ET cover. One column is bare or the control, the second column is planted with vetiver grass and the third column is planted with switchgrass. Climatological and water balance data has been collected from these columns for a 14-month period. During the 14-month data monitoring period, the estimated ET for the vetiver and switchgrass columns were about 2% and 9% higher than the bare column showing that plants can improve the hydrological performance of the vegetated columns. And, it must be noted that by the end of the monitoring period, vetiver and switchgrass reached about 50% and 75% of their mature height, respectively, and the plants were not fully established. Hence, the performance could improve as the plants grow to maturity.

In addition to the 14-month data, water balance of the columns was analyzed for the five-month growing season (May 2019- September 2019) during which period both plants had a steady growth. During the growing season, percolation of control column was about 12% to 14% higher than switchgrass and vetiver columns, respectively. The evaporation was 23% and 37% lower than switchgrass and vetiver columns, respectively. Over the study period of 14 months, the average estimated ET rates for control, switchgrass, and vetiver columns were 0.41 cm/day 0.42 cm/day, and 0.46 cm/day, respectively.

REFERENCES

40 CFR 258.60. (2009). "Title 40: Protection of Environment-PART 258—Criteria For Municipal Solid Waste Landfills." <https://www.ecfr.gov/cgi-bin/text-idx?SID=558a9db9fee0e89333a2588d0fba87c4&mc=true&node=sp40.27.258.d&rgn=div6> (Oct. 7, 2018).

Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P., Lyles, B. F., and Rock, S. A. (2004). "Field Water Balance of Landfill Final Covers." *Journal of Environment Quality*, 33(6), 2317.

Apiwantragoon, P., Benson, C. H., and Albright, W. H. (2015). "Field hydrology of water balance covers for waste containment." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(2).

Banerjee, R., Goswami, P., Lavania, S., Mukherjee, A., and Lavania, U. C. (2019). "Vetiver grass is a potential candidate for phytoremediation of iron ore mine spoil dumps." *Ecological Engineering*, Elsevier, 132(January), 120–136.

Banerjee, R., Goswami, P., Pathak, K., and Mukherjee, A. (2016). "Vetiver grass: An environment clean-up tool for heavy metal contaminated iron ore mine-soil." *Ecological Engineering*, Elsevier B.V., 90, 25–34.

Benson, C. H., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. H. (2007). "Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 133(4), 349–359.

Bréda, N. J. J. (2003). "Ground-based measurements of leaf area index: A review of methods, instruments and current controversies." *Journal of Experimental Botany*, 54(392), 2403–2417.

Bwire, K. M., Njau, K. N., and Minja, R. J. A. (2011). "Use of vetiver grass constructed wetland for treatment of leachate." *Water science and technology : a journal of the International Association on Water Pollution Research*, 63(5), 924–30.

Campbell Scientific Inc. (2011). *Instruction Manual, CS650 and CS655 Water Content Reflectometers,*. Logan , Utah.

Day, W. (1977). "A direct reading continuous flow porometer." *Agricultural Meteorology*, 18, 81–89.

Decagon Devices Inc. (2017). *Dielectric Water Potential Sensors*.

Duncan, J. P., Burk, K. W., Chamness, M. A., Fowler, R. A., Fritz, B. G., Hendrickson, P. L., Kennedy, E. P., Last, G. V, Poston, T. M., Sackschewsky, M. R., Scott, M. J., Snyder, S. F., Sweeney, M. D., and Thorne, P. D. (2007). *Hanford Site National*

Environmental Policy Act (NEPA) Characterization.

Erdogan, R., and Zaimoglu, Z. (2015). "The Characteristics of Phytoremediation of Soil and Leachate Polluted by Landfills." *Advances in Bioremediation of Wastewater and Polluted Soil*, InTech.

Fayer, M. J. (2000). *UNSAT-H Version 3.0: Unsaturated Soil Water and Heat Flow Model. Theory , User Manual , and Examples*. *Model Manual*.

Granley, B. A., and Truong, P. N. (2012). "A Changing Industry: On-site Phytoremediation of Landfill Leachate Using Trees and Grasses-Case Studies." Global Waste Management Symposium, 5.

Hauser, V. L., Weand, B. L., and Gill, M. D. (2001). "Natural Covers for Landfills and Buried Waste." *Journal of Environmental Engineering*, American Society of Civil Engineers, 127(9), 768–775.

Hui, D., Yu, C.-L., Deng, Q., Dzantor, E. K., Zhou, S., Dennis, S., Sauve, R., Johnson, T. L., Fay, P. A., Shen, W., and Luo, Y. (2018). "Effects of precipitation changes on switchgrass photosynthesis, growth, and biomass: A mesocosm experiment." *PloS one*, Public Library of Science, 13(2), e0192555.

Khire, M. V. (2016). "Geoclimatic Design of Water Balance Covers for Municipal Solid Waste Landfills in Texas." *UNCC-CEE-14-100, Lone Star Chapter of the Solid Waste Association of North America, Aug*, 334.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (1997). "Water Balance Modeling of Final Earthen Covers." *Journal of Geotechnical and Geoenvironmental Engineering*, 123(8), 744–754.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (2000). "Capillary Barriers: Design Variables and Water Balance." *Journal of Geotechnical and Geoenvironmental Engineering*, 126(8), 695–708.

Kiniry, J. R., Burson, B. L., Evers, G. W., Williams, J. R., Sanchez, H., Wade, C., Featherston, J. W., and Greenwade, J. (2007). "Coastal bermudagrass, bahiagrass, and native range simulation at diverse sites in Texas." *Agronomy Journal*, 99(2), 450–461.

Leuning, R., and Foster, I. (1990). "Estimation of transpiration by single trees: comparison of a ventilated chamber, leaf energy budgets and a combination equation." *Agricultural and Forest Meteorology*, 51(1), 63–86.

Licht, B. L., Aitchison, E., Schnabel, W., English, M., and Kaempf, M. (2001). "Landfill Caping with Woodland Ecosystems." *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 5(October), 175–184.

Meerdink, J., Benson, C., and Khire, M. (1996). "Unsaturated Hydraulic Conductivity of Two Compacted Barrier Soils." *Journal of Geotechnical Engineering*, (J. Meerdink, ed.), 122(7), 565–576.

Mijares, R. G., and Khire, M. V. (2012). “Field Data and Numerical Modeling of Water Balance of Lysimeter versus Actual Earthen Cap.” *Journal of Geotechnical and Geoenvironmental Engineering*, 138(8), 889–897.

Mijares, R. G., Khire, M. V, and Johnson, T. (2011). “Field-Scale Evaluation of Lysimeters Versus Actual Earthen Covers.” *Geotechnical Testing Journal*, 35(1).

Nadezhdina, N., Al-Okaishi, A., and Madera, P. (2018). “Sap Flow Measurements in a Socotra Dragon’s Blood Tree (Dracaena cinnabari) in its Area of Origin.”

Renner, M., Hassler, S. K., Blume, T., Weiler, M., Hildebrandt, A., and Guderle, M. (2016). “Dominant controls of transpiration along a hillslope transect inferred from ecohydrological measurements and thermodynamic limits.” 2063–2083.

Rock, S. A. (2003). “Vegetative Covers for Waste Containment.” *Phytoremediation. Advances in Biochemical Engineering/Biotechnology*, Springer, Berlin, Heidelberg, 78(1), 157–170.

Sânchez-Carrillo, S., Âlvarez-Cobelas, M., Benitez, M., and Angeler, D. G. (2001). "A simple method for estimating water loss by transpiration in wetlands". *Hydrological Sciences~Journal-des Sciences Hydrologiques*.

Smeal, C., Hackett, M., and Truong, P. (2017). “Vetiver System for Industrial Wastewater Treatment in Queensland , Australia.” (September), 1–13.

Smesrud, J. K., Benson, C. H., Albright, W. H., Richards, J. H., Wright, S., Israel, T., and Goodrich, K. (2012). “Using pilot test data to refine an alternative cover design in Northern California.” *International Journal of Phytoremediation*, 14(SUPPL.), 76–93.

Truong, P. (2019). “Vetiver system for environmental protection.” *Vetican Consulting, Brisbane*.

United States Department of Agriculture (USDA). (2018). “Switchgrass Fact Sheet.” <https://plants.usda.gov/core/profile?symbol=pavi2> (Jan. 10, 2017).

US EPA. (2017). “Municipal Solid Waste Landfills.” <https://www.epa.gov/landfills/municipal-solid-waste-landfills> (Dec. 5, 2018).

USDA, NRCS, N. P. D. (2003). *Cheatgrass Fact Sheet*.

Vogel, T., Votrubova, J., Dohnal, M., and Dusek, J. (2017). “A Simple Representation of Plant Water Storage Effects in Coupled Soil Water Flow and Transpiration Stream Modeling.” *Vadose Zone Journal*, GeoScienceWorld, 16(5), 0.

PAPER NO. 3: WATER BALANCE MODELING OF FIELD-SCALE EARTHEN COVER PLANTED WITH VERIVER GRASS

ABSTRACT

Alternative landfill final covers made up of native soils have been increasingly permitted due to the financial benefits and environmental sustainability. However, often due to lack of validated transpiration models, practitioners ignore the effect of plants when equivalency analysis is carried out for permitting. This study focused on modeling water balance of instrumented test sections of earthen covers. Two 11 m x 11 m test sections, one bare and the other planted with vetiver grass, were constructed at a site located in the southcentral U.S. This location has humid climate. The key objective of this paper is to validate the most commonly used water balance model UNSAT-H for earthen cover located in humid climate with and without plants. Field water balance for the two test sections was collected over a period of one year. The field data indicated that during the one-year monitoring period, there was very little difference between the percolation, soil water storage and ET for the control and vetiver test sections. The UNSAT-H model was able to predict percolation of both control and vetiver test sections relatively accurately. The model underestimated soil water storage for both test sections. Simulated ET for the control was overestimated by 19% and it was underestimated by 9% for the vetiver test section.

INTRODUCTION

Alternative final covers (AFCs) for landfills also known as evapotranspirative (ET) covers which are usually constructed using native soils have been permitted in many states such as California, Arizona, Colorado, Nevada, Iowa, Michigan and Texas for decades (Albright et al. 2004; Khire 2016; Mijares and Khire 2012).According to Resource Conservation Recovery Act (RCRA) Subtitle D regulations, an AFC is permitted if it is proven via field testing and/or numerical modeling that the long-term percolation from the AFC is equivalent to the RCRA Subtitle D or "prescriptive" cover (US EPA 2017). Usually, for evaluating the hydraulic behavior of an AFC using field data, lysimeters are built to measure water balance parameters: precipitation (P), surface runoff (R), change in soil water storage (ΔS), and percolation (P_r) through the cover. Water balance of a lysimeter is expressed in Equation 3-1:

$$ET = P - P_r - R - \Delta S \qquad (3\text{-}1)$$

Transpiration and evaporation are usually combined as ET because it is relatively challenging to measure these variables separately. Evaporation and transpiration occur simultaneously in a vegetated landfill cover. To demonstrate percolation equivalency of an AFC, often numerical models such as UNSAT-H are used. These numerical models require input of climatic data as well as input of transpiration parameters to simulate ET. While transpiration parameters can be measured, there have been relatively few studies on validation of predicted transpiration by water balance models such as UNSAT-H for landfill cover applications. Hence, transpiration of plants is often ignored by practitioners when designing AFCs (Khire 2016). Ignoring transpiration in the design process of a cover is considered conservative and may not be favorable to the landfill owners/operators for landfills located in humid or sub-humid climates. That is because due to relatively high precipitation, it is unlikely to satisfy the percolation equivalency by ignoring the effect of plants on removal of water from the cover via transpiration. It is also possible that the approach of ignoring the effect of plants is not conservative because plant canopy may impede evaporation and plant transpiration may not be enough to compensate for the loss in evaporation.

In general, it is the perception of the professionals in landfill industry that plants on landfill covers help with reducing leachate generation. Since 1990's, plants have been introduced on landfill covers for the main goal of reduction in leachate generation as well as leachate treatment (Erdogan and Zaimoglu 2015; Granley and Truong 2012; Licht et al. 2001).

Vetiver grass has been identified as a plant which can uptake nutrients and heavy metals, and it has been successfully used in Australia, Thailand and China for municipal solid waste (MSW) leachate treatment since the 1990s (Banerjee et al. 2019; Bwire et al. 2011). Vetiver grass can develop a robust root system which helps in the uptake of leachate and improves cover function for erosion and slope stability. The roots of vetiver plant can grow up to 2.8 m in depth and the grass can grow up to 3 m in height (Truong 2019). In majority of the previous studies, vetiver is referred to as a simple, hygienic and low-cost method for chemical treatment of wastewater. However, vetiver has not been tested on ET covers to potentially enhance the water balance performance, i.e., to increase ET and decrease percolation.

In order to meet these objectives, a field-scale study was carried out to investigate the use of vetiver plant and its effect on water balance of an ET cover at a landfill site. The study took place in the southcentral U.S. which has humid climate. Two test sections (one bare and one planted with vetiver) were built and instrumented side by side. The cover consisted of 90 cm-thick lightly compacted native soil. Underneath the cover test sections, a gravel drainage layer underlain by a geomembrane (GM) was built as a lysimeter. Each test section was instrumented with two sensor nests: downslope and upslope of the lysimeter. The test sections were specifically designed and instrumented to provide high precision field data for comparative hydrological evaluation between the two test sections.

UNSAT-H model has a built-in function for partitioning PET into evaporation and transpiration which was developed based on the Hanford site's vegetation (Duncan et al. 2007; Fayer 2000). The Hanford site's vegetation community was also referred to as shrub-steppe in which cheatgrass was the dominant species. Cheatgrass is an annual grass with shallow roots and its mature height is about 10- 60 cm (USDA, NRCS 2003). Cheatgrass is very invasive, as a result at Hanford site it was reported that at many locations it crowded out native species.

The key objective of this study was to evaluate the hydrological behavior of two test sections (with vetiver and bare) and ultimately evaluate the impact of vetiver plants on the water balance. Additional objective was to validate the predictions of UNSAT-H for humid climate where vetiver was the only plant on the vegetated test section. While UNSAT-H has been validated by Fayer (2000), it was for the semi-arid conditions of Hanford Site where the plant species are different than those usually exist at humid locations.

MATERIALS AND METHODS

The field-scale experiments consisted of constructing two 90-cm thick, lightly compacted cover test sections at a landfill located in the southcentral U.S. Each test section is 11m× 11m. One section is without vegetation (control), and the other test section is planted with vetiver grass. Average annual precipitation at the site is about 126.5 cm, and the ratio of potential evapotranspiration (PET) to precipitation is about 1.4 (Khire 2016).

Field Test Sections

The vetiver grass was planted in rows and the average spacing between the plants was 45 cm. At the time of plantation, vetiver grass was about 30 cm tall. It grew to 152 cm at the of the one-year monitoring period. The control test section was bare in the beginning. However, it was covered with weeds by the end of the year. No herbicide was sprayed on the bare test section to minimize its impact on the hydraulic properties of the soil. Nevertheless, the weeds had relatively small foliage and the ground surface was visible through the weeds as the density of weeds was relatively small. For constructing the cover, a 9o-cm storage layer made of native silty clay (USCS Classification CL) mixed with topsoil was loosely compacted. Physical properties of the soil are presented in Table 3-1. The storage layer was very lightly compacted to a unit weight of ~15 kN/m^3 to promote plant growth. A 0.6 m thick pea gravel drainage layer underlain by a GM liner (lysimeter) was placed below the soil cover to collect and measure percolation. The GM has a slope of 12% towards a sump where the percolation of each test section drained. To divert the surface flow from outside the test section and to prevent runoff to be shed from the test section, a 60-cm-tall berm was constructed around the perimeter of each of the test sections. Consequently, all potential runoff infiltrated through the test sections. In Figure 3-1, the configuration of the test sections and relative locations of the instrumentation are shown.

Table 3-1:Geotechnical properties of the cover test sections.

Property	**Storage Layer**
USCS Classification	CL
D_{10} (mm)	0.003
D_{50} (mm)	0.074
D_{60} (mm)	0.15
C_u	50
C_c	2
Liquid Limit (LL)	30
Plasticity Index (PI)	10
G_s	2.53
Hydraulic Conductivity (cm/s) (Lab)	~5×10^{-5} - 1×10^{-4}
Hydraulic Conductivity (cm/s) (Field Data Analysis)	~ 0.5×10^{-4} - 4×10^{-4}

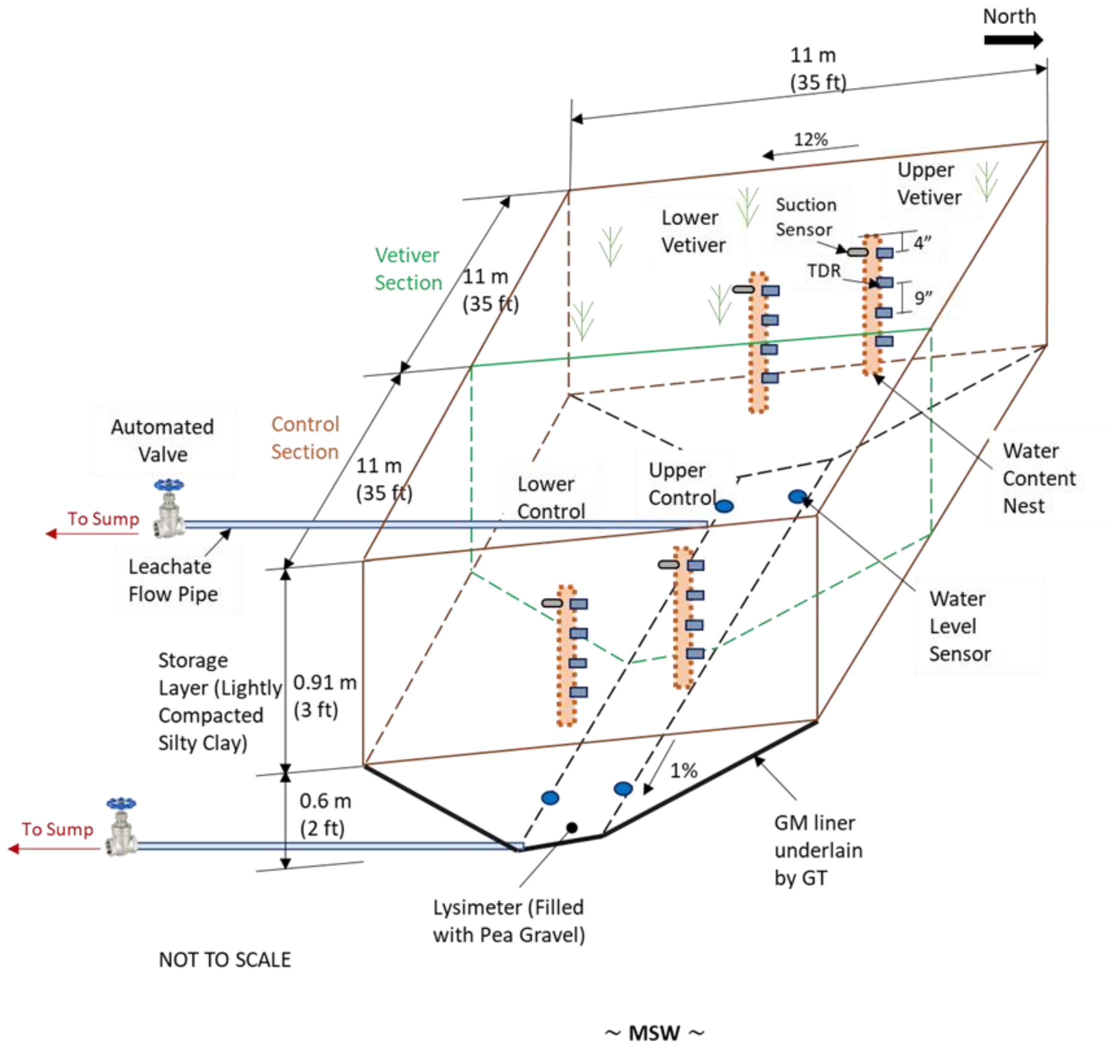

Figure 3-1: Schematic of control and vetiver field test sections.

Monitoring and Data Collection System

Sensors were installed to continuously monitor the performance of the test sections and to record and collect field data. Instrumentation included volumetric water content sensors, soil matric suction sensors, and water level sensors. Each of the two test sections have two sensor nests: one upslope and one downslope as shown in Figure 3-1. Each sensor nests included four water content sensors which are placed at 10 cm, 33 cm, 56 cm and 79 cm depths from the surface. The water content sensors used in this study are time domain reflectometry (TDR) sensors. The TDR sensors have two stainless steel rods. A soil-specific calibration curve was developed for the TDR sensors. Equation 3-2 presents the calibration equation that converts soil temperature, x (℃) and average time period, y (μs) measured by the TDR sensor to the volumetric water content (θ) of the soil.

$$\theta=1.063\,y^2-0.013xy-2.556y+0.016x+1.6 \qquad (3\text{-}2)$$

Matric suction of the storage layer was measured using capacitance-based water potential sensors. At each sensor nest, one matric suction sensor was installed at the depth of 10 cm from the surface. All sensors were connected to a datalogger programmed to record data hourly. A weather station was installed to measure precipitation, air temperature, relative humidity, and solar radiation. There was no wind speed measurement device at the site. Figure 3-2 shows precipitation recorded at the site and at a weather station of National Oceanic and Atmospheric Administration (NOAA) located about 16 km from the site. The site recorded slightly higher precipitation than the NOAA weather station.

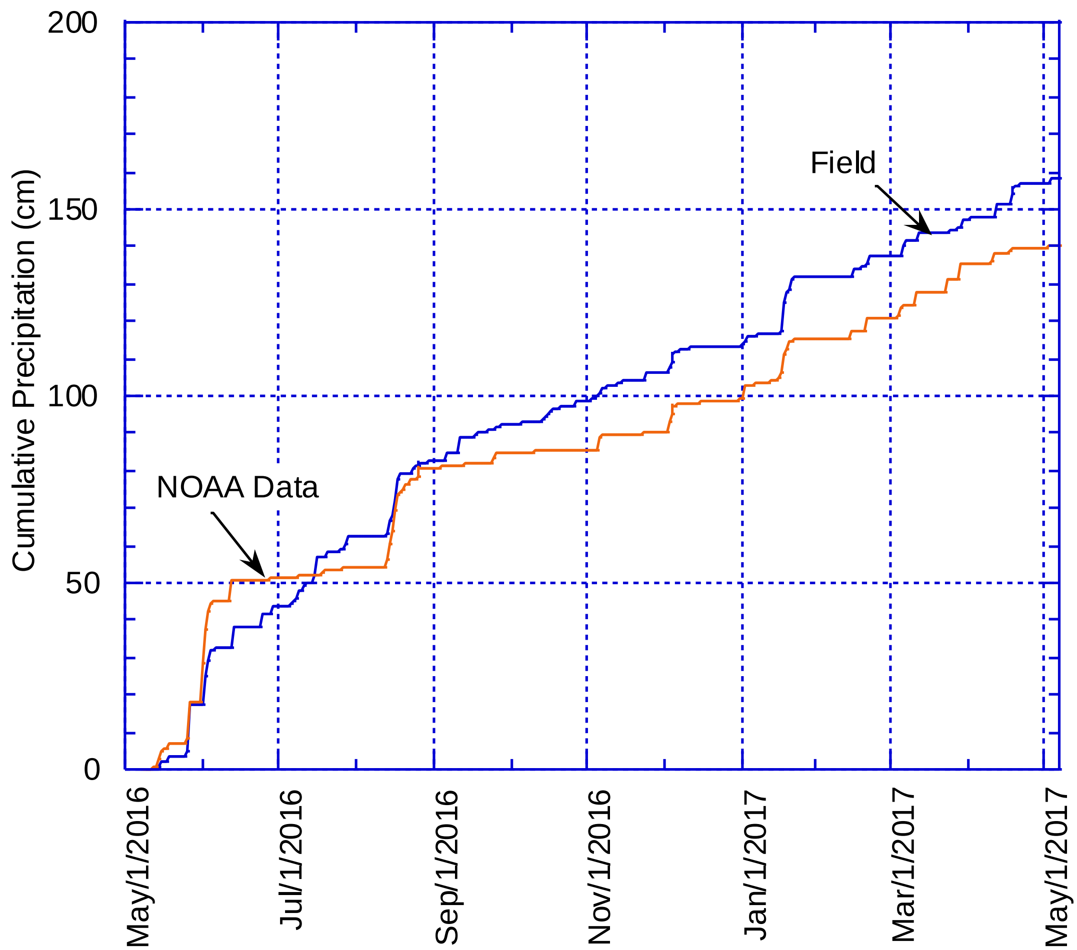

Figure 3-2: Field and NOAA recorded precipitation.

For each test section, two water level sensors were placed at the bottom of the lysimeter to measure percolation. Figure 3-3 shows the calibration curve developed for the lysimeters to convert the water level sensor readings into percolation. Bathymetry was used to develop equation presented in Fig. 3-3. Each lysimeter was designed to store and measure maximum percolation of 16.5 cm before it had to be drained. Automated valves controlled by datalogger were used to drain the lysimeters.

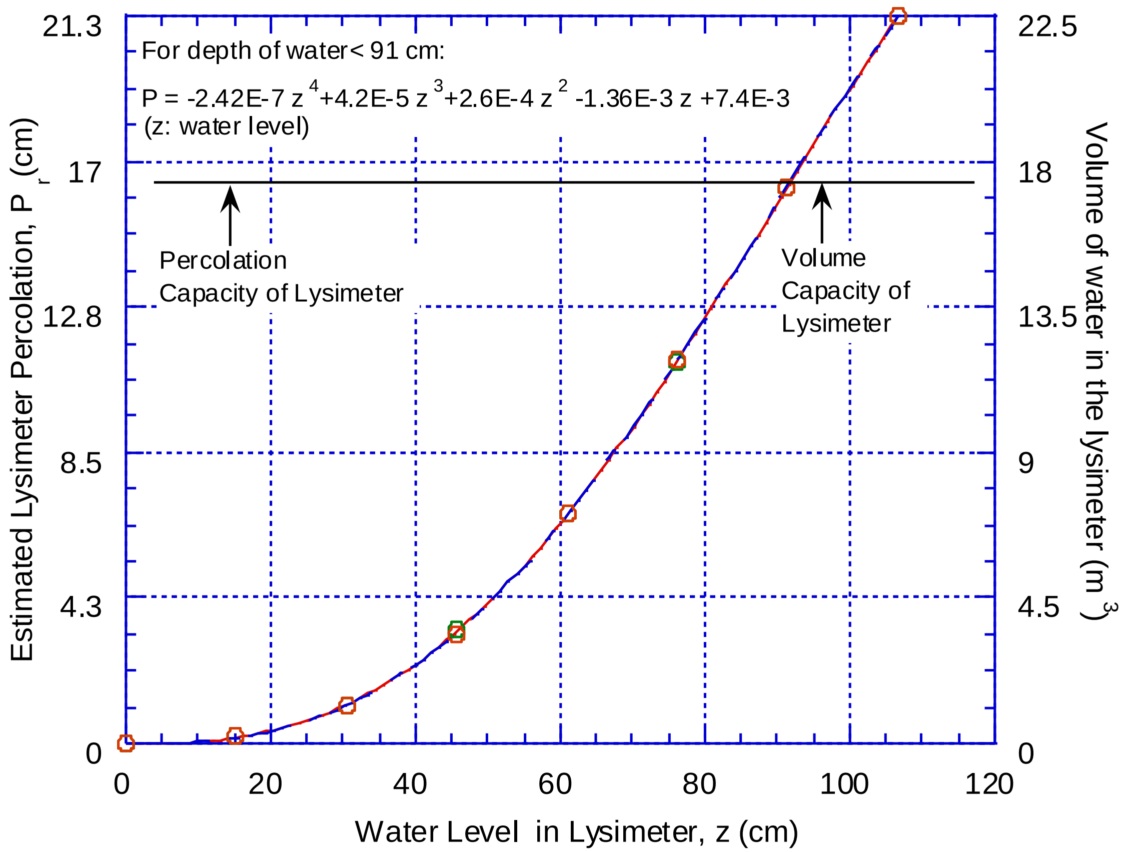

Figure 3-3: Estimating percolation from water level readings.

All sensors were connected to a measurement and logging system consisting of Campbell Scientific CR1000 datalogger. The datalogger was programmed to take readings hourly. Collected field data were transmitted to UNC Charlotte campus for data analysis using a wireless data modem.

Water Balance Modeling

Unsaturated Soil Water and Heat Flow Model (UNSAT-H) was selected for conducting the numerical modeling of the project. UNSAT-H is a finite-difference water balance model which numerically solves a modified form of Richard's equation to calculate the flow of water (or heat) through saturated or unsaturated porous media (Fayer 2000). UNSAT-H simulates water or heat flow in one-dimension and for both steady-state and transient conditions (Fayer 2000). This numerical model has been widely used for numerical simulation of cover systems for water balance performance evaluation or designing purposes (Khire 2016; Khire et al. 1997, 2000; Mijares and Khire 2012; Smesrud et al. 2012). In UNSAT-H model, both evaporation and transpiration are modeled. Evaporation is simulated in three process using Fick's law of diffusion (Fayer 2000). Transpiration is simulated based on the estimates of potential evapotranspiration (PET) which is calculated based on the climatic data (Fayer 2000). The Richard's equation solved by UNSAT-H is presented as Eq. 3-3.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(\psi)\frac{\partial \psi}{\partial z} + k(\psi) \right] - S \tag{3-3}$$

where θ is the volumetric water content, ψ is the matric suction, K(ψ) is the hydraulic conductivity of the porous media at suction ψ, z is the vertical coordinate, S is the sink term representing the plant transpiration, and t is time.

UNSAT-H Input Parameters

A schematic of the UNSAT-H conceptual model adapted from Khire et al. (1997) is presented in Figure 3-4. Input for the UNSAT-H model can be categorized as soil parameters, hydraulic properties of the soil layers, numerical simulation control parameters, initial and boundary conditions, meteorological data, and vegetative data.

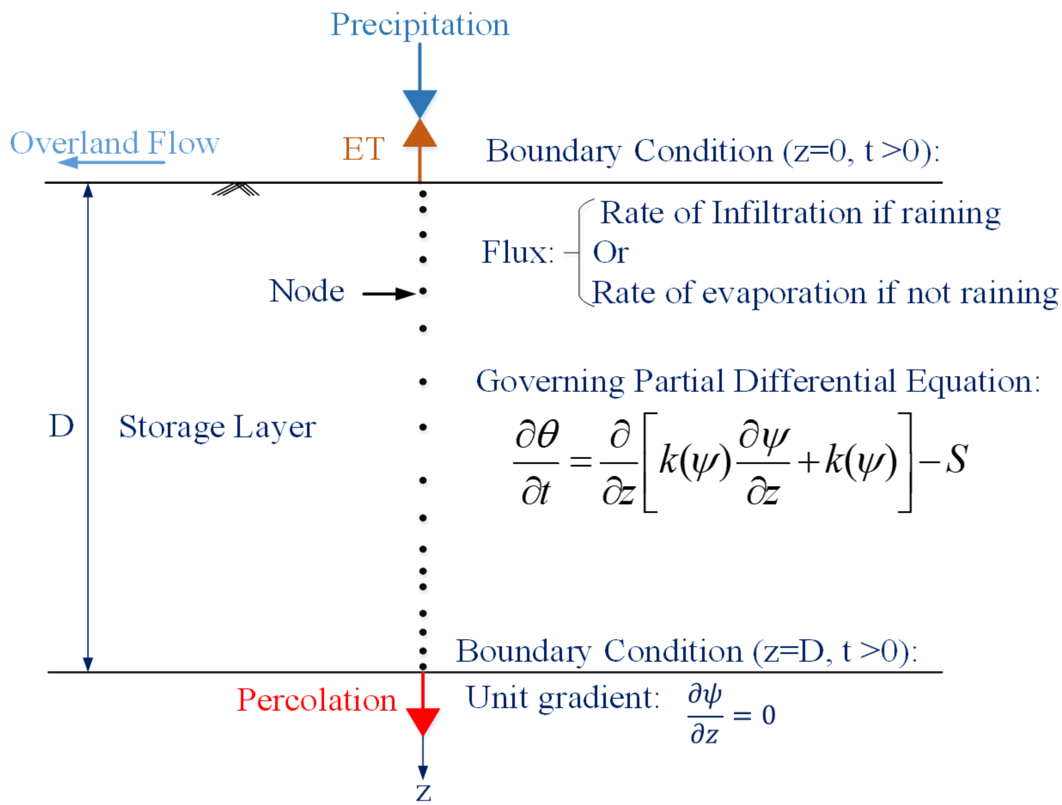

Figure 3-4: Schematic of UNSAT-H conceptual model (Khire et al. 1997).

Soil Parameters: For constructing the ET cover, native silty clay (USCS Classification CL) mixed with topsoil was used. The soil was loosely compacted by a track dozer. The thickness of the storage layer was ~ 90-cm. Because, the in-situ measurements of compaction and water contents at the time of the construction were not provided, the soil was compacted in the lab at similar effort and tested for saturated hydraulic conductivity using flexible wall permeameter. The compaction curves and the associated measured hydraulic conductivities are presented in Figure 3-5.

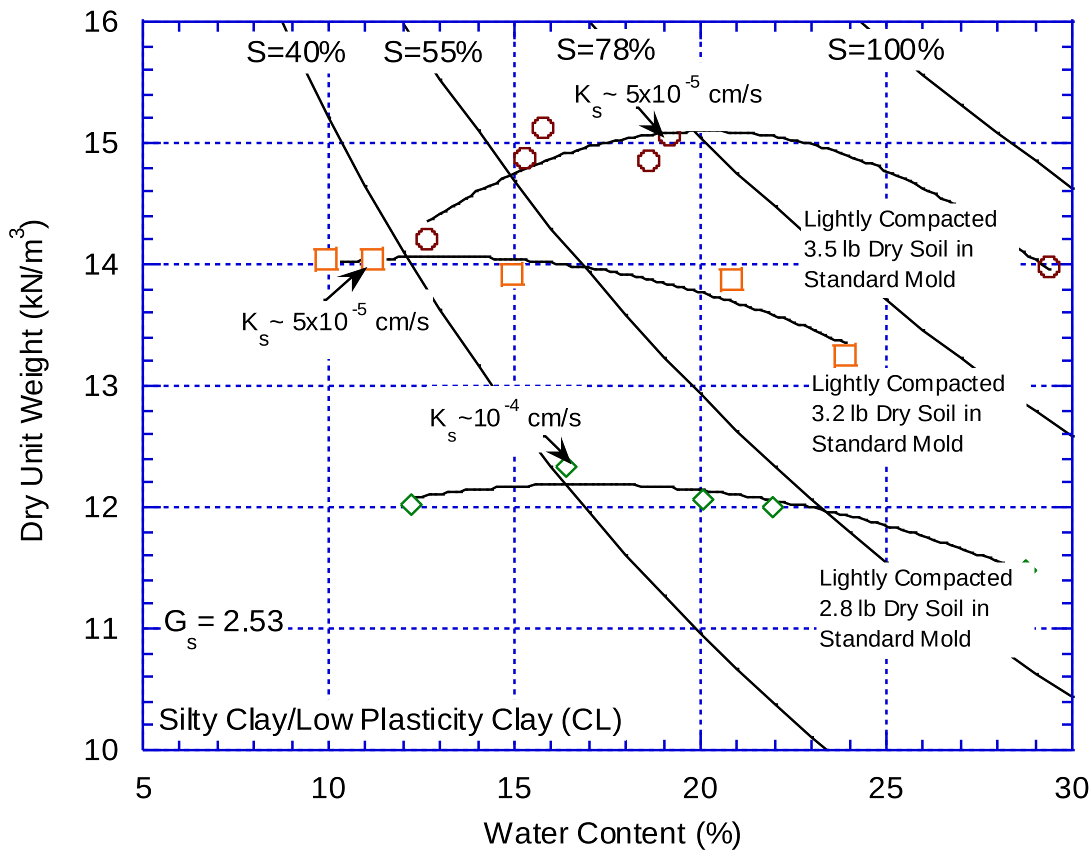

Figure 3-5: Compacted unit weights and measured hydraulic conductivities of the cover.

Hydraulic properties of the storage layer: UNSAT-H model requires soil-water characteristic curves (SWCCs) and unsaturated hydraulic conductivity functions of the cover soil as an input. The van Genuchten (1980) function was used for the SWCCs. The van Genuchten (1980) function is presented in Eq. 3-4.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{1 + (a \cdot \psi)^n} \right\}^m \tag{3-4}$$

where θ_s is the saturated volumetric water content, θ_r is the residual water content, ψ is the matric suction, and α, n and m ($m = 1- n^{-1}$) are fitting parameters.

The unsaturated hydraulic conductivity function can be predicted using the saturated hydraulic conductivities and the van Genuchten fitting parameters defined in Equation 3-5 with the van Genuchten-Mualem model (van Genuchten 1980; Mualem 1976):

$$\frac{K_\psi}{K_s} = \frac{\{\,1-(a\cdot\psi)^{n-1}\cdot[\,1+(a\cdot\psi)^n\,]^{-m}\,\}^2}{[\,1+(a\cdot\psi)^n\,]^{m/2}} \tag{3-5}$$

where K_s is the saturated hydraulic conductivity, and K_ψ is the unsaturated hydraulic conductivity at matric suction ψ.

Saturated hydraulic conductivity of the storage layer was estimated by two methods: applying unit gradient method to field data and by conducting rigid wall permeameter tests. Using unit gradient method saturated hydraulic conductivities of the control and vetiver covers were estimated using the percolation measurements when the cover was saturated using the approach presented (Mijares et al. 2011). The estimated saturated hydraulic conductivities for the control and vetiver covers are 0.5×10^{-4} cm/s and 4×10^{-4} cm/s, respectively. These conductivities are relatively high for a final cover. However, in this project the key goal was to evaluate the effect of plants on the water balance of the cover. In order for the plant roots to establish with relative ease, the cover was compacted with relatively light effort. The fitting parameters of the soil water characteristic curve (SWCC) of the test sections were estimated using co-located readings of water content and matric suction sensors measured in the field. Hydraulic properties of each test section are presented in Table 3-2.

Table 3-2: Hydraulic properties of test sections.

Section	**Material**	**θ_s (cm³/cm³)**	**θ_r (cm³/cm³)**	**α (1/cm)**	**n**	**K_{sat} (cm/s)**
Control	Loose silty clay	0.5	0.05	0.009	1.3	0.5 x 10^{-4}
Vetiver	Loose silty clay	0.5	0.05	0.009	1.3	1.4 x 10^{-4}

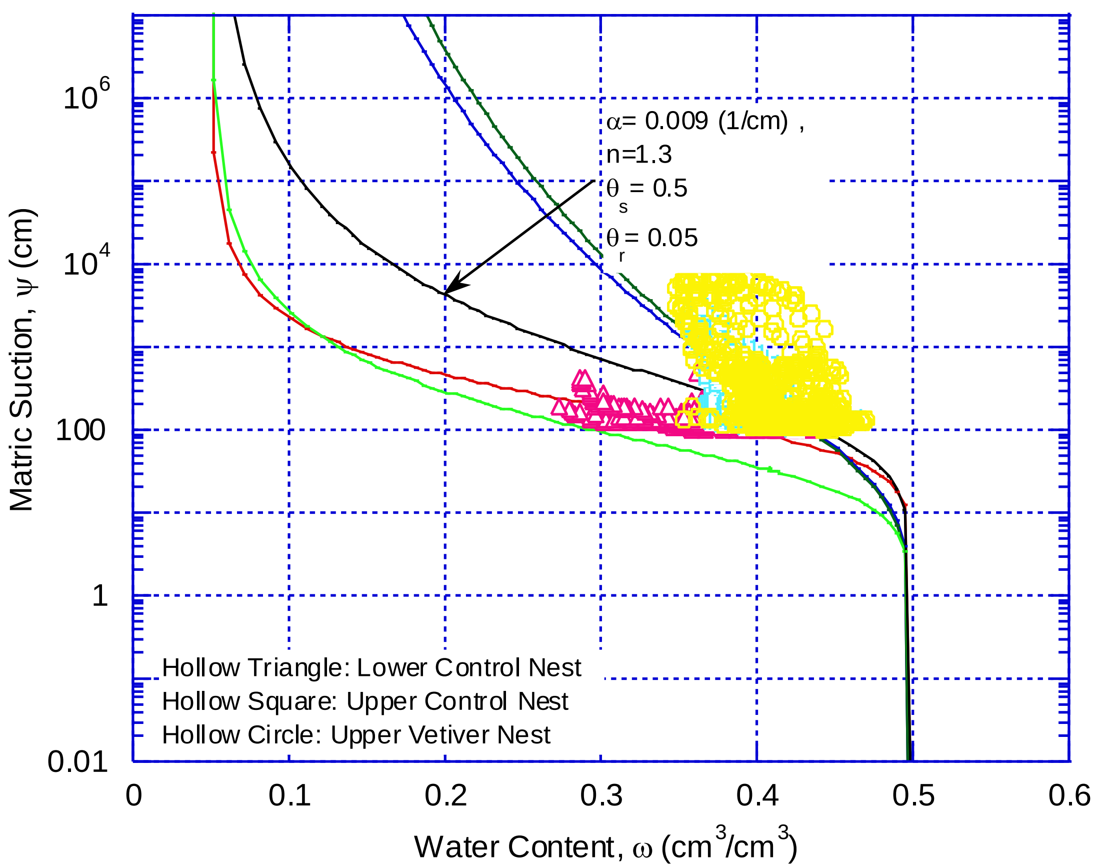

Figure 3-6: SWCC fitted to field data.

N*umerical simulation control parameters:* Spatial discretization of the model domain, temporal discretization, and error tolerances was optimized by conducting sensitivity analysis until the cumulative water balance error did not exceed 0.1%. At the lower and upper boundaries, the nodal spacing was one mm. For any given timestep, the maximum mass balance error was set to be less than 10^{-5} cm. For all the simulations, the maximum and minimum time steps were 0.1 and 10^{-7} hours respectively.

Boundary conditions: A variable flux or evaporative flux boundary was applied at the ground surface which represents precipitation when it is raining and evaporation when there is no precipitation. The input needed for evaporative-flux boundary condition are daily precipitation, maximum and minimum temperatures, average relative humidity, total solar radiation, and average wind speed (Fayer 2000). For simulating the drainage from the storage layer into the lysimeter, a unit gradient bottom boundary condition was used which corresponds to gravity-induced drainage (Fayer 2000; Mijares et al. 2011).

Initial conditions: Initial conditions were specified in the form of soil suctions. These suctions were obtained from matric suctions measured in the field test sections using the MPS-6 sensors at the time of the start of the experiment.

Meteorological data: The weather station installed at the site measured hourly precipitation, air temperature, relative humidity, and solar radiation. The UNSAT-H model requires daily values for precipitation, average wind speed, average cloud cover, total solar radiation, maximum and minimum air temperatures, and dew point temperature. Dewpoint temperatures were calculated using the measured mean air temperature and relative humidity. Wind speed data was obtained from a NOAA station located 16 km from the site. Because the net solar radiation was measured at the site, cloud cover parameter was set to zero for the simulations. In UNSAT-H model, dewpoint temperature, wind speed and cloud cover remain constant throughout the day. The model assumes a sinusoidal variation for air temperature in which the maximum air temperature occurs at 3:00 p.m. and minimum air temperature occurs at 3:00 a.m. (Mijares and Khire 2012). Also, daily solar radiation variations are estimated by the model using a sine function and it peaks at 12:00 p.m. (Mijares and Khire 2012).

Vegetation data: Vegetative data required for UNSAT-H model includes seasonal variation (time dependent) in leaf area index (LAI), maximum rooting depth, root density variation with depth and suction head limits that impact the withdrawal efficiency of plants, and percentage bare area (Fayer 2000).

The root length density function required for UNSAT-H was measured using a sample of vetiver plant collected from the field test section in October 2018. The sample was collected nearly two years after vetiver grass was planted and vetiver plants were fully mature at the time of the sampling. The root had a diameter of 25 cm and maximum depth of 50 cm. Figure 3-7(a) shows a photo of the sample excavated from the field.

The roots were washed to remove soil. The root sample was cut into 7-cm and 5-cm long segments for the first 12-cm depth segment below the ground surface. From 12-cm to the end of the root, each slice was 3-cm long. Depth intervals of the root segment measurements are shown in Figure 3-7(b). Weight of each root segment was recorded. Vetiver grass root average biomass at depths of 27-cm and 48-cm were about 43 (g/m^2) and 4 (g/m^2) respectively. For achieving the normalized root-length density which is required as an input to UNSAT-H, the biomass of each depth interval was divided by total biomass for the entire root length. The normalized root-density function is presented in Figure 3-8. The root-density function that UNSAT-H model uses is presented in Equation 3-6:

$$R = ae^{-zb} + c \tag{3-6}$$

where a, b, and c are fitting coefficients of the normalized root-density function. The values of a, b, and c are 0.507, 0.146, and 0, respectively. Due to lack of LAI information of vetiver, LAI of switchgrass which has a similar canopy as vetiver was used. The LAI of switchgrass was measured during growing season in a field located in Temple, Texas (Kiniry et al. 2007) .The LAI used for the simulations is shown in Figure 3-9. Growth of the plant starts at day 96 and stops at day 202 of the year. Mean values of LAI were used, and the maximum LAI was 6.0. The average percentage of bare area for vetiver was estimated to be around 10% based on visual observations during site visits. For the bare test section, the percent bare area was assumed equal to 100%.

Figure 3-7: Vetiver plant with root collected from the site (a); and root segments cut to develop root-density function (b).

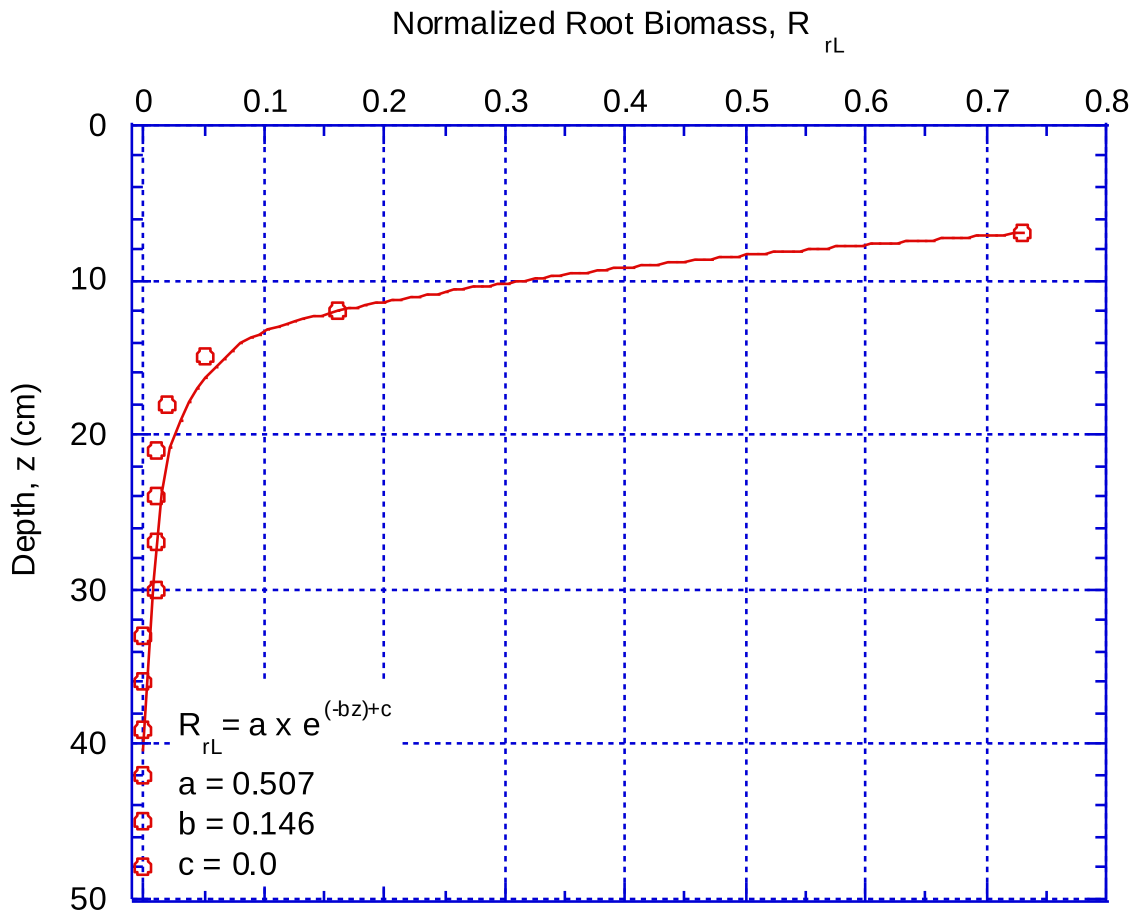

Figure 3-8: Vetiver grass estimated root-length density function.

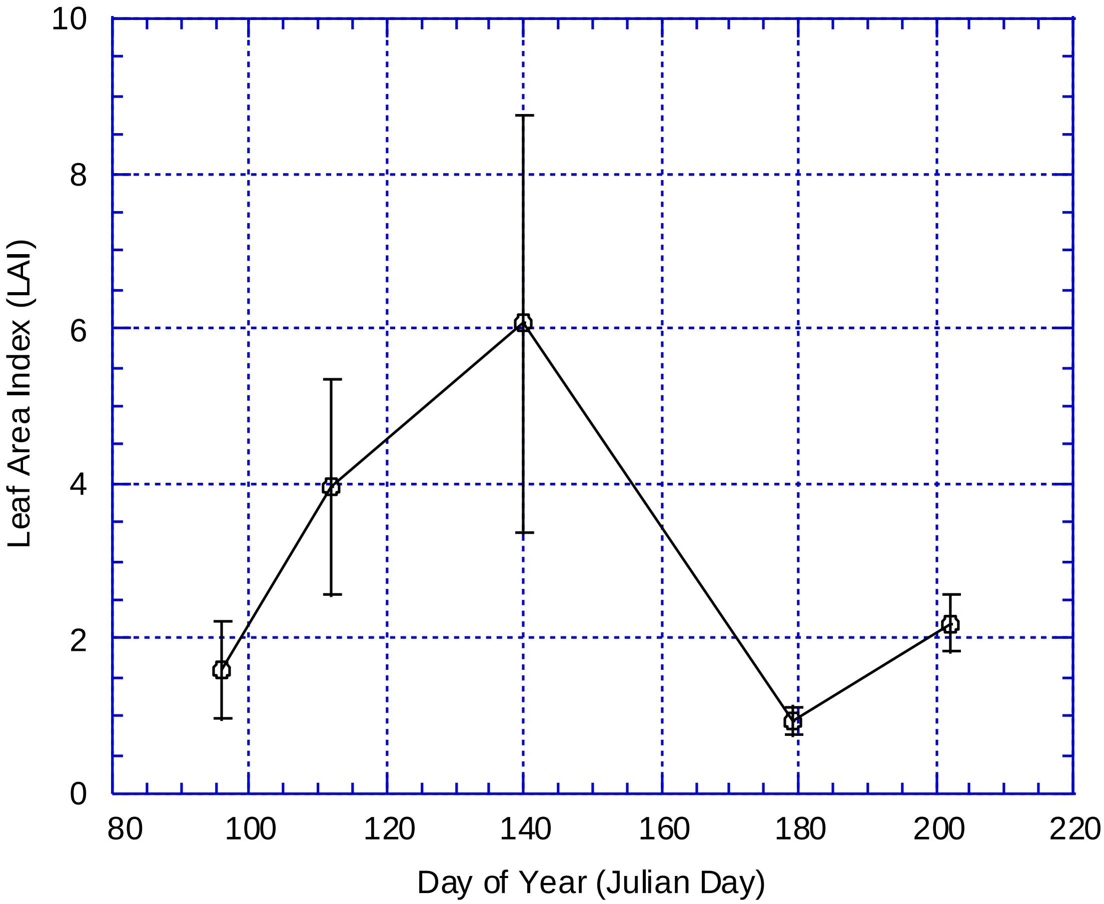

Figure 3-9: Leaf area index (LAI) used for simulation (Kiniry et al. 2007).

FIELD DATA

Weather Data

During the period from May 2016 to May 2017, the site received 158 cm of precipitation which in comparison to the 30-year normal precipitation indicates that the one-year monitoring period was relatively wet. As an indicator of seasonal variations, measured on-site air temperature and on-site measured relative humidity are shown in Figure 3-10. Also, the figure illustrates 30-year mean high and low temperatures for the site which shows that during growing season (1 March to 30 November), field air temperature has been slightly higher than the 30-year mean temperature. Field daily solar radiation is shown in Figure 3-11.

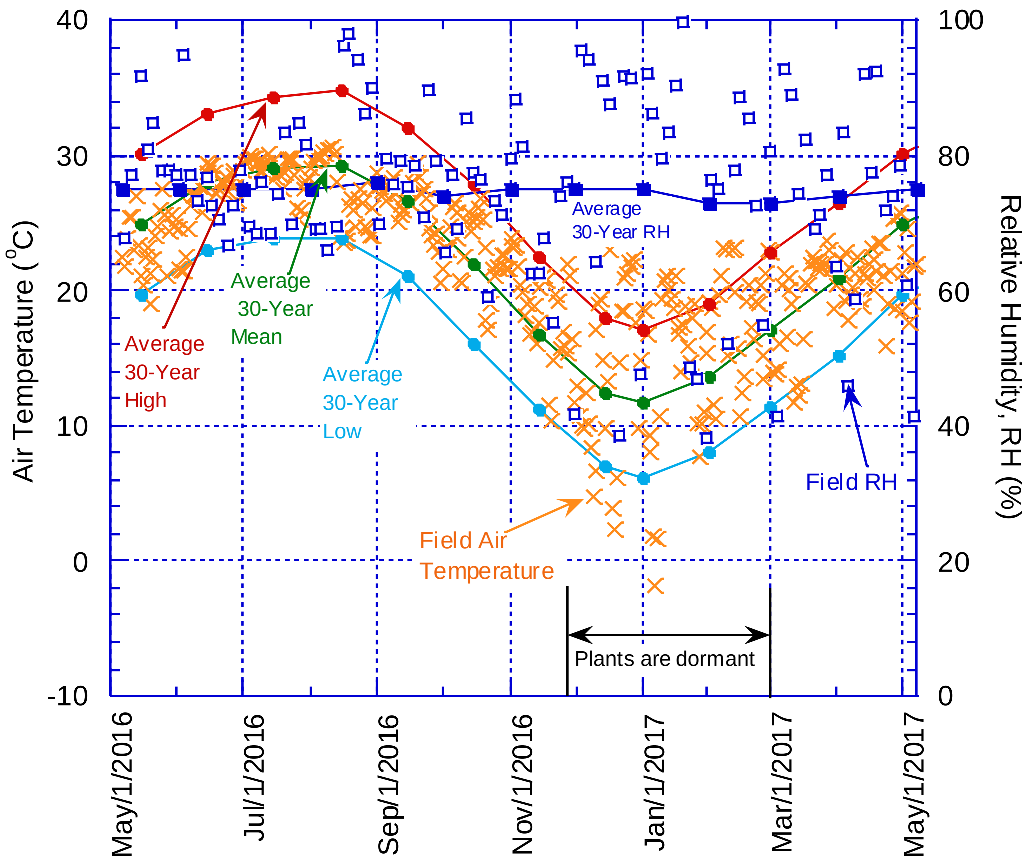

Figure 3-10: Field air temperatures and relative humidity and 30-year averages.

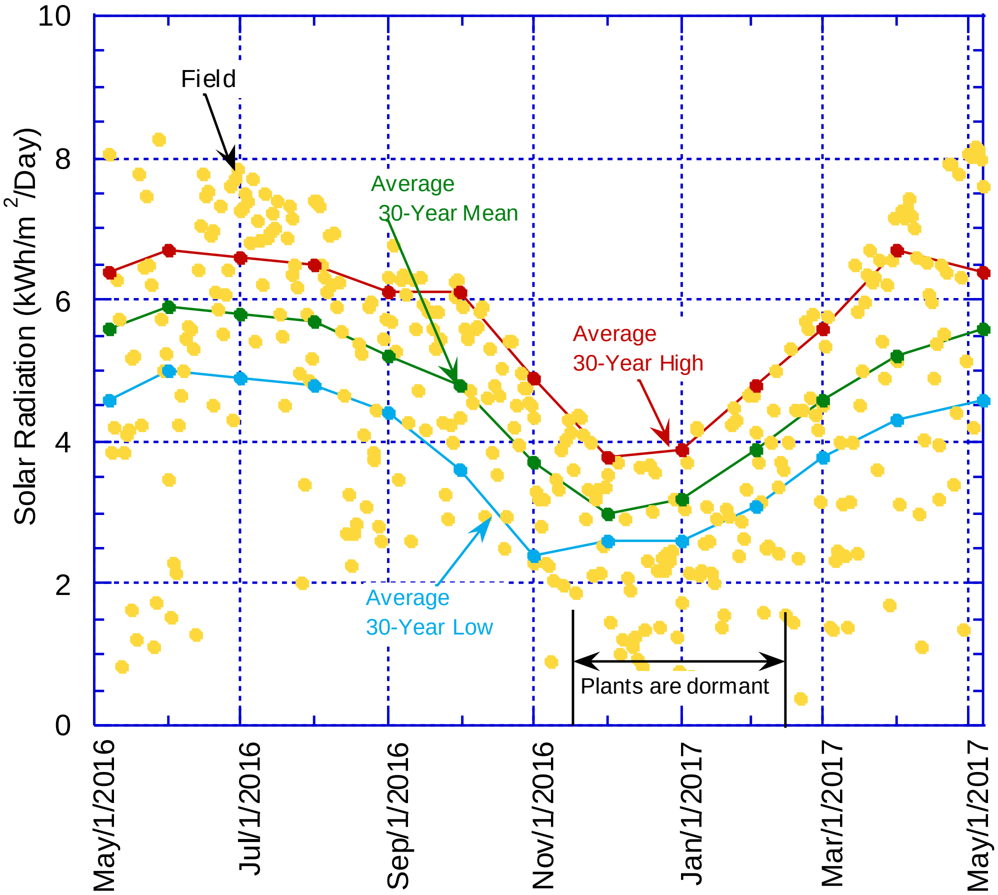

Figure 3-11: Seasonal variation of solar radiation and 30-year normal.

Percolation, Soil Water Storage, and ET

Figures 3-12 and 3-13 show SWS and cumulative percolation, respectively. Using the water balance equation (Eq. 3-1), ET for each test section was estimated (Figure 3-14).

During the one-year monitoring period, the test sections received around 158 cm of precipitation. The SWS for both upper nests are greater than the lower nests (Fig. 3-12). This primarily because infiltration is greater at the bottom of the slope due to the re-infiltration of runoff shed by the upgradient part of the slope. Nevertheless, the changes in SWS of all four nests were about the same during the one-year data monitoring period.

During October, due to relatively low precipitation, the SWS of all nests show a steady decline. The SWS went back initial values once the precipitation increased.

Both vetiver and control test sections had very similar percolation. Estimated evapotranspiration (ET) of both vetiver and control test sections is shown in Figure 3-14 The ET for control and vetiver are about the same. Hence, during the first year of the monitoring period, the evaporation and transpiration from the vetiver is approximately the same as the evaporation from the bare test section.

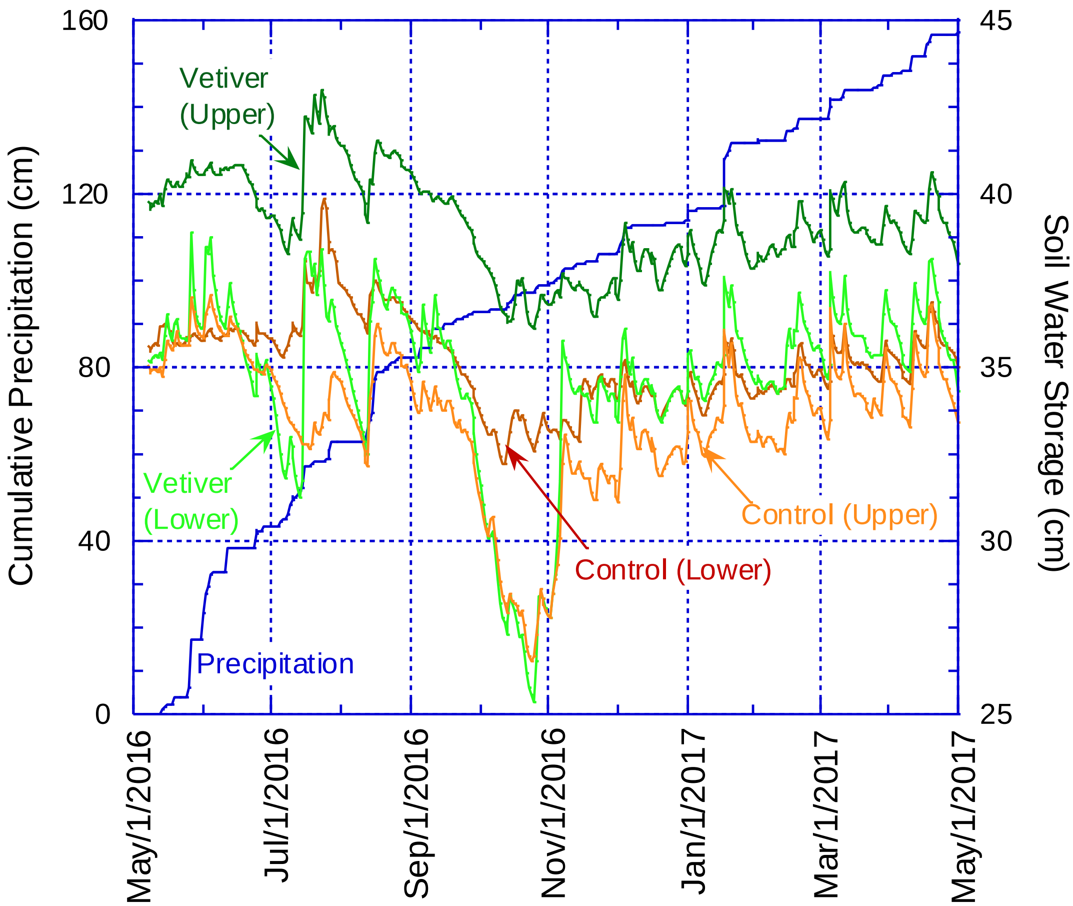

Figure 3-12: Soil water storage for control and vetiver test sections.

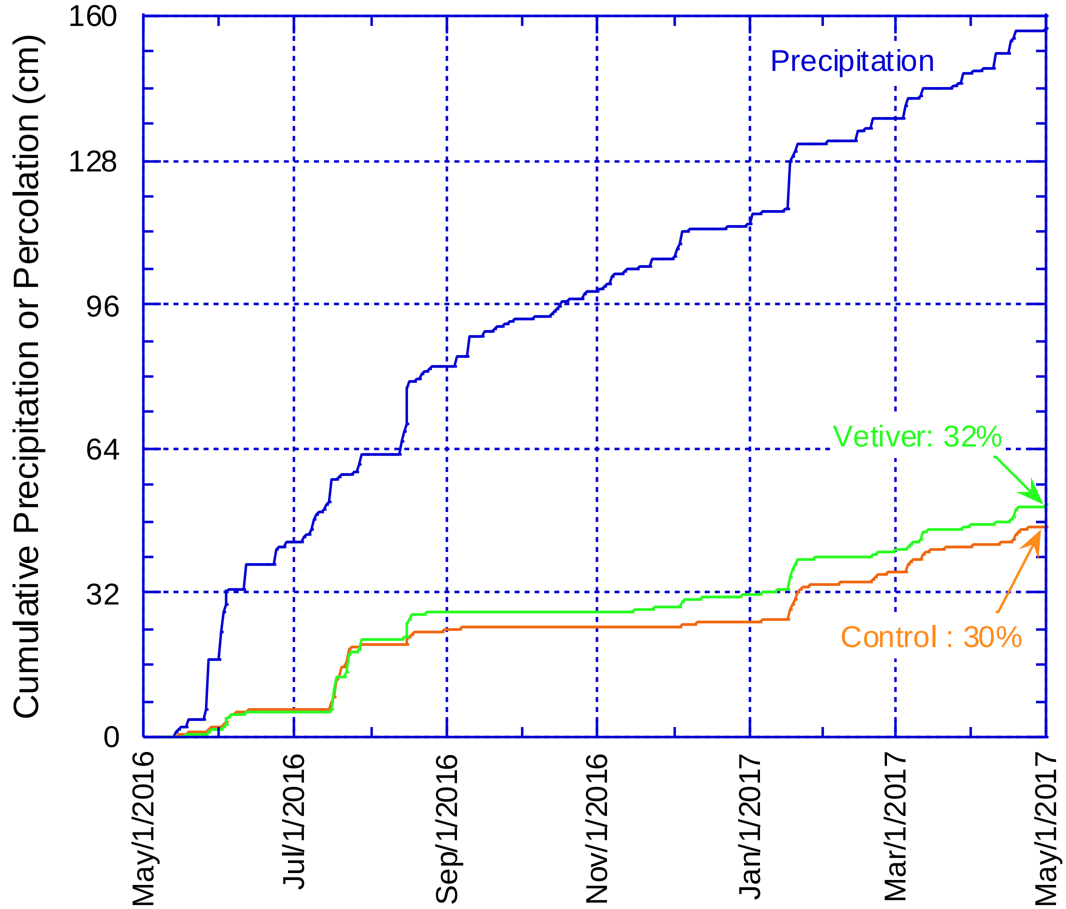

Figure 3-13: Measured field percolation for control and vetiver test sections.

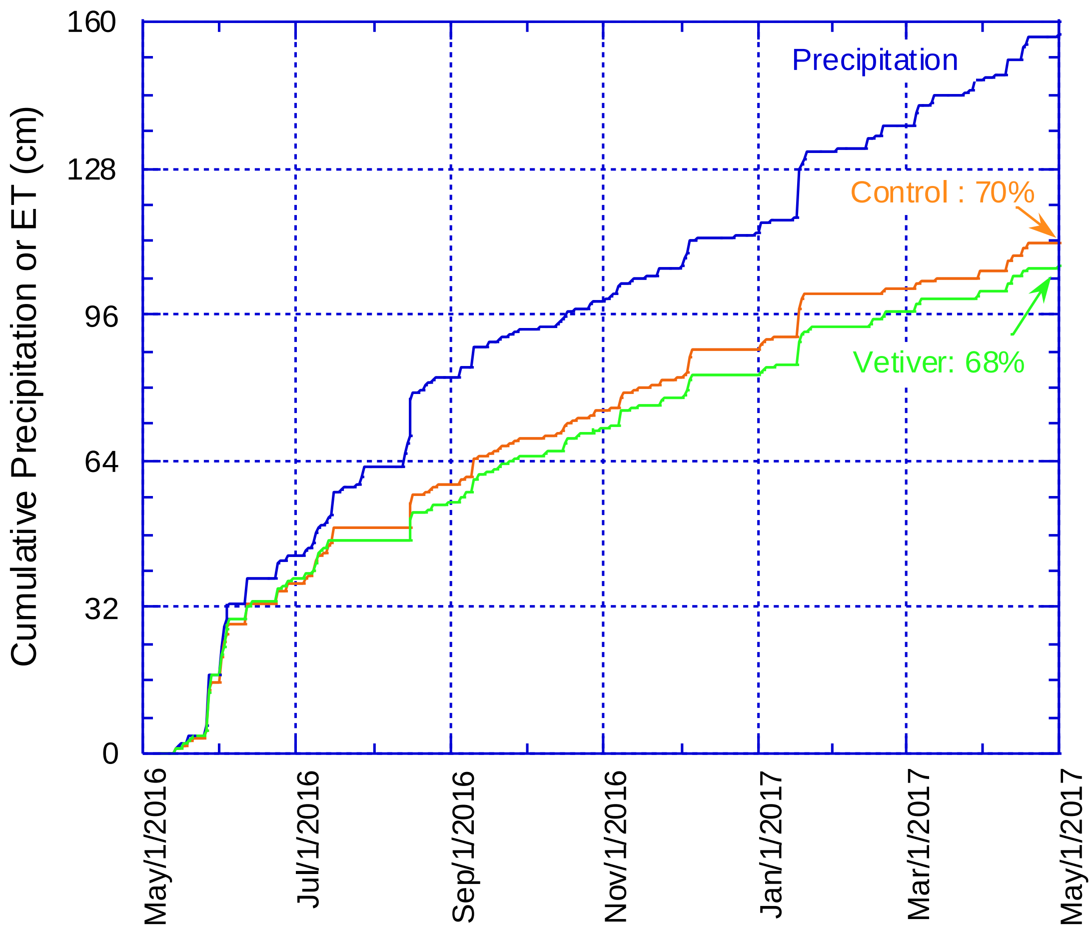

Figure 3-14: Estimated field ET for control and vetiver test sections.

NUMERAICAL MODELING RESULTS

The section presents the percolation, SWS, and ET predicted by UNSAT-H for the one-year monitoring period for control and vetiver test sections.

Control Test Section

Figure 3-15 shows the measured and simulated evaporation, percolation and runoff (RO) for the control test section. Figure 3-16 shows the measured and simulated SWS for the test section. While the model underestimated SWS, the model simulated the relative trends in the SWS fairly well. Mijares and Khire (2012) when simulated water balance of a sub-humid site, identified that UNSAT-H generally underestimates SWS.

During the one-year monitoring period, measured percolation was about 46 cm (~29% of received precipitation). UNSAT-H predicted the total percolation accurately (Figure 3-15). However, UNSAT-H predicted relatively high percolation in the beginning of the monitoring period (~ 30 cm) which was not observed in the field.

Figure 3-15 also shows that UNSAT-H overestimated evaporation by about 21 cm (19%). The model predicted evaporation matches the field data till January 2017. However, after January 2017, the model overestimates evaporation. This maybe because after January, weeds had established on the control test section which may have reduced the evaporation in the field. The model assumed 100% bare ground with no restrictions to evaporation from the foliage of the weeds.

Vetiver Test Section

Figure 3-17 shows the measured and simulated evaporation, percolation and runoff (RO) for the vetiver test section. Figure 3-18 shows the measured and simulated SWS for the test section. While the model underestimated SWS, the model simulated the relative trends in the SWS fairly well. However, SWS was much lower than that was simulated by the model for control (Fig. 3-16).

UNSAT-H predicted the total percolation relatively accurately (Figure 3-17). However, UNSAT-H predicted relatively high percolation in the beginning of the monitoring period (~ 30 cm) which was not observed in the field.

UNSAT-H underestimated evaporation by about 10 cm (9%). The model predicted evaporation matches the field data till September 2016. However, after that the model underestimates evaporation. This maybe because the transpiration function in the model that is based on Cheatgrass from semi-arid climate is not accurate to simulate transpiration from vetiver plants in humid climate.

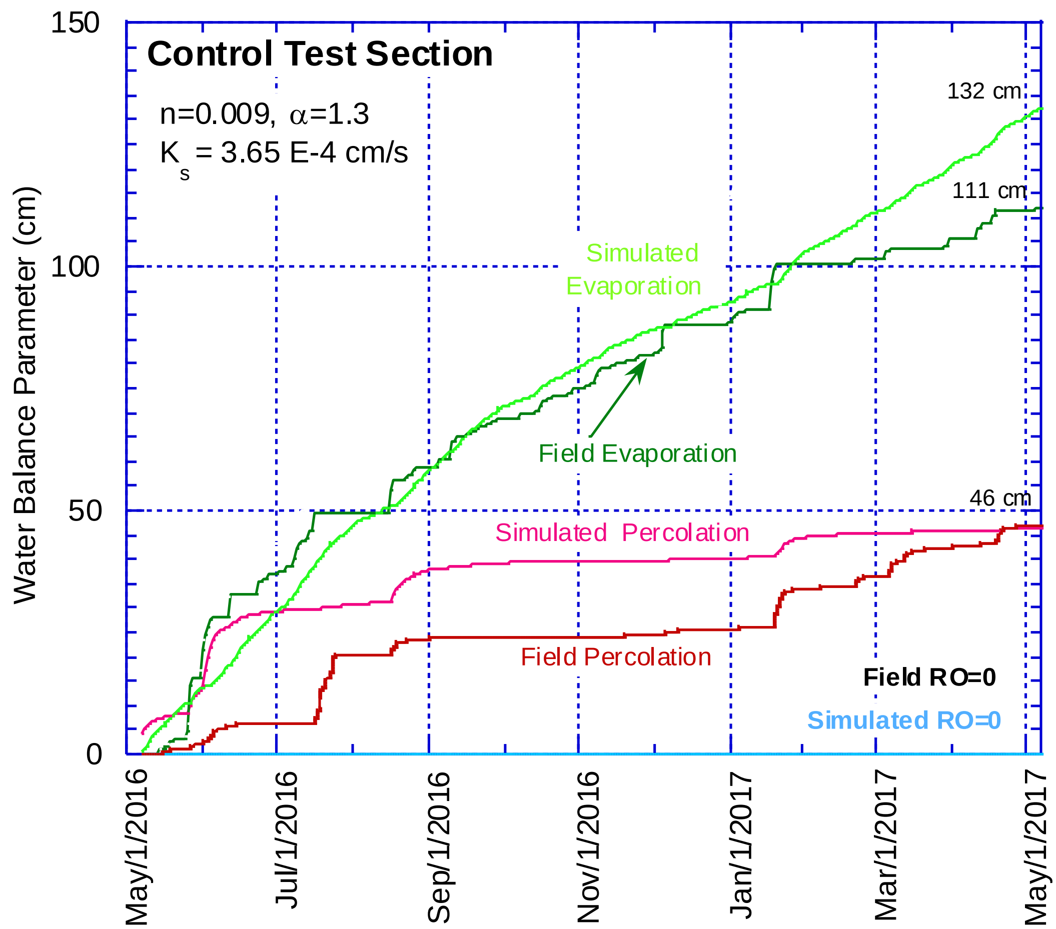

Figure 3-15: Measured and simulated percolation and evaporation for control test section.

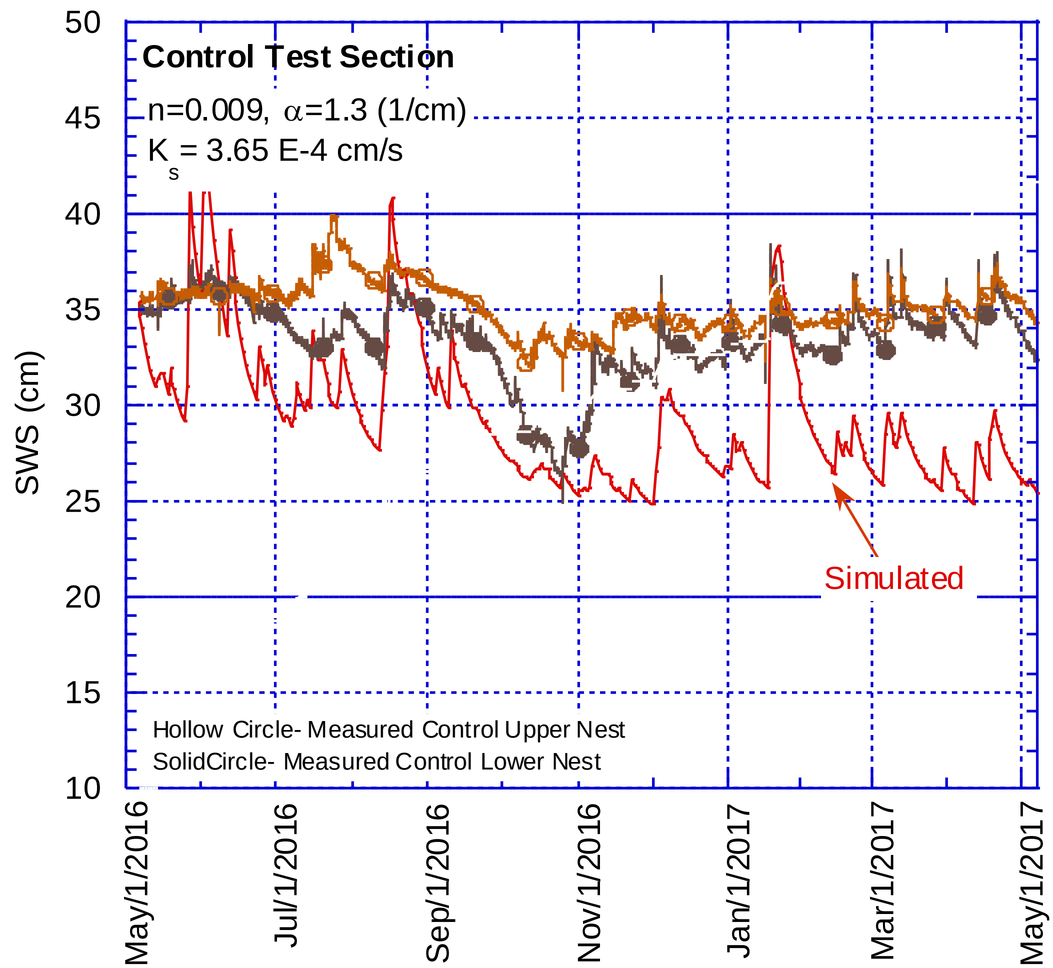

Figure 3-16: Simulated and measured soil water storage (SWS) of control test section.

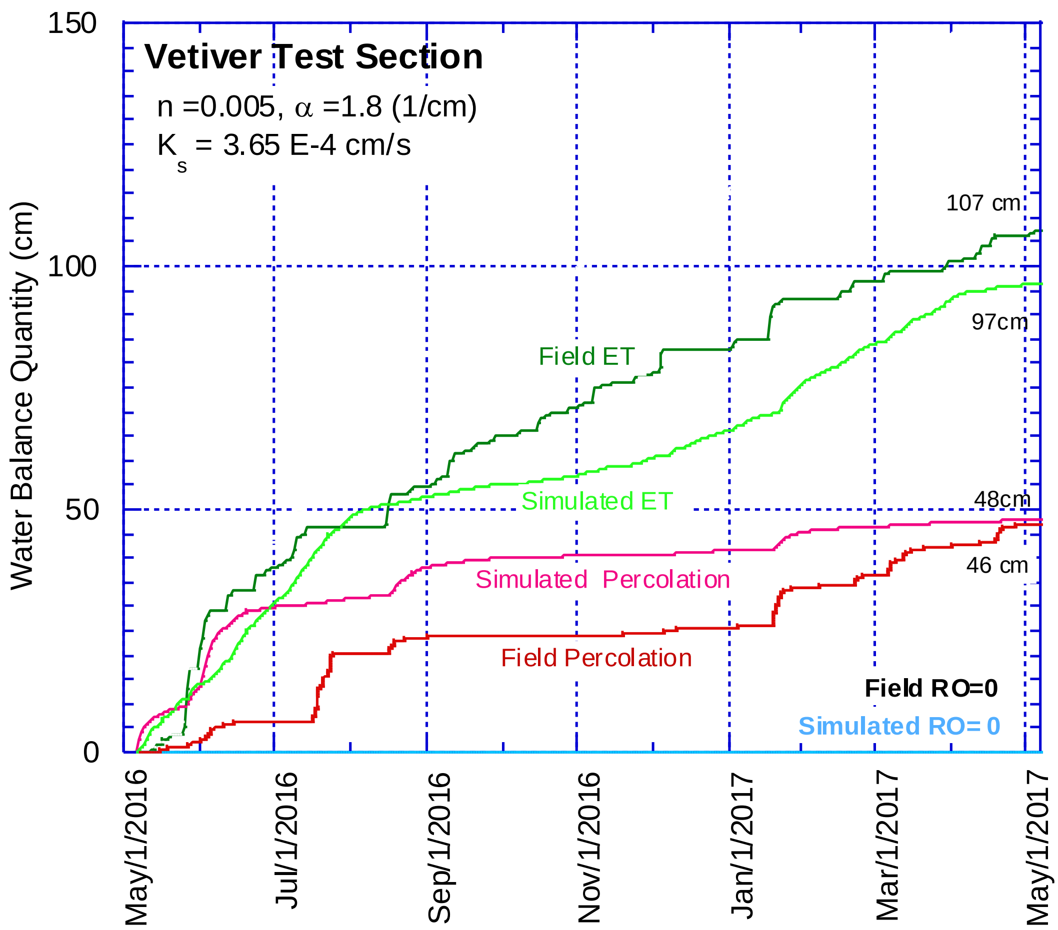

Figure 3-17: Measured and simulated percolation and ET for vetiver test section.

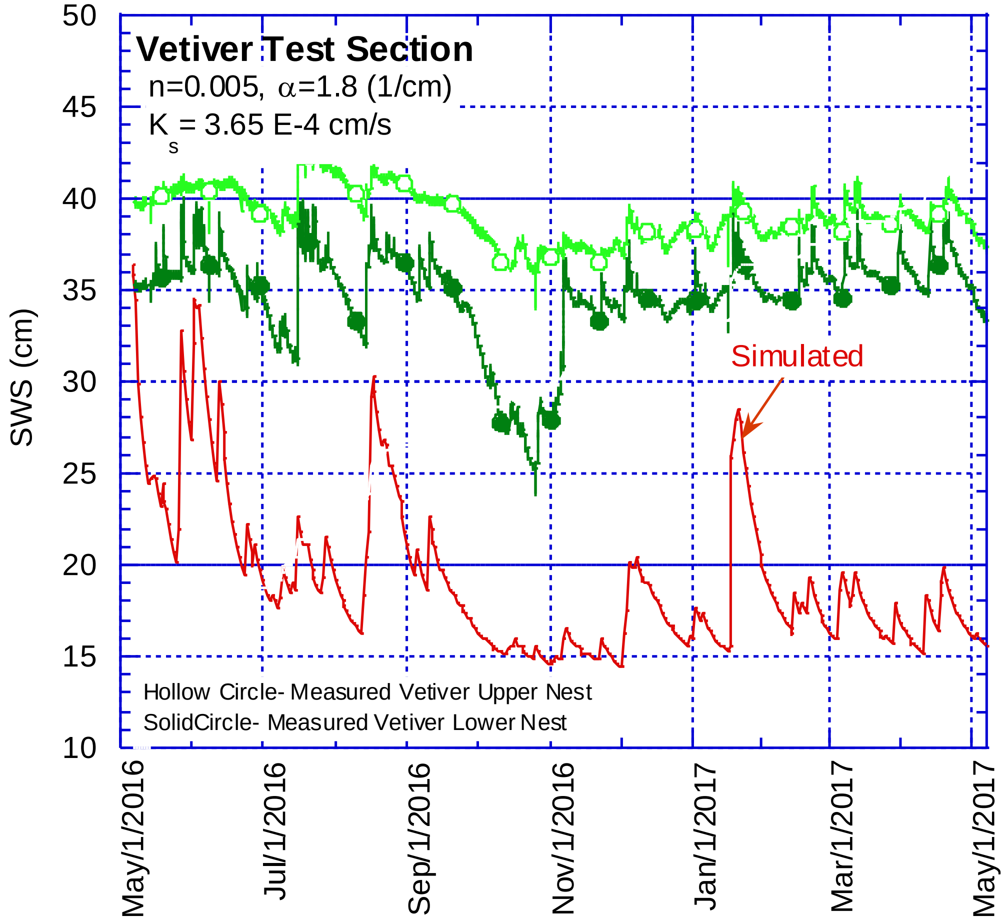

Figure 3-18: Measured and simulated soil water storage (SWS) for vetiver test section.

SUMMMARY AND CONCLUSIONS

Two field-scale test sections of earthen cover, each 90-cm thick were constructed and built and instrumented at a landfill site in the southcentral U.S. This location has humid climate. One test section was bare (control) and the other test section was planted with vetiver plants.

Climatic data and water balance data consisting of precipitation, percolation and soil water contents were monitored for a period of one year. This data was used to estimate

SWS and ET. The data collected during the one-year period indicates that percolation, SWS and ET from both test sections were relatively similar. Vetiver plants did not noticeably influence ET and percolation. It may be because the plants only reached 50% of their matured height by the end of the first year.

The water balance model UNSAT-H was used to simulate and evaluate the differences between the vetiver and control test sections and to test the predictive capabilities of the model for humid climate plants. UNSAT-H predicted the percolation for both test sections relatively accurately. Similarly, the model predicted the relative trends (increase and decrease) in SWS relatively accurately. However, the model overestimated ET for control test section by 19%, and underestimated ET for the vetiver test section by 9%. Thus, further work is needed to improve the predictive capabilities of the model for ET in humid locations.

REFERENCES

40 CFR 258.60. (2009). "Title 40: Protection of Environment-PART 258—Criteria For Municipal Solid Waste Landfills." <https://www.ecfr.gov/cgi-bin/text-idx?SID=558a9db9fee0e89333a2588d0fba87c4&mc=true&node=sp40.27.258.d&rgn=div6> (Oct. 7, 2018).

Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P., Lyles, B. F., and Rock, S. A. (2004). "Field Water Balance of Landfill Final Covers." *Journal of Environment Quality*, 33(6), 2317.

Apiwantragoon, P., Benson, C. H., and Albright, W. H. (2015). "Field hydrology of water balance covers for waste containment." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(2).

Banerjee, R., Goswami, P., Lavania, S., Mukherjee, A., and Lavania, U. C. (2019). "Vetiver grass is a potential candidate for phytoremediation of iron ore mine spoil dumps." *Ecological Engineering*, Elsevier, 132(January), 120–136.

Banerjee, R., Goswami, P., Pathak, K., and Mukherjee, A. (2016). "Vetiver grass: An environment clean-up tool for heavy metal contaminated iron ore mine-soil." *Ecological Engineering*, Elsevier B.V., 90, 25–34.

Benson, C. H., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. H. (2007). "Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 133(4), 349–359.

Bréda, N. J. J. (2003). "Ground-based measurements of leaf area index: A review of methods, instruments and current controversies." *Journal of Experimental Botany*, 54(392), 2403–2417.

Bwire, K. M., Njau, K. N., and Minja, R. J. A. (2011). "Use of vetiver grass constructed wetland for treatment of leachate." *Water science and technology : a journal of the International Association on Water Pollution Research*, 63(5), 924–30.

Campbell Scientific Inc. (2011). *Instruction Manual, CS650 and CS655 Water Content Reflectometers,*. Logan , Utah.

Day, W. (1977). "A direct reading continuous flow porometer." *Agricultural Meteorology*, 18, 81–89.

Decagon Devices Inc. (2017). *Dielectric Water Potential Sensors*.

Duncan, J. P., Burk, K. W., Chamness, M. A., Fowler, R. A., Fritz, B. G., Hendrickson, P. L., Kennedy, E. P., Last, G. V, Poston, T. M., Sackschewsky, M. R., Scott, M. J., Snyder, S. F., Sweeney, M. D., and Thorne, P. D. (2007). *Hanford Site National*

Environmental Policy Act (NEPA) Characterization.

Erdogan, R., and Zaimoglu, Z. (2015). "The Characteristics of Phytoremediation of Soil and Leachate Polluted by Landfills." *Advances in Bioremediation of Wastewater and Polluted Soil*, InTech.

Fayer, M. J. (2000). *UNSAT-H Version 3.0: Unsaturated Soil Water and Heat Flow Model. Theory , User Manual , and Examples*. *Model Manual*.

Granley, B. A., and Truong, P. N. (2012). "A Changing Industry: On-site Phytoremediation of Landfill Leachate Using Trees and Grasses-Case Studies." Global Waste Management Symposium, 5.

Hauser, V. L., Weand, B. L., and Gill, M. D. (2001). "Natural Covers for Landfills and Buried Waste." *Journal of Environmental Engineering*, American Society of Civil Engineers, 127(9), 768–775.

Hui, D., Yu, C.-L., Deng, Q., Dzantor, E. K., Zhou, S., Dennis, S., Sauve, R., Johnson, T. L., Fay, P. A., Shen, W., and Luo, Y. (2018). "Effects of precipitation changes on switchgrass photosynthesis, growth, and biomass: A mesocosm experiment." *PloS one*, Public Library of Science, 13(2), e0192555.

Khire, M. V. (2016). "Geoclimatic Design of Water Balance Covers for Municipal Solid Waste Landfills in Texas." *UNCC-CEE-14-100, Lone Star Chapter of the Solid Waste Association of North America, Aug*, 334.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (1997). "Water Balance Modeling of Final Earthen Covers." *Journal of Geotechnical and Geoenvironmental Engineering*, 123(8), 744–754.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (2000). "Capillary Barriers: Design Variables and Water Balance." *Journal of Geotechnical and Geoenvironmental Engineering*, 126(8), 695–708.

Kiniry, J. R., Burson, B. L., Evers, G. W., Williams, J. R., Sanchez, H., Wade, C., Featherston, J. W., and Greenwade, J. (2007). "Coastal bermudagrass, bahiagrass, and native range simulation at diverse sites in Texas." *Agronomy Journal*, 99(2), 450–461.

Leuning, R., and Foster, I. (1990). "Estimation of transpiration by single trees: comparison of a ventilated chamber, leaf energy budgets and a combination equation." *Agricultural and Forest Meteorology*, 51(1), 63–86.

Licht, B. L., Aitchison, E., Schnabel, W., English, M., and Kaempf, M. (2001). "Landfill Caping with Woodland Ecosystems." *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 5(October), 175–184.

Meerdink, J., Benson, C., and Khire, M. (1996). "Unsaturated Hydraulic Conductivity of Two Compacted Barrier Soils." *Journal of Geotechnical Engineering*, (J. Meerdink, ed.), 122(7), 565–576.

Mijares, R. G., and Khire, M. V. (2012). “Field Data and Numerical Modeling of Water Balance of Lysimeter versus Actual Earthen Cap.” *Journal of Geotechnical and Geoenvironmental Engineering*, 138(8), 889–897.

Mijares, R. G., Khire, M. V, and Johnson, T. (2011). “Field-Scale Evaluation of Lysimeters Versus Actual Earthen Covers.” *Geotechnical Testing Journal*, 35(1).

Nadezhdina, N., Al-Okaishi, A., and Madera, P. (2018). “Sap Flow Measurements in a Socotra Dragon’s Blood Tree (Dracaena cinnabari) in its Area of Origin.”

Renner, M., Hassler, S. K., Blume, T., Weiler, M., Hildebrandt, A., and Guderle, M. (2016). “Dominant controls of transpiration along a hillslope transect inferred from ecohydrological measurements and thermodynamic limits.” 2063–2083.

Rock, S. A. (2003). “Vegetative Covers for Waste Containment.” *Phytoremediation. Advances in Biochemical Engineering/Biotechnology*, Springer, Berlin, Heidelberg, 78(1), 157–170.

Sânchez-Carrillo, S., Âlvarez-Cobelas, M., Benitez, M., and Angeler, D. G. (2001). "A simple method for estimating water loss by transpiration in wetlands". *Hydrological Sciences~Journal-des Sciences Hydrologiques*.

Smeal, C., Hackett, M., and Truong, P. (2017). “Vetiver System for Industrial Wastewater Treatment in Queensland , Australia.” (September), 1–13.

Smesrud, J. K., Benson, C. H., Albright, W. H., Richards, J. H., Wright, S., Israel, T., and Goodrich, K. (2012). “Using pilot test data to refine an alternative cover design in Northern California.” *International Journal of Phytoremediation*, 14(SUPPL.), 76–93.

Truong, P. (2019). “Vetiver system for environmental protection.” *Vetican Consulting, Brisbane*.

United States Department of Agriculture (USDA). (2018). “Switchgrass Fact Sheet.” <https://plants.usda.gov/core/profile?symbol=pavi2> (Jan. 10, 2017).

US EPA. (2017). “Municipal Solid Waste Landfills.” <https://www.epa.gov/landfills/municipal-solid-waste-landfills> (Dec. 5, 2018).

USDA, NRCS, N. P. D. (2003). *Cheatgrass Fact Sheet*.

Vogel, T., Votrubova, J., Dohnal, M., and Dusek, J. (2017). “A Simple Representation of Plant Water Storage Effects in Coupled Soil Water Flow and Transpiration Stream Modeling.” *Vadose Zone Journal*, GeoScienceWorld, 16(5), 0.

SUMMARY AND CONCLUSIONS

The key objectives of this dissertation were to: (1) compare water balance of covers with and without plants and evaluate the effect of plants on overall ET, SWS, and percolation in humid climate; and (2) validate the numerical model UNSAT-H for water balance predictions of covers with plants in humid climate.

In order to fulfill the objectives of this research, instrumented field-scale cover test sections were built at a site located in the southcentral U.S. In addition, instrumented column-scale covers were built in the southeastern U.S. Both sites are located in humid climates. For the field-scale experiments, two 11 m long x 11 m wide x 0.9 m thick ET cover test sections were built side by side. A 0.6 m deep pea-gravel layer underlain by a geomembrane (lysimeter) was installed beneath each test section to collect percolation. The test sections were instrumented to measure precipitation, soil water storage, and percolation. Matric suction, water content, and water level sensors were installed in two sensor nests in each test section to monitor and measure water balance parameters. A weather station was installed at the location to monitor precipitation, solar radiation, air temperature, and relative humidity. These test sections were identical except, one test section was planted with vetiver grass and the other test section was bare (control). Water balance of the vegetated and control test sections was evaluated in two phases using two ET estimation methods: (1) by direct measurement of precipitation, percolation, and soil water storage during the period from May 2016 until May 2017; and (2) estimating ET as water loss from lysimeter and storage layer by allowing the lysimeters to flood during second and third years corresponding to period October 2017 to August 2019.

The water balance model UNSAT-H was used to simulate the field water balance and validate the ET predictions of UNSAT-H for humid climate studied in this project.

In addition to the field-scale experiment carried out in the southcentral U.S., three identical soil columns (25.5 cm diameter) consisting of 76 cm thick compacted sandy silt overlain by 35 cm thick topsoil were instrumented to measure water balance parameters. These columns are located in a southeastern U.S. location which also has humid climate. One of the columns was planted with a vetiver plant, one with a switchgrass plant, and the third column was bare. The data was analyzed to assess the ET from the three columns. All three columns were instrumented to measure matric suctions and water contents. A weather station consisting of hardware and sensors to measure precipitation, air temperature, humidity, solar radiation and wind speed was also installed. The columns were placed outdoors, and data collection was carried out for about 14 months. Key results are summarized as follows.

(1) During the first year of the field-scale study (Phase 1), cumulative ET was 70% and 68% of total precipitation for control and vetiver test sections, respectively. The cumulative percolation and soil water storage (SWS) for both test sections were about the same. The 12-month average ET rates of control and vetiver test sections were 0.31 cm/day and 0.30 cm/day, respectively. This shows that vetiver plants had very little influence on the water balance of the cover. At the end of the first year, the vetiver plants had grown about half of their typical mature height.

(2) During Phase 1, the maximum SWS for both test sections was about 95% of the SWS at saturation. However, the average SWS for test sections remained in the 70% to 80% range.

(3) During the second and third years (Phase 2) of the field-scale study, ET rates were estimated while the lysimeter valves were closed and the lysimeters were allowed to fill up. The data analysis showed that ET rates ranged from 0.1 mm/day to 8.5 mm/day for control and zero cm/day to 7 mm/day for the vetiver test section when using the lower sensor nest was used. ET rates ranged from 0.2 mm/day to 6.3 mm/day for control and zero cm/day to 3.6 mm/day for the vetiver test section when the upper sensor nest was used. The ET rates for vetiver were slightly less than ET rates for control. During Phase 2, the vetiver grass canopies were fully established, and the plants had reached their typical mature height of about 3 m.

(4) The SWS for control and vetiver were relatively similar over the three-year period. Thus, the plants did not noticeably alter the water removal characteristics. While in this study the ET that was measured was evaporation and transpiration combined, it may be possible that as the vetiver canopy established, the evaporation was cut down and the deficit in ET was picked up as transpiration by the vetiver plants. However, that could not be confirmed.

(5) UNSAT-H model was used to simulate the field water balance. The model predicted percolation relatively accurately. However, it under-estimated SWS of both control and vetiver test sections. Its under-estimated ET for the vetiver test section by about 9% and overestimated ET for control by about 19%.

(6) During the 14-month large-scale column study, the ET from vetiver and switchgrass were about 2% and 9% higher than the bare column, respectively. This shows that plants can enhance ET due to water uptake and increase in transpiration. By the end of the 14-month monitoring period, vetiver and switchgrass reached

about 50% and 76% of their mature height, respectively. Thus, the ET may change as the plants further grow towards fully matured height and canopy.

(7) In addition to the 14-month water balance of the columns, water balance of the columns was analyzed for the 5-month growing season (May 2019- September 2019) which is a subset of the 14-month monitoring period. During this growing season, canopies of the both plants grew and were much larger compared to that at the beginning of the experiment. During these five-months, percolation from the control was about 12% and 14% greater and evaporation was 23% and 37% less than switchgrass and vetiver columns, respectively.

REFERENCES

40 CFR 258.60. (2009). "Title 40: Protection of Environment-PART 258—Criteria For Municipal Solid Waste Landfills." <https://www.ecfr.gov/cgi-bin/text-idx?SID=558a9db9fee0e89333a2588d0fba87c4&mc=true&node=sp40.27.258.d&rgn=div6> (Oct. 7, 2018).

Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P., Lyles, B. F., and Rock, S. A. (2004). "Field Water Balance of Landfill Final Covers." *Journal of Environment Quality*, 33(6), 2317.

Apiwantragoon, P., Benson, C. H., and Albright, W. H. (2015). "Field hydrology of water balance covers for waste containment." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(2).

Banerjee, R., Goswami, P., Lavania, S., Mukherjee, A., and Lavania, U. C. (2019). "Vetiver grass is a potential candidate for phytoremediation of iron ore mine spoil dumps." *Ecological Engineering*, Elsevier, 132(January), 120–136.

Banerjee, R., Goswami, P., Pathak, K., and Mukherjee, A. (2016). "Vetiver grass: An environment clean-up tool for heavy metal contaminated iron ore mine-soil." *Ecological Engineering*, Elsevier B.V., 90, 25–34.

Benson, C. H., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. H. (2007). "Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils." *Journal of Geotechnical and Geoenvironmental Engineering*, 133(4), 349–359.

Bréda, N. J. J. (2003). "Ground-based measurements of leaf area index: A review of methods, instruments and current controversies." *Journal of Experimental Botany*, 54(392), 2403–2417.

Bwire, K. M., Njau, K. N., and Minja, R. J. A. (2011). "Use of vetiver grass constructed wetland for treatment of leachate." *Water science and technology : a journal of the International Association on Water Pollution Research*, 63(5), 924–30.

Campbell Scientific Inc. (2011). *Instruction Manual, CS650 and CS655 Water Content Reflectometers,*. Logan , Utah.

Day, W. (1977). "A direct reading continuous flow porometer." *Agricultural Meteorology*, 18, 81–89.

Decagon Devices Inc. (2017). *Dielectric Water Potential Sensors*.

Duncan, J. P., Burk, K. W., Chamness, M. A., Fowler, R. A., Fritz, B. G., Hendrickson, P. L., Kennedy, E. P., Last, G. V, Poston, T. M., Sackschewsky, M. R., Scott, M. J., Snyder, S. F., Sweeney, M. D., and Thorne, P. D. (2007). *Hanford Site National Environmental Policy Act (NEPA) Characterization*.

Erdogan, R., and Zaimoglu, Z. (2015). “The Characteristics of Phytoremediation of Soil and Leachate Polluted by Landfills.” *Advances in Bioremediation of Wastewater and Polluted Soil*, InTech.

Fayer, M. J. (2000). *UNSAT-H Version 3.0: Unsaturated Soil Water and Heat Flow Model. Theory , User Manual , and Examples*. *Model Manual*.

Granley, B. A., and Truong, P. N. (2012). “A Changing Industry: On-site Phytoremediation of Landfill Leachate Using Trees and Grasses-Case Studies.” Global Waste Management Symposium, 5.

Hauser, V. L., Weand, B. L., and Gill, M. D. (2001). “Natural Covers for Landfills and Buried Waste.” *Journal of Environmental Engineering*, American Society of Civil Engineers, 127(9), 768–775.

Hui, D., Yu, C.-L., Deng, Q., Dzantor, E. K., Zhou, S., Dennis, S., Sauve, R., Johnson, T. L., Fay, P. A., Shen, W., and Luo, Y. (2018). “Effects of precipitation changes on switchgrass photosynthesis, growth, and biomass: A mesocosm experiment.” *PloS one*, Public Library of Science, 13(2), e0192555.

Khire, M. V. (2016). “Geoclimatic Design of Water Balance Covers for Municipal Solid Waste Landfills in Texas.” *UNCC-CEE-14-100, Lone Star Chapter of the Solid Waste Association of North America, Aug*, 334.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (1997). “Water Balance Modeling of Final Earthen Covers.” *Journal of Geotechnical and Geoenvironmental Engineering*, 123(8), 744–754.

Khire, M. V, Benson, C. H., and Bosscher, P. J. (2000). “Capillary Barriers: Design Variables and Water Balance.” *Journal of Geotechnical and Geoenvironmental Engineering*, 126(8), 695–708.

Kiniry, J. R., Burson, B. L., Evers, G. W., Williams, J. R., Sanchez, H., Wade, C., Featherston, J. W., and Greenwade, J. (2007). “Coastal bermudagrass, bahiagrass, and native range simulation at diverse sites in Texas.” *Agronomy Journal*, 99(2), 450–461.

Leuning, R., and Foster, I. (1990). “Estimation of transpiration by single trees: comparison of a ventilated chamber, leaf energy budgets and a combination equation.” *Agricultural and Forest Meteorology*, 51(1), 63–86.

Licht, B. L., Aitchison, E., Schnabel, W., English, M., and Kaempf, M. (2001). “Landfill Caping with Woodland Ecosystems.” *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 5(October), 175–184.

Meerdink, J., Benson, C., and Khire, M. (1996). “Unsaturated Hydraulic Conductivity of Two Compacted Barrier Soils.” *Journal of Geotechnical Engineering*, (J. Meerdink, ed.), 122(7), 565–576.

Mijares, R. G., and Khire, M. V. (2012). “Field Data and Numerical Modeling of Water Balance of Lysimeter versus Actual Earthen Cap.” *Journal of Geotechnical and Geoenvironmental Engineering*, 138(8), 889–897.

Mijares, R. G., Khire, M. V, and Johnson, T. (2011). “Field-Scale Evaluation of Lysimeters Versus Actual Earthen Covers.” *Geotechnical Testing Journal*, 35(1).

Nadezhdina, N., Al-Okaishi, A., and Madera, P. (2018). “Sap Flow Measurements in a Socotra Dragon’s Blood Tree (Dracaena cinnabari) in its Area of Origin.”

Renner, M., Hassler, S. K., Blume, T., Weiler, M., Hildebrandt, A., and Guderle, M. (2016). “Dominant controls of transpiration along a hillslope transect inferred from ecohydrological measurements and thermodynamic limits.” 2063–2083.

Rock, S. A. (2003). “Vegetative Covers for Waste Containment.” *Phytoremediation. Advances in Biochemical Engineering/Biotechnology*, Springer, Berlin, Heidelberg, 78(1), 157–170.

Sânchez-Carrillo, S., Âlvarez-Cobelas, M., Benitez, M., and Angeler, D. G. (2001). "A simple method for estimating water loss by transpiration in wetlands". *Hydrological Sciences~Journal-des Sciences Hydrologiques*.

Smeal, C., Hackett, M., and Truong, P. (2017). “Vetiver System for Industrial Wastewater Treatment in Queensland , Australia.” (September), 1–13.

Smesrud, J. K., Benson, C. H., Albright, W. H., Richards, J. H., Wright, S., Israel, T., and Goodrich, K. (2012). “Using pilot test data to refine an alternative cover design in Northern California.” *International Journal of Phytoremediation*, 14(SUPPL.), 76–93.

Truong, P. (2019). “Vetiver system for environmental protection.” *Vetican Consulting, Brisbane*.

United States Department of Agriculture (USDA). (2018). “Switchgrass Fact Sheet.” <https://plants.usda.gov/core/profile?symbol=pavi2> (Jan. 10, 2017).

US EPA. (2017). “Municipal Solid Waste Landfills.” <https://www.epa.gov/landfills/municipal-solid-waste-landfills> (Dec. 5, 2018).

USDA, NRCS, N. P. D. (2003). *Cheatgrass Fact Sheet*.

Vogel, T., Votrubova, J., Dohnal, M., and Dusek, J. (2017). “A Simple Representation of Plant Water Storage Effects in Coupled Soil Water Flow and Transpiration Stream Modeling.” *Vadose Zone Journal*, GeoScienceWorld, 16(5), 0.