HYDRAULIC PERFORMANCE EVALUATION OF EVAPOTRANSPIRATION COVER SYSTEMS

by

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Abstract

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Although alternative covers such as the evapotranspiration (ET) landfill cover system promise to provide equivalent or greater performance than conventional cover systems, uncertainties remain on the performance of these type of cover systems. The uncertainties associated with performance may derive from the relative newness of these covers (when compared to conventional landfill cover systems); and their dependency on relatively site-specific factors such as: climatic, vegetation, and soil conditions. As a results, the Texas Commission on Environmental Quality (TCEQ) requires a landfill facility to design and then verify the design and performance through site specific field scale testing (TCEQ 2012). Utilizing field scale lysimeters [having dimensions greater than 10 x 10-m (30 x 30-feet)] coupled with in-situ soil instrumentation is the preferred method of field verification by TCEQ (TCEQ 2012). Therefore; the motivation of this study was to develop an understanding of the short-term hydraulic performance and vegetation mix assessment of ET cover systems at the City of Denton, Texas Municipal Solid Waste Landfill utilizing six (6) 40-ft by 40-ft lysimeters. A plethora of sensors, instrumentation, and monitoring methods were utilized in an effort to effectively measure and analysis critical parameters of the ET cover systems such as: climatic conditions, surface runoff, soil water storage, soil water potential, vegetation, surface conditions, and percolation.

Construction of six (6) 40-ft by 40-ft lysimeters was a time-consuming process which required a number of tasks (with multiple steps associated with each task) to be completed. Construction of the lysimeters started June 17th, 2014 and was completed November 1st, 2014 [a span of four (4) and a half months]. The tasks which were completed during the construction of the lysimeters are provided as follows: (1) embankment construction; (2) embankment excavation; (3) geomembrane placement; (4) geomembrane boot construction; (5) percolation collection system construction; (6) geocomposite drain placement; (7) 3-ft compacted clay placement; (8) topsoil sidewall and bentonite placement; (9) berm construction; (10) 1-ft of topsoil placement; (11) collection tank placement and installation; (12) instrumentation; (13) vegetation and erosion mat placement; and (14) clean-up activities.

Preliminary results for the six (6) ET cover systems are generally characterized by large quantities of runoff, percolation, and soil water storage. The least amount of percolation was measured from the ET cover systems sodded and seeded with Bermuda, indicative of the best performance. These preliminary percolation results do not appear to be encouraging for the performance of the cover, with all the ET cover systems producing substantial amounts of percolation. However, it is important to note the following: (1) the results are from the short-term performance of the ET cover systems; (2) there has been a large amount of precipitation that has occurred during the monitoring period, much greater than the historic average; (3) vegetation appears to be established; however, the roots have not been observed to extend to a great depth within the cover systems; and (4) desiccation cracking and rodent burrows have been observed in the cover systems which may result in preferential flow pathways. The ET cover systems will continue to be monitored and their performance evaluated over a greater amount of time.

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Chapter 1

Introduction

1.1 Background

Final cover systems are located between the waste and atmosphere on a landfill (Figure 1.1), and are intended to maintain functionality and remain in place for an extended period of time (USEPA 2003). Additionally, these cover systems are intended to minimize infiltration into the waste, promote surface runoff, control gas emissions and odors, minimize erosion, and maintain aesthetics (Hauser 2009 and USEPA 2003). Typically, conventional cover systems (Figure 1.2a) utilize low-permeability barrier layers (i.e., geomembranes and geosynthetic clay liners); while Evapotranspiration (ET) cover systems (Figure 1.2b) rely on ET and the water storage capacity of soil to minimize infiltration into the waste, and are increasingly being utilized to satisfy the cover system performance requirements (USEPA 2003).

An ET cover system is an earthen cover which is an alternative to a conventional cover typically used for waste containment systems. The ET cover system is often required to be equivalent in terms of percolation to the conventional cover (i.e. the expected percolation rate to the underlying waste from an ET cover must be equal to or less than the expected percolation rate from a conventional cover) (Malusis and Benson 2006). ET cover systems have a greater likelihood of long-term success when compared to conventional covers because they are designed to act similar to nature (Benson et al. 2002). The basic principle behind ET cover systems is that the infiltrated water is stored within the cover during elevated precipitation and/or minimal evapotranspiration (i.e. vegetative dormancy) periods and then is returned to the atmosphere during drier and/or greater ET times (Barnswell and Dwyer 2011, Benson et al. 2002, Khire et al. 2000, Malusis and Benson 2006, and Stormont and Morris 1998). ET cover systems are governed by water balance principles, meaning the amount of percolation through the cover system is based upon the amount of precipitation, surface runoff, ET, and change in soil water storage. These type of cover systems are receiving considerable attention due to uncertainties associated with the long-term durability of fine-grained barrier layers and the relatively high cost of conventional covers (Albright et al. 2004).

However, performance verification of ET cover systems by utilizing tests plots such as lysimeters are often required.

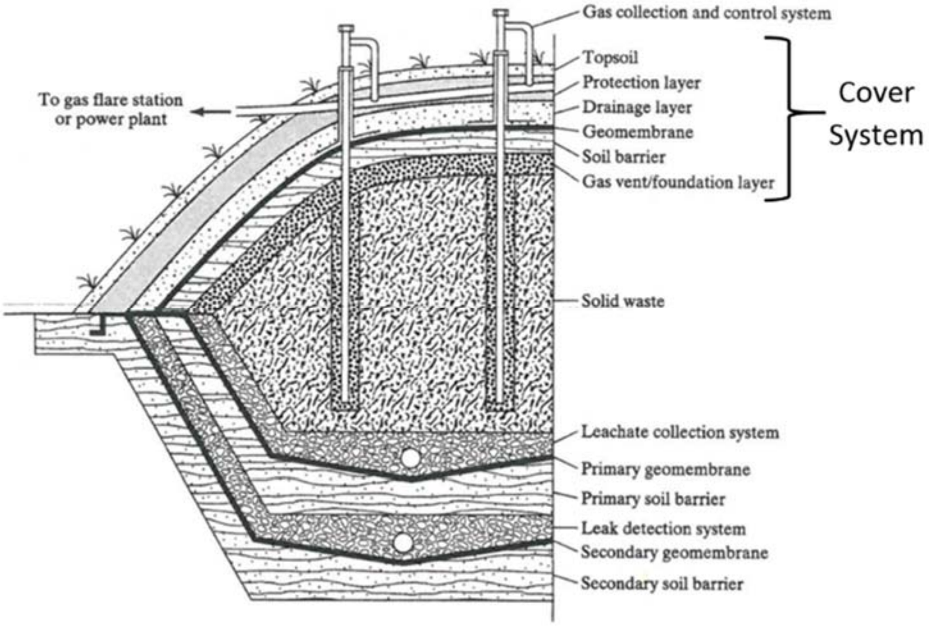

Figure 1.1: Schematic diagram of a municipal solid waste landfill (modified from Qian et al. 2002).

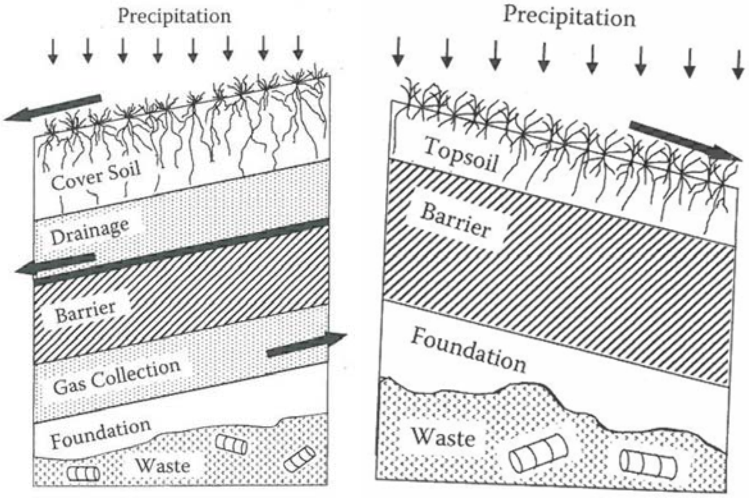

Figure 1.2: Cross section of a) typical conventional cover system and b) ET cover system (Hauser 2009).

Lysimeters are typically utilized to measure moisture fluxes through soil; and generally incorporate infiltration, runoff, and soil water storage measurement systems or devices. These lysimeters often resemble large bathtubs which are filled with soil (the cover system), incorporating an impermeable layer (i.e. geomembrane) and drainage layer (i.e. geocomposite drain) to effectively collect then measure percolated water through the soil. Additionally, soil moisture probes are often utilized to measure soil water storage and a piping system on the top of the cover is used to collect and measure runoff. A lysimeter having area dimensions of 10 x 10-m (33 x 33-ft.) is considered to adequately represent the preferential flow (i.e., holes, cracks, etc.) and spatial variability factors (i.e. heterogeneity in vegetation and hydraulic properties of an actual landfill cover (Benson et al. 2001 and Malusis and Benson 2006).

1.2 Problem Statement

Although alternative covers such as the ET cover system promise to provide equivalent or greater performance than conventional cover systems, uncertainties remain on the performance of these type of cover systems. The uncertainties associated with performance may derive from the relative newness of these covers (when compared to conventional cover systems); and their dependency on relatively site-specific factors such as: climatic, vegetation, and soil conditions. As a results, the Texas Commission on Environmental Quality (TCEQ) requires a landfill facility to design and then verify the design and performance through site specific field scale testing (TCEQ 2012). Utilizing field scale lysimeters [having dimensions greater than 10 x 10-m (30 x 30-feet)] coupled with in-situ soil instrumentation is the preferred method of field verification by TCEQ (TCEQ 2012). Therefore; it is necessary for a municipal solid waste (MSW) landfill which desires to implement an ET cover system (such as the City of Denton MSW Landfill) to construct and monitor on-site lysimeter(s) for site performance assessment. Site specific ET cover system performance analysis has not been previously conducted in the vicinity of the City of Denton MSW Landfill.

ET cover systems are designed to rely on the transpiration from the plants growing on the cover system and their root systems penetrating into the soil to remove infiltrated water. As a result, it is necessary to maintain a healthy plant root system growing in the ET cover system to effectively and reliably remove infiltrated water (Hauser 2009). Additionally, it is recommended to plant a diverse mixture of vegetation species which are native to the site due to performance variation between plant species and the evolution of the vegetation to thrive at the site (Hauser 2009). Therefore, it is beneficial to implement multiple plant mixtures when conducting these lysimeter tests in an effort to obtain the plant mixture which will thrive at the site and effectively transpire the infiltrated water from the cover system.

Typical MSW landfill design utilizes two (2) main cover profiles (Figure 1.1); the first being a relatively steep sloped section on the side of the landfill, and the other is a relatively flat section at the top of the landfill. The differences in the slope between these profiles may significantly affect the amount of percolation through the cover system. This is due to the slope of the land surface (the cover system) is a significant watershed factor (Bedient et al. 2008). As a result, it is critical to conduct lysimeter tests with varying slope conditions which are representative of the full-scale landfill ET cover system and incorporate a runoff collection system which is likely to collection all of the runoff.

The occurrence of rodent burrows, vegetation performance, desiccation cracking, subsidence, and other detrimental factors can significantly affect the performance of ET cover systems. Therefore; it is critical to implement regular site visits to monitor and record the presence of these factors.

Due to TCEQ requirements and the potential ET cover system performance variations from differing vegetation mixtures and slope conditions, it was decided to implement six (6) lysimeters which could effectively evaluate these variations in the ET cover system. Additionally, it should be noted that such an extensive lysimeter study on large-scale ET cover systems at a single location has not been previously conducted. Differences from previous studies include:

- ET cover monitoring for climatic conditions in Texas (specifically Denton area);
- Utilizing a wide variety of vegetation mixes and analyzing their effect on performance; and
- Incorporating routine monitoring to evaluate cover conditions (i.e., desiccation cracking, subsidence, vegetation performance, fires, ponding of water, rodent burrows, etc.).

1.3 Objective of the Study

The primary objective of this study was to develop an understanding of the short-term (1.3-years) hydraulic performance of ET cover systems with various vegetation mixes at the City of Denton Municipal Solid Waste Landfill. The effectiveness of the ET cover systems was monitored in the field by constructing and utilizing six (6) 40-ft x 40-ft lysimeters.

Specific objectives of the study are outlined as follows:

1. Review ET cover system components and concepts, performance evaluation systems and design, and pervious ET cover system performance studies;

2. Design and develop field-scale monitoring systems to investigate climatological and ET cover system performance parameters;
3. Construction of six (6) 40-ft x 40-ft lysimeters and install instrumentation to monitor the effectiveness of ET cover system;
4. Evaluate the short-term (1.3-years) hydraulic, vegetation, and cover performance of each of the ET cover systems based upon the field-scale lysimeters; and
5. Evaluate the effects of cover (i.e., desiccation cracking, subsidence, rodent burrows, etc.) and climatic conditions on the short-term effectiveness of ET cover systems.

1.4 Dissertation Outline

The current study is segregated into six chapter as summarized below:

- Chapter 1 provides an introduction and presents the problem, objective of the study, and outline of this dissertation;
- Chapter 2 provides a literature review on ET cover system components, concepts of flow and storage, performance evaluation systems, and previous studies on ET cover systems;
- Chapter 3 provides construction and design considerations of evapotranspiration cover system monitoring systems, and monitoring climatological and evapotranspiration cover system performance parameters;
- Chapter 4 presents the step-by-step lysimeter and ET cover system construction and instrumentation installation for the evaluation of the ET cover systems;
- Chapter 5 presents the monitoring results, analysis, comparison, and discussion of the ET cover systems, vegetation and cover observations, and climatological conditions; and
- Chapter 6 summarizes the discussion, conclusions, and limitation of the current study and provides recommendations for future studies.

Chapter 2

Literature Review

2.1 Cover System and Components

An alternative earthen final cover (AEFC) or evapotranspiration cover (ET) is an earthen cover which is an alternative to a conventional cover typically used for waste containment systems (Figure 1.2). The AEFC is often required to be equivalent in terms of percolation to the conventional cover (i.e., the expected percolation rate to the underlying waste from an AEFC must be equal or less than the expected percolation rate from a conventional cover) (Malusis and Benson 2006). This type of alternative waste cover acts to limit the rate of percolation into the underlying waste by relying on water balance principles (Malusis and Benson 2006; Nyhan 2005). AEFCs have a greater likelihood of long-term success when compared to conventional covers because they are designed to act similar to nature (Benson et al. 2002). The basic principle behind ET covers are that the infiltrated water is stored within the cover during elevated precipitation and/or minimal evapotranspiration (i.e., vegetative dormancy) periods and then is returned to the atmosphere during drier and/or greater ET (Barnswell and Dwyer 2011; Benson 2001; Benson et al. 2002; Khire et al. 2000; Malusis and Benson 2006; and Stormont and Morris 1998).

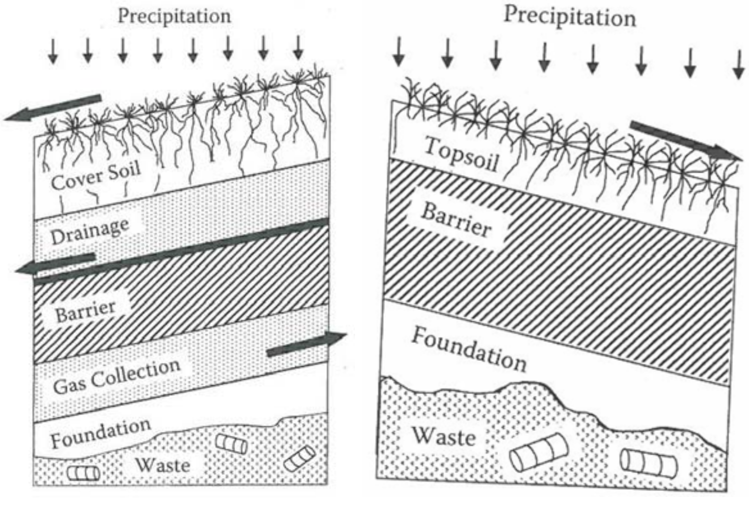

Figure 2.1: Cross section of a) typical conventional cover system and b) ET cover system (Hauser 2009).

These types of alternative covers are receiving considerable attention due to uncertainties associated with the long-term durability of fine-grained barrier layers and the relatively high cost of conventional covers (Albright et al. 2004).

- Common and ddditional names:
    - Store-and-release covers,
    - Evapotranspiration (ET) covers,
    - Water balance cover, and
    - Alternative covers.

The nomenclature “ET cover” will be utilized throughout this document.

The common configurations of ET cover systems are provided in Figure 2.2, and are monolithic and capillary barriers. As shown in the figure, the monolithic cover system consists of a layer of fine-textured soil and vegetation overlying the waste mass. The capillary barrier incudes a fine-textured layer underlain by a clean coarse-grained layer.

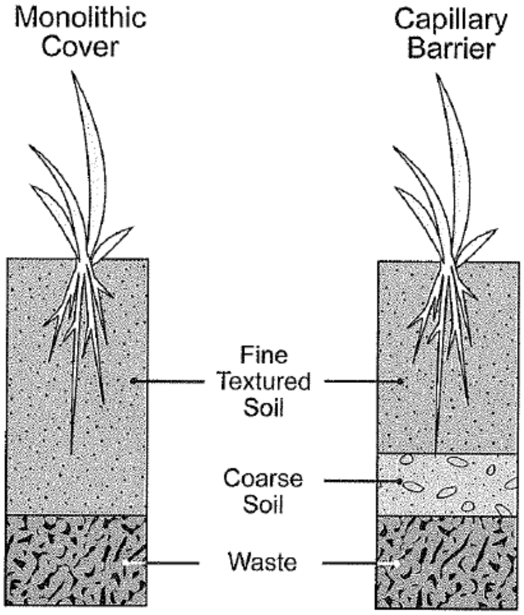

Figure 2.2: Basic configurations of monolithic and capillary barrier ET cover systems (Albright et al. 2004).

2.2 Concepts of Flow, Storage, and Water Balance

2.2.1 *Introduction*

The idealized annual relationship between potential ET (PET), soil-moisture, and precipitation (rainfall) is provided in Figure 2.3. It should be noted that field capacity of the soil shown in the figure above which water will drain from the soil by gravity (discussed in greater detail later in this chapter). As shown in the figure, infiltrated water is removed from the soil (from the atmospheric/soil boundary down) during times when the PET is greater than the rainfall (idealized during the spring and summer). During times when rainfall is greater than PET (idealized during the autumn and winter), water tends to infiltrate into the soil from the atmospheric/soil boundary and cause the water content in the soil to increase. Ideally the entire soil system will not reach field capacity prior the PET becoming greater than rainfall. ET cover systems act as a sponge to manage water as shown in the figure by:

- Providing sufficient water storage capacity within the soil system to prevent percolation from the bottom of the cover system during periods when rainfall (precipitation) exceed PET (as illustrated in Figure 2.3 and Figure 2.4); and
- Providing enough stored water removal potential from the cover system during periods when ET exceeds rainfall (precipitation).

Figure 2.3 also serves to demonstrate the importance of the soil being at a soil moisture deficit prior to times when the PET is greater than rainfall, as field capacity and water drainage from the soil by gravity may be reached earlier.

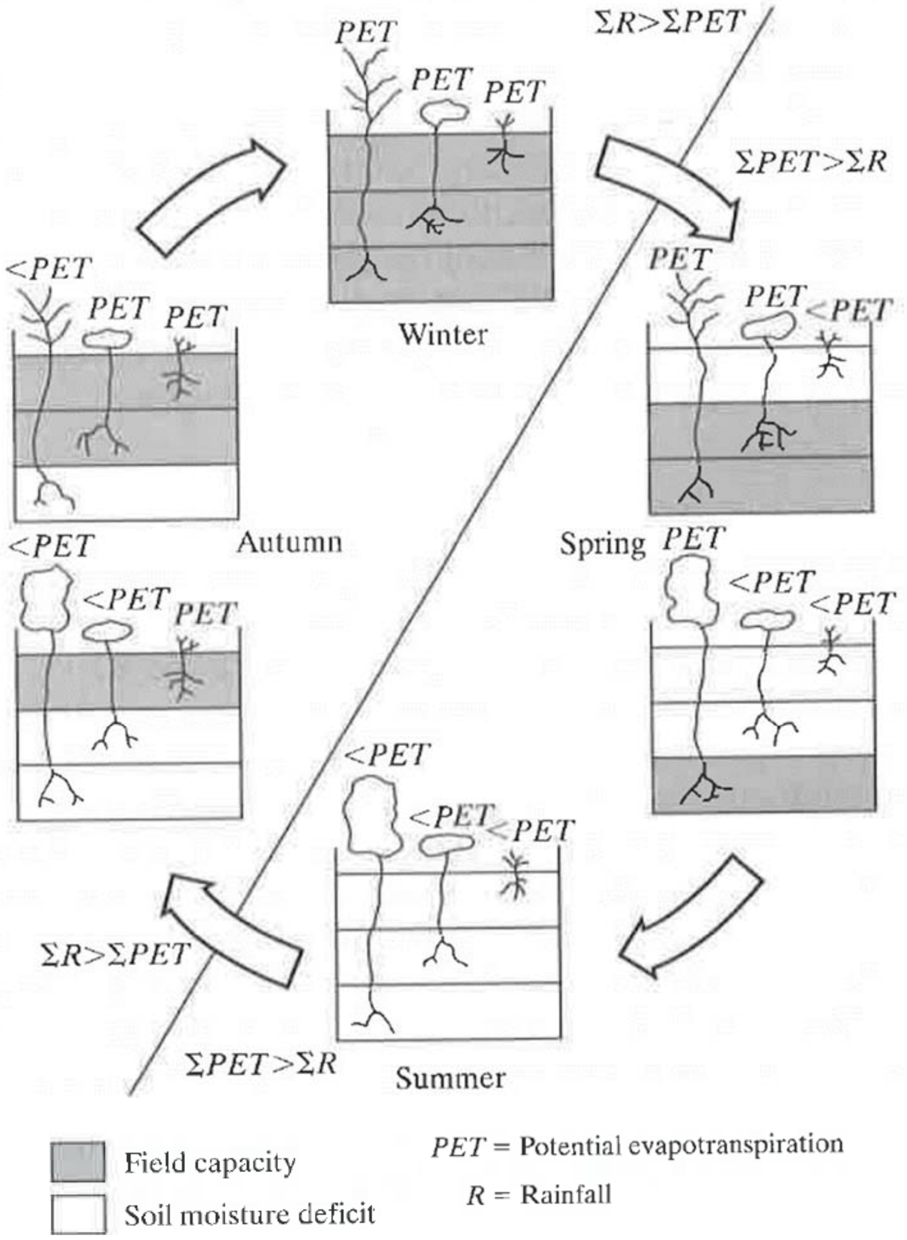

Figure 2.3: Idealized annual soil moisture cycle (Bendient et al., 2008).

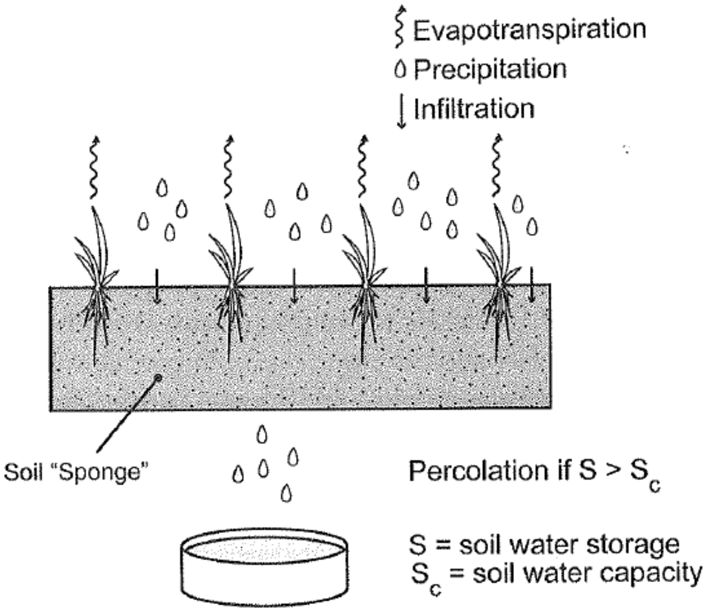

Figure 2.4: Conceptual function of ET cover systems (modified from Albright et al., 2004).

2.2.2 *Saturated Soil Properties and Flow Concepts*

During periods when the cover has a high quantity of water stored in the system, flow of water in the saturated soil may be described by Darcy's Law (Figure 2.5). Darcy's law describes the relationship between the flow rate of water (Q), hydraulic gradient [i, the difference in hydraulic potential (H) acting over the length of the flow path (L)], saturated hydraulic conductivity (k_s), and the cross-sectional area (A) of the soil through which flow is happening as follows:

$$Q = K_S \frac{\Delta H}{L} A = K_S i A \tag{2.1}$$

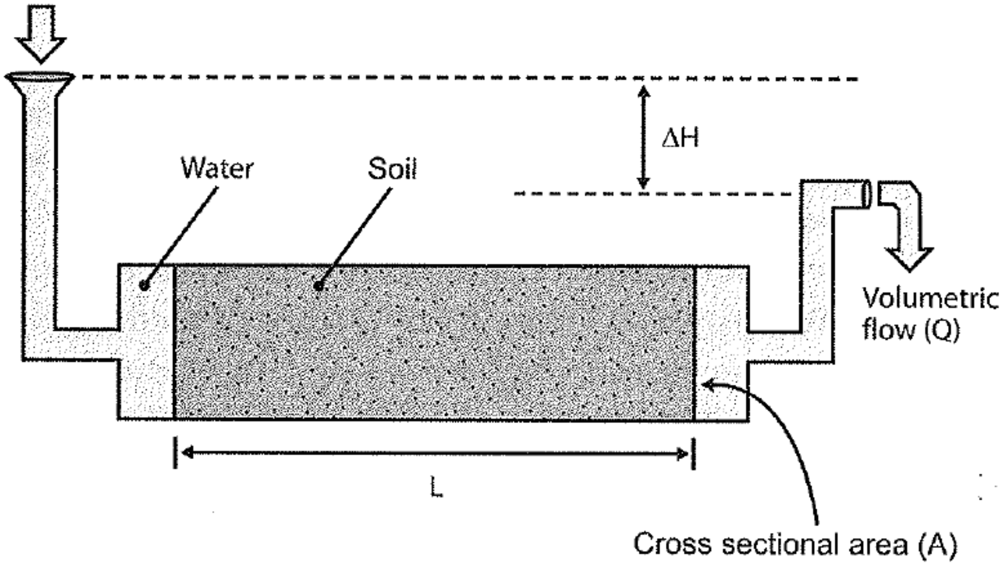

Figure 2.5: Saturated hydraulic conductivity schematic: measured flow through a porous media (modified from Albright et al., 2004).

2.2.3 *Unsaturated Soil Properties and Flow Concepts*

Water in the cover system in the soil pores is in tension and the pore water pressure is negative when the soil(s) is unsaturated. The negative pressure in the soils is matric suction (ψ) and is commonly referred to as suction. This concept of suction is provided in Figure 2.6; where capillary forces hold the water within the tube under tension (negative suction) above the water surface, and below the surface the water pressure is positive (increasingly as depth increases). The water in the soil is retained because of capillary forces that create suction by a similar effect as explained previously. Additionally, water is retained in unsaturated soil by adsorptive forces between the soil surface and water molecules (Albright et al., 2004).

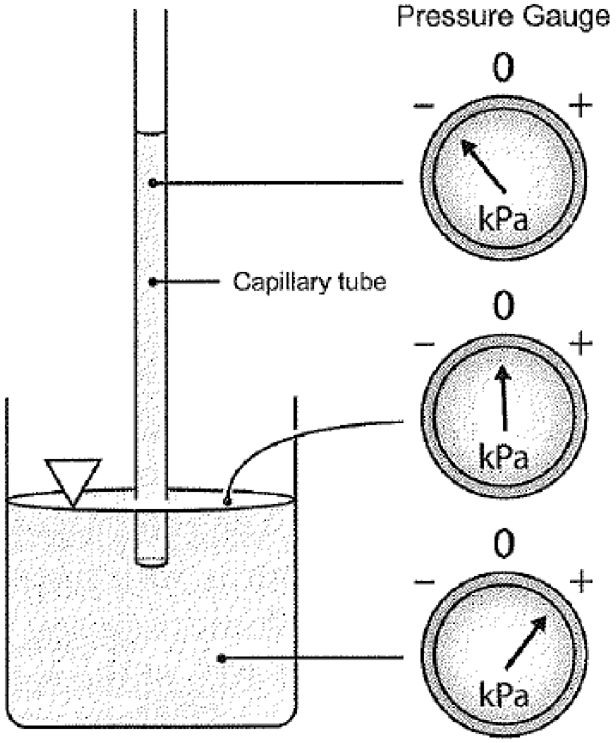

Figure 2.6: Illustration of suction concepts (Albright et al., 2004).

The water content for a soil as a function of suction can be described by the soil water retention curve (SWCC) (Figure 2.7). The SWCC incorporated the following terms and definitions:

- Saturated water content (Θ_s) – condition of soil at zero suction
- Residual water content (Θ_r) – driest condition of the soil, which corresponds to the water content below which water removal becomes practically impossible
- Air entry value (ψ_a) – suction at which the larges pores desaturate
- Field capacity (Θ_c) – generally determined as the moisture content at a suction of 33 kPa
- Wilting point (Θ_m) – generally described as the moisture content in the soil at a suction of 1,500 kPa (Albright et al., 2004).

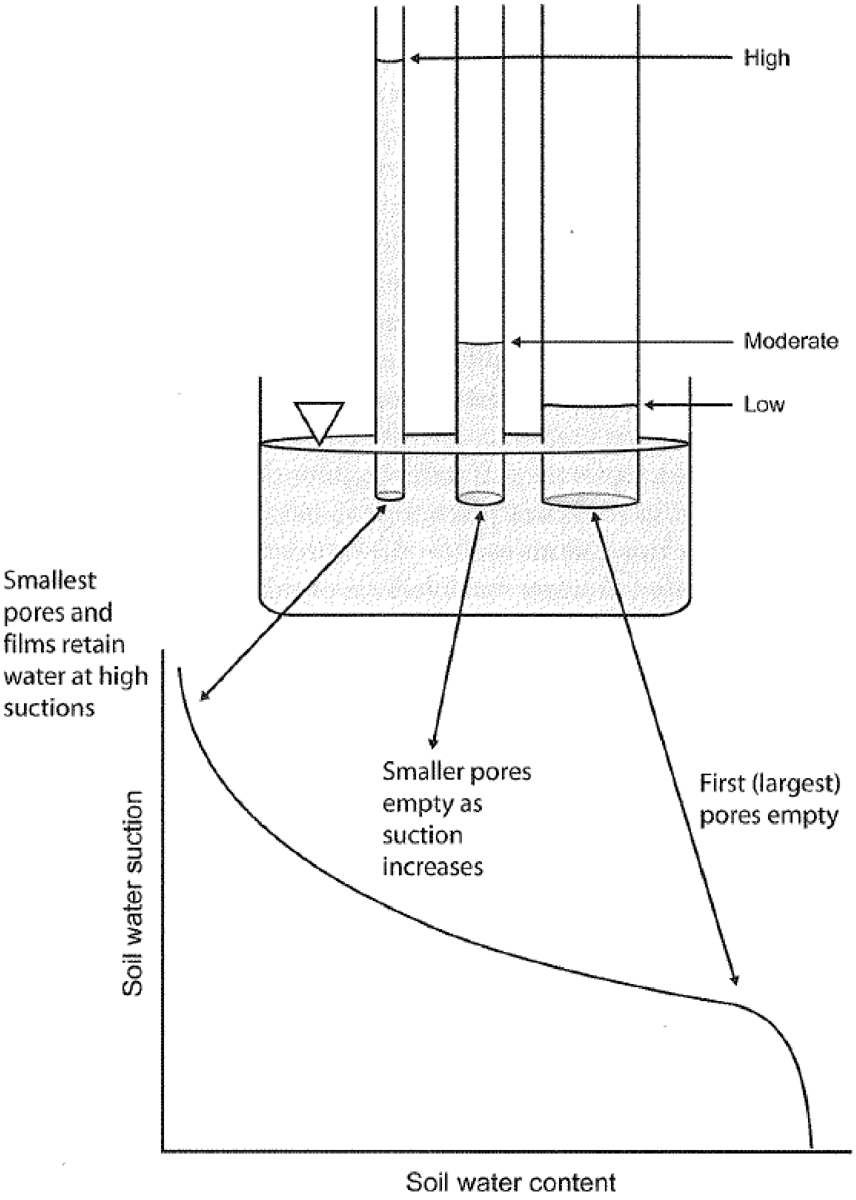

Figure 2.7: Schematic showing the relationship between pore diameter, suction at which water is held in pores of various size, and water content (Albright et al., 2004).

The hydraulic conductivity between saturated (maximum hydraulic conductivity) and dry conditions can decrease substantially as schematically shown in Figure 2.8 (although exaggerated). As the soil moisture content decreases in the soil (suction increases), pore spaces in the soil become partly or completely filled with air. As conduits that can transmit water through the soil become smaller and less numerous (at low water contents the soil may only exist as films on the soil particles), the hydraulic conductivity decreases (Figure 2.9).

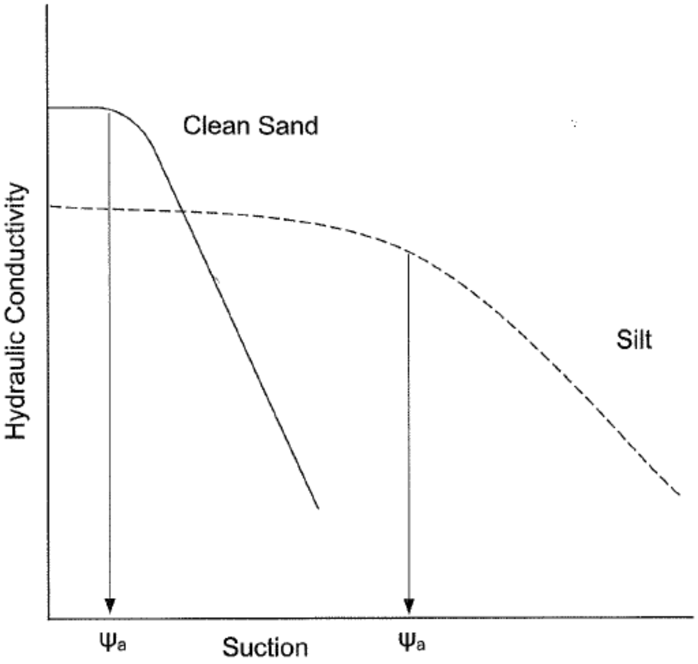

Figure 2.8: Relationship between soil suction and hydraulic conductivity (Albright et al. 2004).

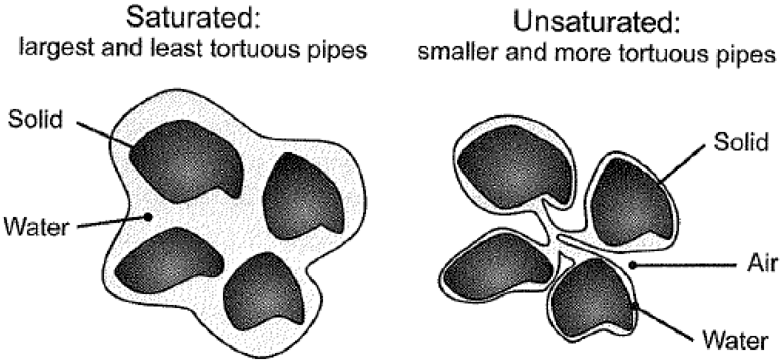

Figure 2.9: Simplified representation of the relationship between soil water content and the water-filled pore space that controls hydraulic conductivity (Albright et al., 2004).

2.2.4 *Soil Water Storage Concepts*

As mentioned previously, ET cover systems act as a sponge to prevent water from flowing through the bottom (percolation). The storage concepts of these ET cover system can be explained with Figure 2.10, Figure 2.11, and Figure 2.12. For ease of understanding and clarity purposes, the following quote from Albright et al. (2004) is provided:

> Two soils are submerged to saturation (Figure 2.10), one a clean uniform sand (relatively large particles of similar particle size) and the other a silty sand (a finer-textured and more broadly graded soil). The fraction of total soil volume occupied by pore space varies between soil textures, with finer-textured soils generally having a higher fraction of total soil volume as pores. However, for this example each soil is assigned a pore volume of 40% for the total soil volume, with the remaining 60% represented by soil grains. Thus, both soils have a porosity of 0.40.
>
> The two soils are raised out of the water and allowed to drain freely (Figure 2.11). Water will drain until the suction that develops in the pore water is large enough to resist the gravity forces causing drainage. Much more water drains from the sand than from the silt, which is intuitive. The sand has larger pores, and thus small suctions can develop to retain water within the pore structures. The amount of water remaining in the sand is about 10% of the total soil volume, whereas it is about 44% for the silty sand (these numbers are arbitrary, but do approximate actual soils and are meant to demonstrate concepts). These soils, which have drained freely and have reached equilibrium, are often described as being at field capacity water content (Θ_c). A variety of definition of field capacity exist, including (1) the amount of water the soil can hold against the force of gravity; (2) the amount of water left in the soil after draining from saturation by gravity for 24 or 48 hr; (3) the state of saturated soil when all the soil moisture that is able to freely drain away have done so; or (4) the water content corresponding to a suction of 33 kPa. This last definition, which is quantitative, is common in practice and is used henceforth.

When plants are added and roots exist through the soil (Figure 2.12), additional water can be removed by transpiration. Plants remove water until they wilt (i.e., the cessation of transpiration); this water content is referred to as the wilting point (indicated by the arrows in Figure 2.12), and is less than the field capacity. Wilting occurs when the plant can no longer maintain plant cell turgidity against the evaporative demand placed by the atmosphere on one end of the plant (the leaf surfaces) and the tension under which the soil water is held at the other end of the plant (the roots). Intuition may prove less useful in understanding the wilting point because, at this state, all soils may appear to be simply “dry” with little discernable difference in water content between soil textures. However, at the wilting point, the water content of the coarse-textured sand is lower than that of the finer-textured silt. Also, in this example, the water content of the silt at the wilting point is greater than that of the sand at field capacity.

By convention, the wilting point is often assigned as the water content at a suction of 1,500 kPa. However, the soil water content at the wilting point varies with plant species and with climate; desert plants often can transpire water to a much higher suction than plants from more humid environments. The 1,500 kPa definition is reasonably representative for plants in more humid environments, but for semi-arid and arid environments the wilting point can be 4,000 to 10,000 kPa.

…[ET] covers act as storage tanks that are filled when the rate of water addition by precipitation exceeds that of water removal by ET, and are emptied when ET exceeds precipitation. A full “storage tank” corresponds to field capacity (Θ_c) and an empty tank corresponds to the wilting point (Θ_m). The cover will not drain as long as the soil water content does not exceed field capacity and the water content in the cover will not drop below the wilting point. The difference between these two quantities ($\Theta_c - \Theta_m$) represents the volume of pore space that is available to store water per total volume of soil. This difference if referred to as the unit available storage ($\Theta_u = \Theta_c - \Theta_m$), and is used to determine the required thickness to store a known amount of water…

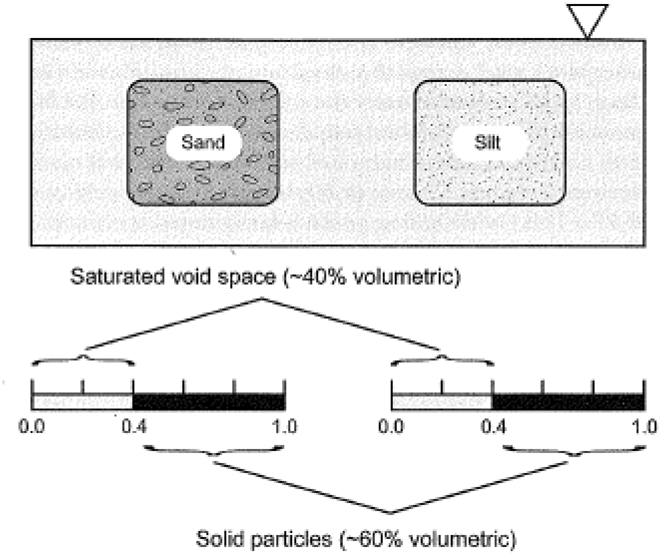

Figure 2.10: Schematic illustrating the void space concept (Albright et al. 2004).

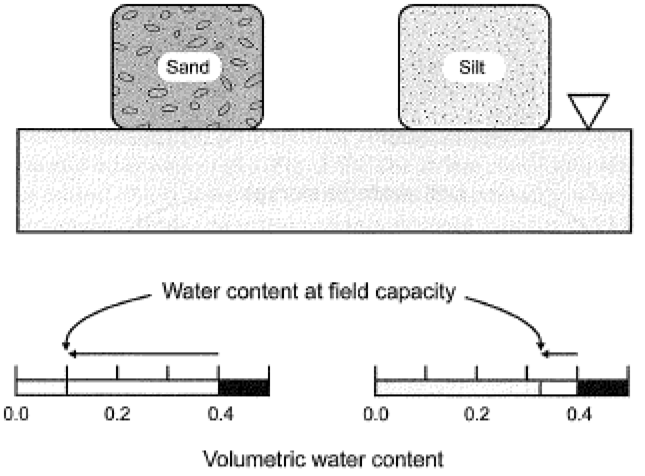

Figure 2.11: Schematic illustrating field capacity concept (Albright et al. 2004).

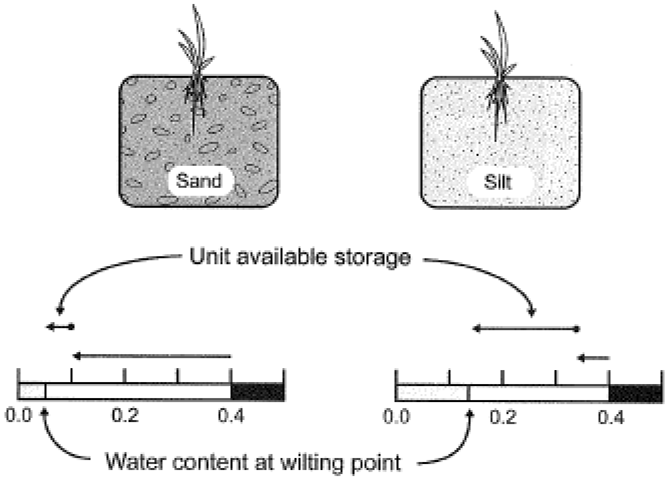

Figure 2.12: Schematic illustrating the wilting point concept (Albright et al. 2004).

2.2.5 *Water Balance Equation and Components*

The water balance equation which governs the inflow, outflow, and storage changes in these types of covers can be expressed as follows:

$$P_r = P - R - ET - \Delta SWS \tag{2.2}$$

Where; P is the precipitation, R is the runoff, P_r is the percolation through the bottom of the cover system, ET is evapotranspiration, and ΔSWS is the change in soil water storage over an arbitrary period of time (Figure 2.13). Information related to each of these parameters and their effect on the percolation are discussed subsequently.

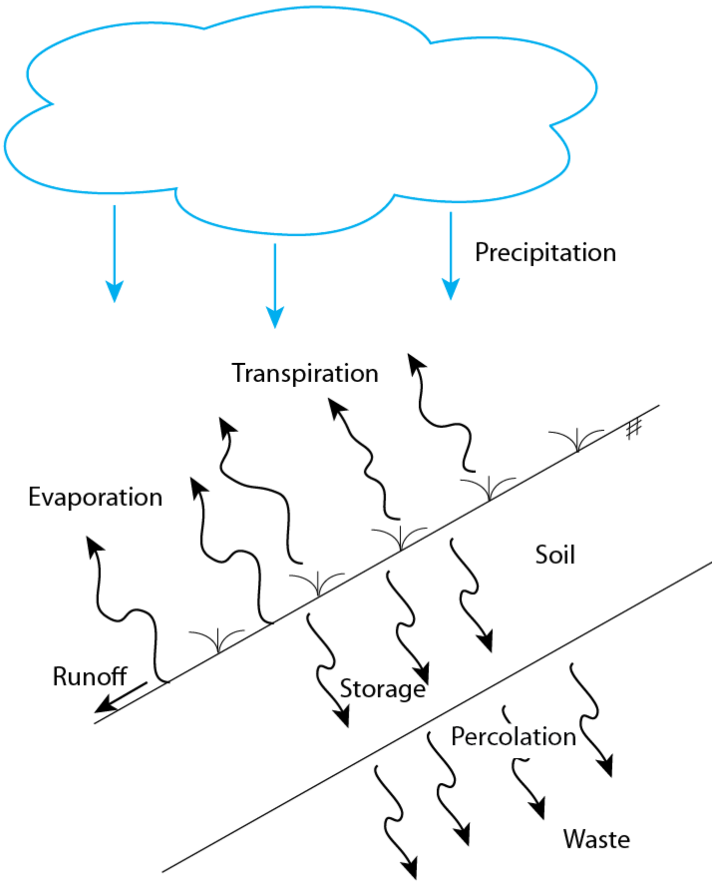

Figure 2.13: Schematic representing the cover system water balance for a landfill.

2.2.5.1 Precipitation (Meteorological)

The total quantity of precipitation as well as its form and distribution can have a large effect on the water storage capacity required for the cover system (Rock et al., 2012). For example, the cover system may be required to accommodate a spring snowmelt that results in the quantity of water at the cover to be relatively high; or winter (relatively low PET) with persistent light precipitation. It is important that the cover system has enough storage capacity for periods of time when vegetation is dormant (low PET). Meteorological conditions will have an effect on the other water balance equations and shall be discussed in their respective sections.

Albright et al. (2004) noted that the highest percolation rate and percentage of precipitation of the ACAP sites were produced by the alternative cover systems in humid areas. Alternatively, in seven (7) of the ten (10) alternative covers within arid, semiarid, and subhumid climates; very low precipitation rates (i.e. < 1.5-mm/yr and 0.2% of precipitation, on average) were measured. Additionally, five (5) of these covers transmitted less than 0.1-mm of percolation throughout the monitoring period. As mentioned previously, it was observed in the ACAP study that receiving precipitation during the winter months (October through March) when the ET rate is low, may also lead to higher percolation rates. Finally, percolation occurring during every wet season may be an indication that the alternative cover does not provide enough soil water storage capacity.

2.2.5.2 Runoff

The principle factors that have an effect on the surface runoff can generally be grouped into two (2) major types: (1) climatic factors (rainfall duration and intensity, season, and the meteorological or soil conditions prior to the storm) and (2) watershed factors (land slope, shape, soil, and land use).

The total quantity of runoff from a given precipitation events is related to the rainfall intensity and duration. The infiltration rate into a cover system will generally decrease with time in the initial stages of a precipitation event. Therefore, a short duration but higher intensity precipitation event may produce little to no runoff, whereas a lesser intensity but long duration precipitation event could result in substantial runoff. Rainfall intensity influence both the volume and rate of runoff produced by a precipitation event. The infiltration rate of a soil is exceeded by a greater margin for intense precipitation events than does a gentle rain. Therefore, the total volume of runoff is less for the gentle rain when compared to an intense rain even through the total quantity of precipitation for the two (2) events is the same. Additionally, an intense precipitation event may decrease the infiltration rate as a result of its destruction action on the soil surface structure.

There is a definite season pattern in many areas when major precipitation is likely to occur. Additionally, during the dormant season (i.e., winter), vegetation coverage may be significantly reduced causing an increase in runoff during precipitation events.

The meteorological conditions prior to a precipitation event may affect the soil moisture level of a cover system at the time of the event. Low temperature, winds, solar radiation, and high humidity may decrease evaporation and transpiration. Therefore, increasing (or minimizing the rate of decrease) the soil moisture content in the cover system (providing less storage) and decreasing infiltration.

The infiltration can be substantially impacted by frozen soil and frost depth. When frozen conditions are present, little or no infiltration may occur when moderate or high infiltration rate would have occurred during non-frozen conditions.

The typical landfill incorporates a relatively steep sideslope and a relatively flat top deck (Figure 2.14); therefore, slope effects on runoff is critical. The major effect of cover system slope is on the rate of runoff (runoff will flow faster on a steeper slope), and has a minor effect on the runoff volume. Depression in the soil surface can reduce runoff or even create pools of water. ACAP results found that the surface runoff was statistically independent of the cover slope (Albright et al., 2002). However, the relatively small size of the test sections utilized in the study compared to the typical landfill cover may have caused the lack of a slope effect (Albright et al., 2002). It should be noted that the density of vegetation and hydraulic conductivity of the cover soil (i.e., atmosphere interface factors) have a greater influence on surface runoff than the presence of a resistive barrier layer (e.g., geomembrane liner system) within the cover soil (Albright et al., 2002). Alternatively, Nyhan (2005) concluded that daily runoff had a significant relationship with both slope and time (seasonality of flow). Nyhan (2005) also recommended an ET cover slope of 15% to maximize evaporation and minimize seepage, and would incorporate a system to collect and divert the interflow water away from the waste mass.

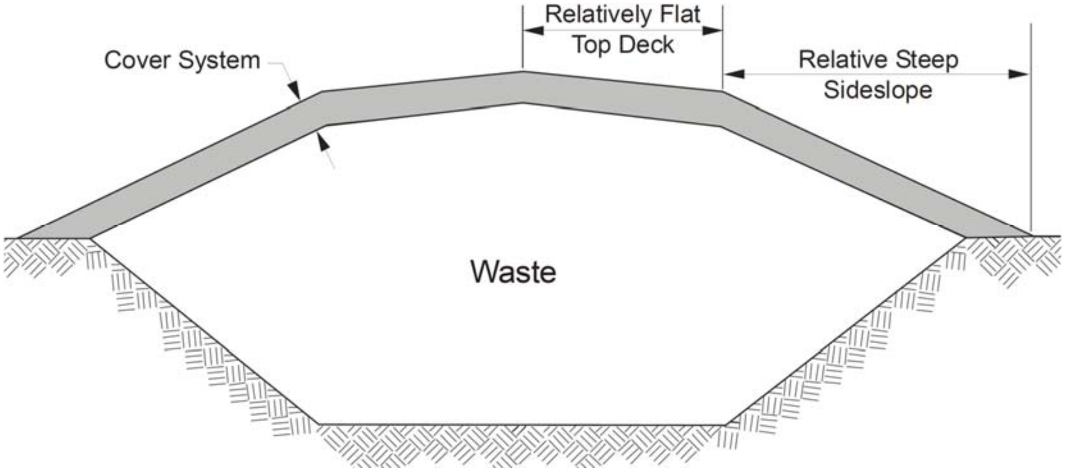

Figure 2.14: Typical landfill cover system (USEPA, 2004).

The type of soil incorporated into the cover system will have a major effect on the runoff due to the differences in infiltration rate for various soils. The rate of infiltration into the cover system will be limited by the infiltration rate (hydraulic conductivity) of the soil, and runoff will occur when the rainfall intensity exceeds the soil infiltration rate (hydraulic conductivity). Therefore, soils with low infiltration (or hydraulic conductivities) rates (i.e., clays and silts) will tend to result in greater amounts of runoff when compared to higher infiltration rate soils (i.e., sands). Hydraulic properties such as the saturated hydraulic conductivity (k_s) and the soil water characteristic curve (SWCC) have a large influence on the percolation rate through landfill final cover and into the underlying waste (e.g., Khire et al., 1997; Ogorzalek et al., 2008; and Bohnhoff et al., 2009).

The vegetation growing on the cover system will have a significant influence on infiltration from precipitation; therefore, have a significant influence on runoff. The infiltration rate is greater (lowest runoff) for grassland when compared to bare soil. The root systems of the vegetation will perforate the soil, keeping it unconsolidated and porous; therefore, increasing the infiltration and decreasing the rate of runoff. Vegetation residues protect the soil surface from raindrop impact and reduce the particle breakup; therefore, reducing erosion of the cover system soil. Vegetation serves to provide obstruction to runoff and surface roughness; therefore, reducing the velocity of surface flow and providing a greater time period for infiltration to occur.

ACAP results showed that surface runoff was generally a small fraction of the water balance, ranging from 0.0% to 10.2% of the precipitation (Albright et al. 2002).

2.2.5.3 Evapotranspiration

Evaporation is the process that water in liquid or solid state is transformed into water vapor, which mixes with atmosphere. Transpiration is the loss of vapor through the small openings in the vegetation tissues (e.g., leaves), and normally only occurs during hours of photosynthesis (typically only during daylight hours). The combination of evaporation and transpiration is known as evapotranspiration (ET) and the maximum ET is referred to as potential ET (PET). Actual ET is less than or equal to PET, and PET is commonly computed by the Penman-Monteith equation as follows:

$$PET = \frac{\left(\frac{\delta}{\xi}\right)J_n + 0.35\left[(e_s - e)\left(0.5 + \frac{U}{100}\right)\right]}{\frac{\delta}{\xi} + 1} \tag{2.3}$$

Where δ is the reate of change in e_s with temperature, ξ is the psychrometric constant, J_n is the net solar radiation, e_s is the saturated vapor pressure corresponding to the air temperature 2-meters above ground surface, e is the atmosphereic vapor pressure at 2-meters above ground surface, and U is the wind velocity at 2-meters above ground surface. This equation concludes that the rate of ET is affected by several factors as follows:

- Temperature – the rate of ET decreases as the temperature decreases;
- Humidity – as the humidity increase, the rate of ET decreases;
- Wind speed – the rate of ET increases as the wind speed increases;
- Water availability – ET will not occur if the soil in the cover system is dry;
- Soil type – the type of soil determines ease of which water is removed by ET; and
- Plant type – as discussed previously, some plants are able to remove more water from the soil than others and rate of transpiration differs for various plant species.

Nyhan et al. (1997) stated that evaporation tends to increase with an increase in slope, suggesting that it was due to the ability of larger slopes to intercept more solar radiation. This usually results in a decrease in the interflow and percolation within the slope of the cover (Nyhan 2005). It was shown by Barnswell and Dwyer (2011) that considerably greater percolation was produced with immature plant mixtures in comparison to mature plant mixtures within lysimeters. Additionally, the amount of percolation produced by extreme rain events is affected by the time within the growing season that such an event occurs (Barnswell and Dwyer 2011). The ACAP study concluded that instances that the vegetation does not effectively remove water from the cover soil (causing an insufficient quantity of soil water storage) may lead to higher than average percolation rates at a site. It is suggested that pedogensis and maturity of the vegetation may cause the behavior of the cover systems to change in humid climates. Additionally, the root channels and desiccation cracks may form throughout the cover depth during drying periods (Albright et al. 2004). Soil covers typically have large inventories of water at the start of spring, and gradually decreased to a minimum during the fall (Nyhan 2005). The evapotranspiration during these times of high PET cause the upper portion of the cover to gradually dry and the water in the lower portion begins to move upward (Hillel 1971; Suleiman and Ritchie 2003). A plant community which has roots throughout the cover and active year-round would be ideal for an ET covers (Nyhan 2005). Additionally, placing vegetation (such as evergreen shrubs) to reduce percolation due to large snow melts is recommended for ET cover systems (Nyhan 2005).

2.2.5.4 Soil Water Storage

The ability of the cover soil to provide sufficient water storage capacity to control moisture and water percolation into the underlying waste is a critical design feature of ET cover systems. The storage capacity of ET cover systems typically accounts for the unsaturated and saturated hydraulic properties of the cover soils (as previously discussed), soil type, soil thickness, and other factors that may result in an increase or decrease in the ability of soil to store water.

As previously discussed, the type of cover soil is a critical factor in the quantity of storage of the cover system. Fine-textured soils (silts and clays) are typically utilized in the ET cover sections as they have greater porosity; therefore, greater storage capacity when compared to sandy soils. Additionally, the storage capacity of a soil is dependent on the quantity of fine-textured particles and the bulk density. It has been noted by Anderson et al. (1993) that the bulk density of the soil can change over time. Where the bulk density of a silt loam was compacted to 14 kN/m^3; and in four growing seasons, the bulk density had decreased to approximately 12.6 kN/m^3.

The thickness required of the storage layer depends on the required storage capacity based upon the other water balance factors. The storage layer(s) may be required to accommodate time periods when ET rates are low and/or when plants are dormant, or extreme weather conditions (e.g., extreme precipitation events or snowmelts). Intuitively, the greater the soil thickness incorporated into the cover system, the greater the storage capacity for a certain soil type.

It should be noted that Nyhan (2005) found that there was a relationship between the soil water storage within the cover with both slope and time (seasonal inventory).

The hydraulic properties and storage capacity of cover systems may change over the service life of the cover due to the natural pedogensis processes such as insect and animal burrowing, freeze-thaw cycling, wet-dry cycling, and plant root growth (Chamberlain and Gow 1979; Beven and Germann 1982; Suter et al. 1993; and Albrecht and Benson 2001). Albrecht and Benson (2001) concluded that soils that desiccation cracked during drying showed the hydraulic conductivity of the soil to increase by as much as 500 times. Additionally, extended periods of hydration are unlikely to heal the damage as a result of desiccation (unless there is a considerable increase in effective stress).

The required thickness of a monolithic ET cover can be estimated based upon the SWCC and anticipated water storage requirement as follows (Albrecht et al., 2004):

1. Determine the water content at the wilting point (θ_m) at 1,500 kPa and field capacity (θ_c) at 33 kPa, utilizing either the van Genuchten's equation or estimated visually from the SWCC.
2. Estimate the required thickness (L) utilizing the the following equation and the required storage (S_r):

$$L \geq \frac{S_r}{\theta_c - \theta_m} \tag{2.4}$$

3. Determine the suction (ψ_T) and water content (Θ_T) at the top of the cover assuming an equilibrium gradiant, utilizing the following equation and van Genuchten's equation or the SWCC:

$$\psi_T = 33\ kPa + (L * \gamma_w) \tag{2.5}$$

4. Determine the average water content of the cover at field capacity utilizing the following equation:

$$\theta_c = \frac{\theta_c - \theta_T}{2} \tag{2.6}$$

5. Use the average water content calculated in Step 4 as Θ_C in Equation 2.3 to recompute the cover thickness.
6. Repeat steps 3 through 5 until the thickness no longer considerably changes.

2.3 Cover Performance Evaluation Systems

2.3.1 *Introduction*

Lysimeters are typically used to measure moisture fluxes through soil and several issues must be addressed in their design. Several of these issues include the geometry of the lysimeter, the hydraulic properties of the backfill, and the anticipated infiltration rate (Bews et al., 1999). Additionally, understanding and accounting for preferential flow through macrofeatures (i.e., holes, burrows, cracks, etc.) and spatial variability (i.e., heterogeneity in vegetation and hydraulic properties) is essential for a quality lysimeter design. These factors can substantially affect the percolation through the soil and thus a lysimeter large enough to accurately (compared to soil systems outside of the lysimeter) account for such factors (Malusis and Benson 2006). It is suggested by Benson et al. (2001), that a lysimeter having area dimensions of 10 x 10-m (33 x 33-ft.) is required to adequately represent these preferential flow and spatial variability factors.

The resolution of percolation rate of some carefully designed pan lysimeters [i.e., the Alternative Cover Assessment Program (ACAP)] can be as low as 0.1-mm/yr (Benson et al. 2001). However, there are some major drawbacks of the large-scale pan lysimeter that can adversely affect the accuracy of the measured percolation. Several of the most significant drawbacks of the pan lysimeter are:

- The base geomembrane used to collect the percolated water can cause a barrier to the vapor diffusion;
- The interface between the cover soil and underlying drainage material may result in a capillary break effect;
- They are costly and difficult to construct and thus limiting the number of lysimeters that can be installed; and
- Possible leaks or malfunctions in the base geomembrane which may prevent the collection of all percolated water (Malusis and Benson, 2006).

These drawbacks are discussed subsequently.

2.3.2 *Vapor Diffusion*

The geomembrane at the base of the lysimeter creates a thermally driven vapor flow barrier causing a conservative error in the measured percolation rate (Malusis and Benson 2006). Upward flow of water when atmospheric temperatures are cooler (winter) is blocked but not collected by the geomembrane at the base of lysimeter, and the downward flowing water due to thermal gradients when atmospheric temperatures are warmer (summer) is blocked and collected by the lysimeter (Malusis and Benson 2006). The thermal fluxes caused by the warmer atmospheric temperatures can be as large as 1-mm over a three-month period (Malusis and Benson 2006).

2.3.3 *Capillary Break Effect*

The contrasting hydraulic properties between the cover soil and drainage layer (e.g., geocomposite drain) can cause a capillary break effect and could result in an underestimation of the percolation rate (Malusis and Benson 2006). Flow of the infiltrated water into the drainage system may be prevented by the capillary break effect until the cover soil above the drainage system is nearly at saturated conditions (Malusis and Benson 2006). Water contents of the soil immediately above the drainage system being greater than the field capacity without causing percolation is an indication of the capillary barrier effect (Malusis and Benson 2006).

Such capillary effects can be negligible if similar capillary breaks are expected outside the lysimeter, or coarse-grained soils overlay the drainage layer (Malusis and Benson 2006), or if the capillary effect barrier is deep enough that the soil can act as an infinitely long column (Albright et al., 2002). Covers which are placed on municipal solid waste having air entry suctions approximately 0.01-0.03-m or underlain by a coarse-grained biota barrier (e.g., crushed rock) can lead to negligible capillary effects within the lysimeter (Malusis and Benson 2006). It should be noted that the capillary break in the actual field conditions at many waste disposal sites is represented by the capillary break created within the pan lysimeter (Albright et al., 2002). However, if the capillary effects are not negligible, the capillary effect can be minimized by installing a geosynthetic root barrier above a fine-textured interim cover soil located between the drainage layer and the base of the cover (Malusis and Benson 2006). Uptake of water within the interim cover soil by the root system is prevented by the root barrier and flow if prevented because of the capillary effect from the drainage layer below. As a result, the interim cover soil remains wet after it is wetted for the first time (Malusis and Benson 2006). Additionally, the capillary break affect can be corrected by using an automated equilibrium tension lysimeter (AETL). The water status at the bottom of the soil profile is continuously adjusted such that conditions outside and inside the lysimeter are in equilibrium (Masarik et al. 2004).

The capillary effect can be assessed by the construction of a soil column implemented with tensiometers (Stormont and Anderson 1998).

2.3.4 *Alternatives*

Drainage (pan or weighing lysimeters provide the most reliable and direct evaluation of the soil-water balance of alternative earthen final covers (Gee and Hillel 1988); however, several alternatives are available that can directly or indirectly measure moisture flux and/or percolation through a soil structure. Several alternatives such as water content and potential sensors are generally at least one order of magnitude less precise than measurements made by a lysimeter (Benson et al. 2001). Examples of alternative measurement methods are:

- Flux meters,
- Soil moisture sensors,

- Electrical resistivity, and
- Thermal Conductivity probes.

Flux meters are useful to provide direct point measurements of percolation, but may not accurately represent the spatial variability and preferential flow that can be present in large scale cover systems (Malusis and Benson 2006).

Soil moisture sensors can and have been used for qualitative and quantitative monitoring of ET cover systems (Malusis and Benson 2006). Monitoring if the wetting front has reached the base of the cover or verifying that the removal and storage of water is occurring by monitoring the temporal variation in water content or soil-water storage are examples of qualitative applications of soil moisture sensors (Malusis and Benson 2006). Quantitative applications of soil moisture sensors comprise of calculating percolation by using the water-content data and establishing a soil-water storage or “threshold” water content, which if exceeded, causes unsatisfactory cover performance (Malusis and Benson 2006). Darcy’s law requires the hydraulic properties of the cover soil to be established to calculate percolation rates from the water content data provided by the soil moisture sensor (Malusis and Benson 2006). Such required hydraulic properties include the saturated hydraulic conductivity and the soil water characteristic curve (SWCC), and a theoretical model is used to define the unsaturated hydraulic conductivity function (Malusis and Benson 2006). Although these calculations are simple and straightforward, they are prone to substantial errors due to spatial variability, pedogensis, inaccuracies in the hydraulic conductivity model, scale effects, and preferential flow (Malusis and Benson 2006). Uncertainties due to ambiguities in the drift of the instrument calibrations and hydraulic gradient can confound soil moisture sensor quantitative applications (Malusis and Benson 2006). However, utilizing soil moisture sensors within the lysimeter can provide multiple beneficial attributes. Incorporating multiple sensor nets (i.e., a group of moisture sensors in close proximity) inside and outside of the lysimeter can assess boundary effects and obtain an understating of site-wide spatial variation, may be useful in identifying mechanisms possibly responsible for non-compliance of the cover. Additionally, soil moisture sensors can be useful in assessing the hydrologic processes that affect percolation (e.g., root water uptake or soil water storage), or ensuring the lysimeter reliability (Malusis and Benson 2006).

Schnabel et al. (2012) conducted an evaluation of soil moisture content within an ET lysimeter using electrical resistivity tomography (ERT). It was thought that utilizing ERT will provide soil moisture data over a much larger area of soil than could be obtained from nested soil moisture probes (Schnabel et al. 2012). The soil moisture data over a larger area could allow for quantification and visualization of heterogeneous areas which may be undetectable when utilizing other measuring devices (Schnabel et al. 2012).

Thermal conductivity probes have been used within a lysimeter by Abichou et al. (2005) to provide a matric suction profile in the soil. These thermal conductivity probes were placed at the same depth as the moisture content sensors within the lysimeter and calibrated using a soil sample obtained from the same location and depth as where they were placed (Abichou et al. 2005).

2.4 Previous Studies on Cover Systems

2.4.1 *Introduction*

Landfill cover systems have been evaluated by a number of researchers in the past. Conclusions from different studies do not always completely agree; and multiple instrumentation and monitoring methods have been utilized to study landfill cover systems. Information, results, and conclusions from select cover system studies are provided subsequently.

2.4.2 *Northwestern Ohio Drainage Lysimeter Study*[1]

Barnswell and Dwyer (2011) utilized lysimeters in an effort to design ET covers for MSW landfill in northwestern Ohio which would produce percolation rates of less than 32 cm/year. The ET covers were constructed in six (6) drainage lysimeters (1.52-m diameter and 1.52-m depth) as shown in Figure 2.15. The lysimeters incorporated a conical bottom containing coarse sand to allow for percolation collection and a PVC pipe that extended along the sidewall. A pump was installed in the PVC pipe and operated daily for percolation removal. The ET cover systems incorporated dredged sediment and was either seeded with native plants consisting of species commonly found in tall-grass prairies (immature plants) or had plants transferred from a tall-grass prairie which had been restored for more than 10 years (mature plants). Plant

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[1] For clarity and brevity, ideas provided in this section are courtesy of Barnswell and Dwyer. (2011) unless otherwise noted.

species which were not originally planted were eliminated throughout the study period. The cover systems were watered at a rate of 31.12 to 95.72 cm/year and included a simulated 100-year rainfall event (11.7 cm over a period of 24 hours) in July and another in October. The ET cover systems were monitored over a 1-year period.

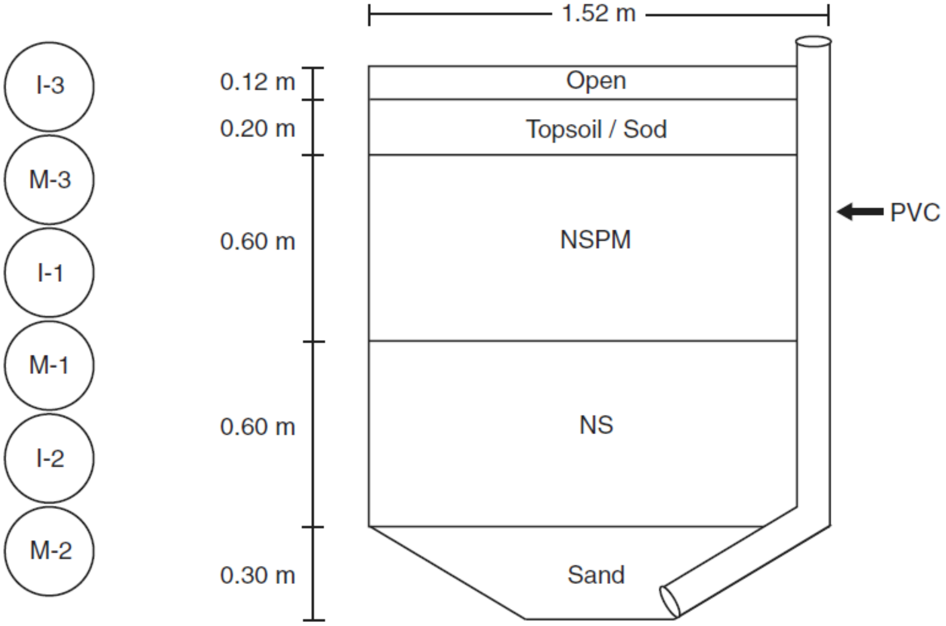

Figure 2.15: Drainage lysimeters: (left) plan view of the six drainage lysimeters with the experimental treatments (M = mature plant mixture, I = immature plant mixture); (right) details of the in-ground drainage lysimeter (Barnswell and Dwyer, 2011).

The 100-year rainfall events caused a significant increase in the soil water storage of the ET covers and resulted in considerable amounts of percolation in all of the lysimeters but M-3. It was indicated by Barnswell and Dwyer (2011) that in M-3 the water was being removed from the cover system by ET during the growing season and allowed for the water from the 100-year rainfall event in October to be stored in the system without exceeding the storage capacity. Additionally, it was found that both plant mixtures were able to remove the stored water from the cover system; however, the mature plant mixture was able to remove greater amounts of water. This was the expected result as the rate of ET is influenced by root depth and density (Ehlers et al. 1991), biomass production (Hanks 1974), leaf area (Vertessy et al. 1995), and others as previously discussed. All of which increases with an increase in plant development. An increase in water storage was measured during the winter months (during plant mixture dormancy) and resulted in percolation in four (4) of the six (6) cover systems. It was observed that the ET cover systems planted with an immature plant mixture produced considerably more percolation than the cover systems tested with mature plant mixture. Additionally, it was suggested that the time period during the growing season in which extreme rainfall events occur in an important factor in the production of percolation. It appeared that extreme rainfall events during the early or mid-stages of the growing season may result in greater percolation when compared to those occurring during the later stages.

2.4.3 *ACAP Test Plots*[2]

The USEPA Superfund Innovative Technology Evaluation Program initiated the Alternative Cover Assessment Program (ACAP) in 1998 as a cooperative program of private, regulatory, and research organizations (Albright, 1998; Bolen et al., 1992). ACAP consisted of 24 10-m x 20-m test sections [14 alternative cover and ten (10) conventional cover system] constructed at 11 different sites (Figure 2.16, Table 2.1, Table 2.2, Figure 2.17, Figure 2.18, and Figure 2.19) (Albright et al., 2004). The monitoring sites represented climate ranging from humid to arid and from cold to hot; and at several of the sites [eight (8) sites], side-by-side comparisons of cover systems were made.

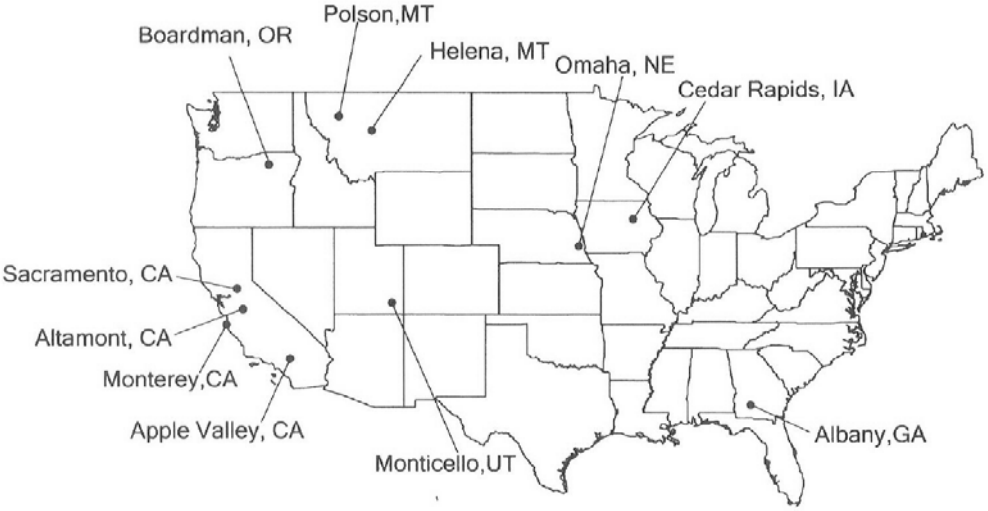

Figure 2.16: Locations of alternative cover assessment project (ACAP field studies (Albright et al., 2004).

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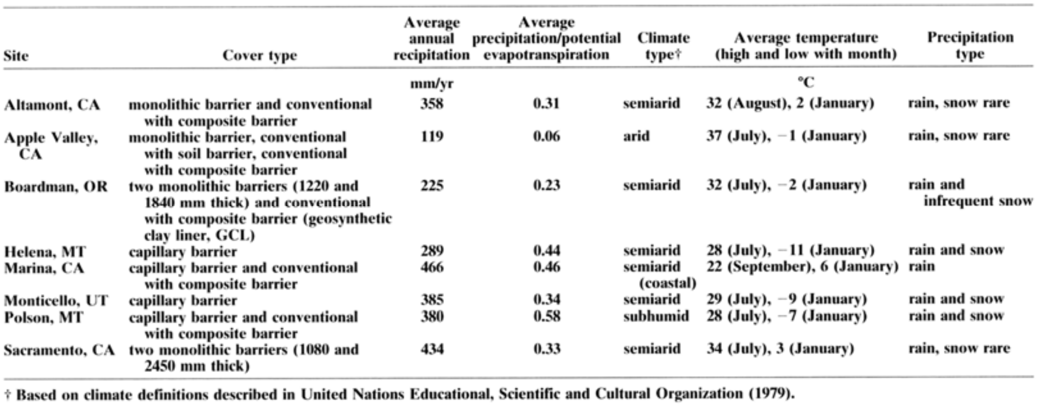
[2] For clarity and brevity, ideas provided in this section are courtesy of Albright et al. (2004) unless otherwise noted.

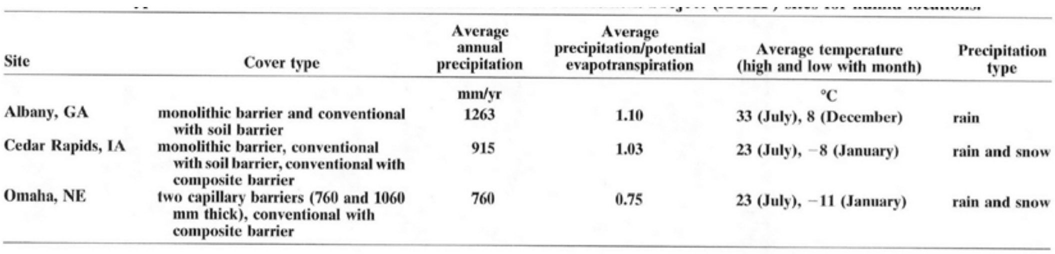
Table 2.1: Cover types and climate characteristics of Alternative Cover Assessment Project (ACAP) sites for arid, semiarid, and sub-humid locations (Albright et al., 2004).



Site	Cover type	Average annual recipitation	Average precipitation/potential evapotranspiration	Climate type†	Average temperature (high and low with month)	Precipitation type
		mm/yr			°C	
Altamont, CA	monolithic barrier and conventional with composite barrier	358	0.31	semiarid	32 (August), 2 (January)	rain, snow rare
Apple Valley, CA	monolithic barrier, conventional with soil barrier, conventional with composite barrier	119	0.06	arid	37 (July), −1 (January)	rain, snow rare
Boardman, OR	two monolithic barriers (1220 and 1840 mm thick) and conventional with composite barrier (geosynthetic clay liner, GCL)	225	0.23	semiarid	32 (July), −2 (January)	rain and infrequent snow
Helena, MT	capillary barrier	289	0.44	semiarid	28 (July), −11 (January)	rain and snow
Marina, CA	capillary barrier and conventional with composite barrier	466	0.46	semiarid (coastal)	22 (September), 6 (January)	rain
Monticello, UT	capillary barrier	385	0.34	semiarid	29 (July), −9 (January)	rain and snow
Polson, MT	capillary barrier and conventional with composite barrier	380	0.58	subhumid	28 (July), −7 (January)	rain and snow
Sacramento, CA	two monolithic barriers (1080 and 2450 mm thick)	434	0.33	semiarid	34 (July), 3 (January)	rain, snow rare

† Based on climate definitions described in United Nations Educational, Scientific and Cultural Organization (1979).

Table 2.2: Cover types and climate characteristics of Alternative Cover Assessment Project (ACAP) sites for humid locations (Albright et al., 2004).



Site	Cover type	Average annual precipitation	Average precipitation/potential evapotranspiration	Average temperature (high and low with month)	Precipitation type
		mm/yr		°C	
Albany, GA	monolithic barrier and conventional with soil barrier	1263	1.10	33 (July), 8 (December)	rain
Cedar Rapids, IA	monolithic barrier, conventional with soil barrier, conventional with composite barrier	915	1.03	23 (July), −8 (January)	rain and snow
Omaha, NE	two capillary barriers (760 and 1060 mm thick), conventional with composite barrier	760	0.75	23 (July), −11 (January)	rain and snow

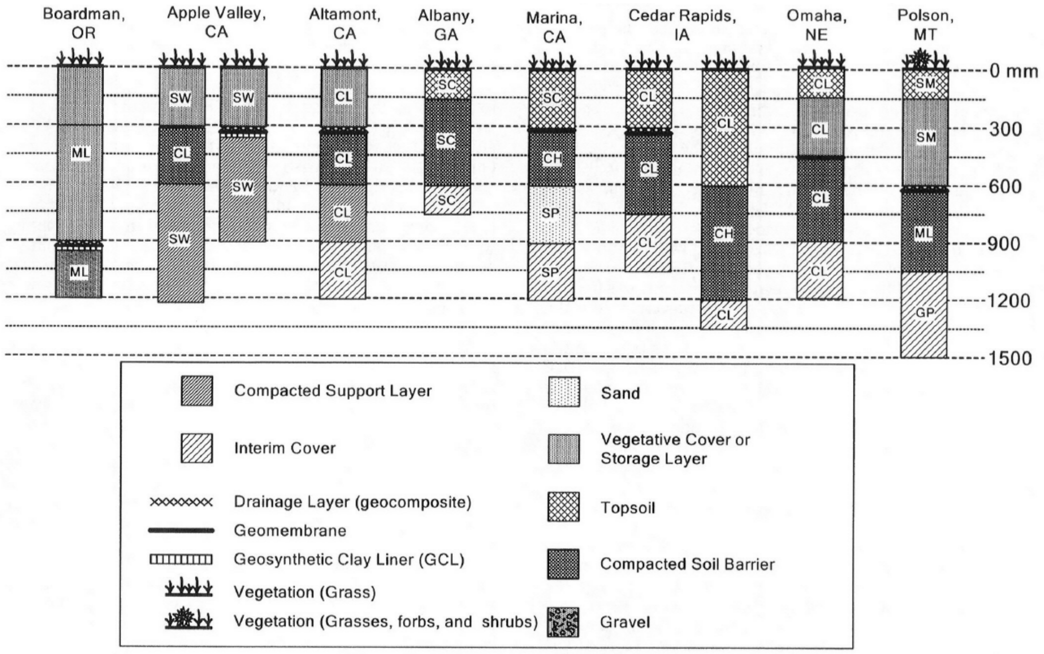


Figure 2.17: Profiles for conventional covers evaluated by the Alternative Cover Assessment Project (ACAP). Two-letter designations are designations in the Unified Soil Classification System per ASTMD D-2487: CL, low-plasticity clay; CH, high-plasticity clay; GC, clayey gravel; GP, poorly graded gravel; ML, low-plasticity silt; SC, clayey sand; SM, silty sand; SP, poorly graded sand; and SW, well-graded sand (Albright et al., 2004).

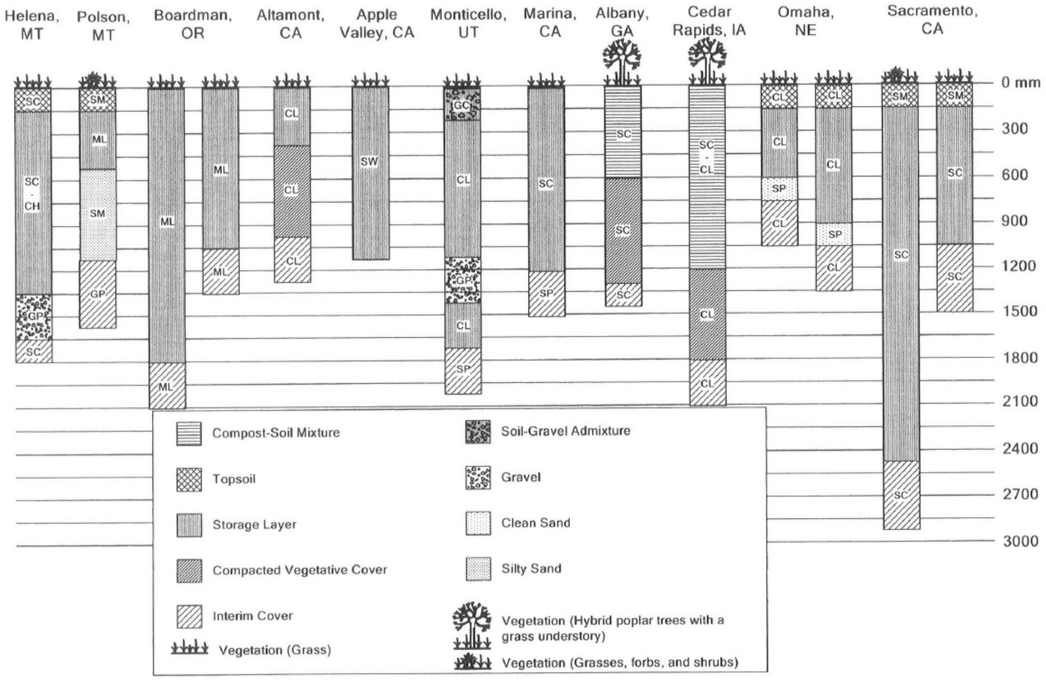


Figure 2.18: Profiles for alternative covers evaluated by the Alternative Cover Assessment Project (ACAP). Two-letter designations are designations in the Unified Soil Classification System per ASTMD D-2487: CL, low-plasticity clay; CH, high-plasticity clay; GC, clayey gravel; GP, poorly graded gravel; ML, low-plasticity silt; SC, clayey sand; SM, silty sand; SP, poorly graded sand; and SW, well-graded sand (Albright et al., 2004).

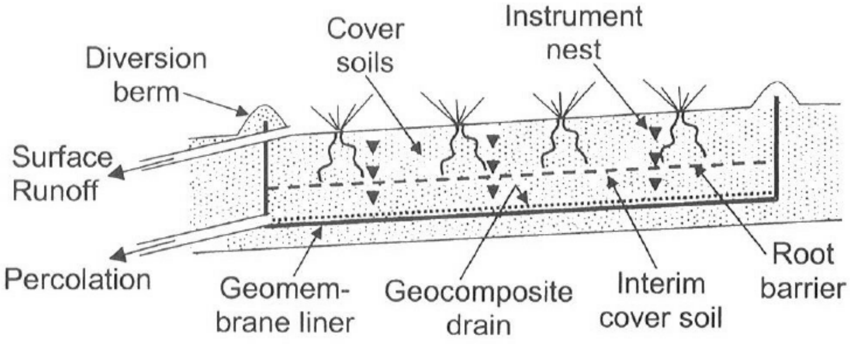


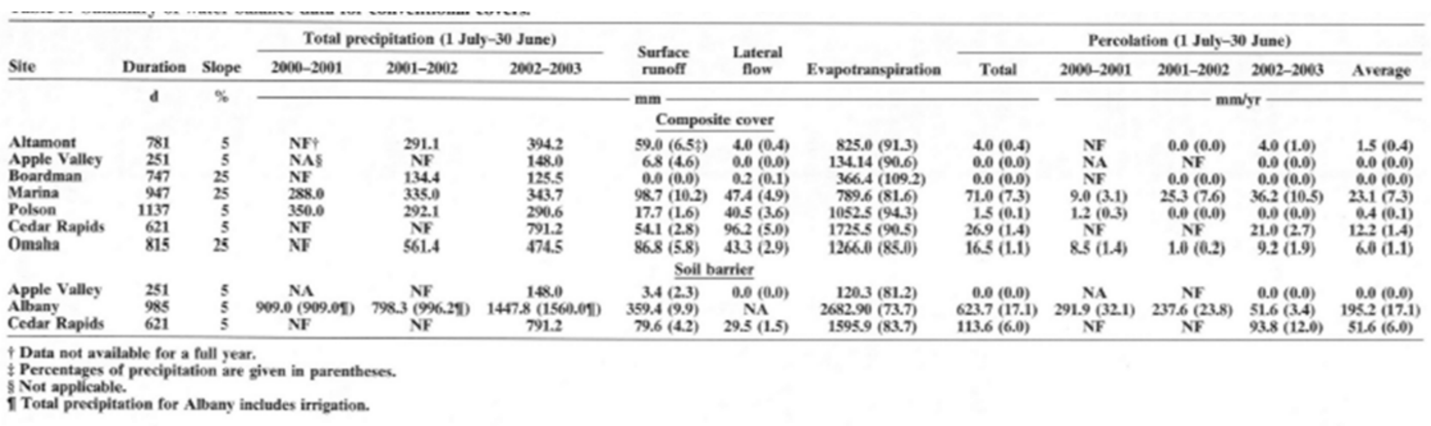
Figure 2.19: Schematic of lysimeter used for monitoring the water balance of the Alternative Cover Assessment Project (ACAP) test sections (Albright et al., 2004).

The water balance quantities for the test sections of ACAP are summarized in Table 2.3 and Table 2.4. As indicated in the tables, surface runoff was generally a small fraction of the water balance, averaging 3.8% of the precipitation and ranging from 0 to 10.2%. It was observed that there was no statistically significant difference ($p > 0.05$) between the means of the data sets (type of cover, slope of cover, and climate). It was noted by Albright et al. (2004) that the absence of a statistically significant slope effect may be caused by the relatively small-scale of the test sections relative to the scale of a typical landfill cover. Additionally, surface runoff appeared to be controlled more by conditions at the soil/atmosphere interface (density of vegetation, roughness of surface, and hydraulic conductivity of the surficial soil) than the presence of a resistive barrier layer within the cover system. At several of the sites, a gradual trend of lower annual surface runoff was monitored, which may reflect the increase in maturity of the plant communities and indicate the importance of surface features on the runoff.

The most percolation of all of the covers (percolation and percentage of precipitation) was measured in the ET cover systems at humid sites. Average percolation rates through the monitoring period ranged from 33.3 mm/year (6.1% of precipitation) to 159.6 mm/year (18.4% of precipitation). In some of the humid climates monitoring alternative covers, when the storage capacity was exceeded, percolation was measured. However, percolation was observed regardless of soil water storage for a monolithic cover (Albany, GA). Immature vegetation may be the cause of the relatively high percolation rates for alternative cover systems in humid climates (Benson et al., 2002). Additionally, percolation rates diminished by a factor of 25 as trees became established at one of the sites (Benson et al., 2002).

Alternatively, in seven (7) of the ten (10) ET cover systems at arid, semiarid, and subhumid sites measured low percolation rates [on average less than 1.5 mm/year (0.2% of precipitation)]. However, percolation was measured at two (2) of the sites during times when the soil water storage was below the storage capacity of the cover and heavy surface runoff and precipitation events had occured. It was suggested by Albright et al. (2004) that this percolation was caused by localized ponding or preferential flow (not detected by the soil moisture sensors). Differences in the quantity of percolation from cover systems in similar climatic conditions may be explained by several factors, with distribution and quantity of precipitation being one of them. It was observed that sites that received most of their precipitation during the winter months (corresponding to when the ET rate is lowest) showed more percolation than those sites that received less precipitation during the winter than the summer. Additionally, deficiencies in the cover systems was a contributing factor (e.g., minimal transpiration and deficient soil water storage capacity). It was observed that most of the percolation that occurred at the Sacramento site, occurred during a year with the lowest annual precipitation. This year corresponded to a time when the vegetation did not effectively remove the water from the cover season during the growing season. Vegetation plays an equally vital role when compared to soil in ET cover systems because the vegetation removes the stored water and returns it to the atmosphere (Benson et al., 2002). Additionally, precipitation occurred more gradually this year (2001), causing more infiltration, higher peak in soil water storage, and less runoff (Benson et al., 2002). It was concluded that the Marina site ET cover system did not have adequate soil water storage capacity. This was concluded because a dramatic increase in percolation rate was measured during each wet season when the soil water storage capacity was exceeded.

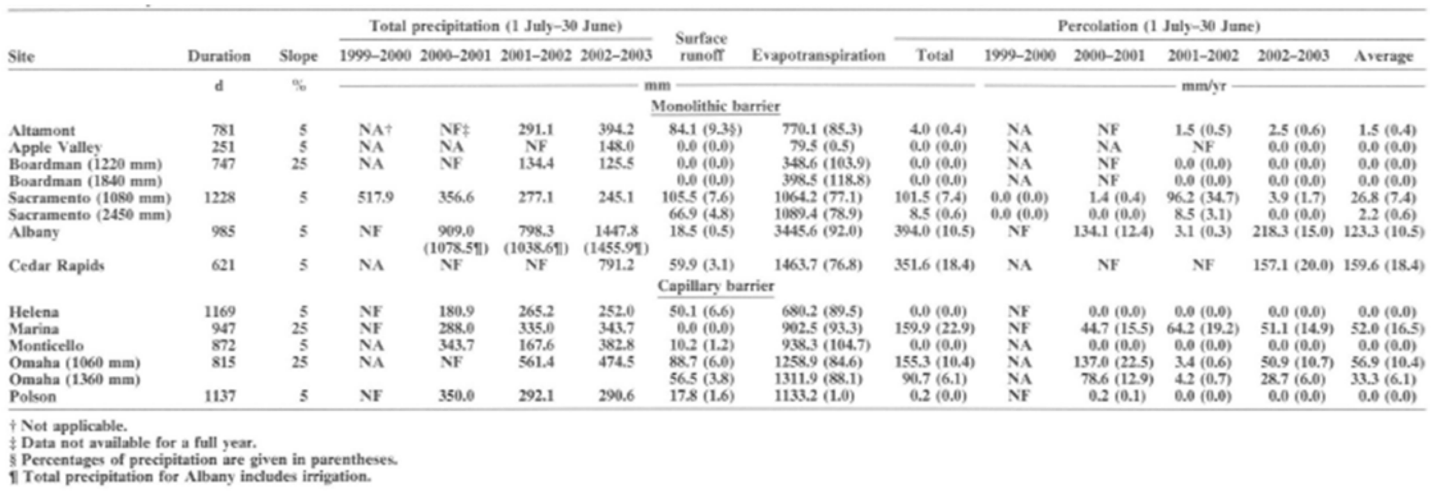
Table 2.3: Summary of water balance data for conventional covers (Albright et al., 2004).



Site	Duration	Slope	Total precipitation (1 July–30 June)			Surface runoff	Lateral flow	Evapotranspiration	Percolation (1 July–30 June)				
			2000–2001	2001–2002	2002–2003				Total	2000–2001	2001–2002	2002–2003	Average
	d	%	mm						mm/yr				
						Composite cover							
Altamont	781	5	NF†	291.1	394.2	59.0 (6.5‡)	4.0 (0.4)	825.0 (91.3)	4.0 (0.4)	NF	0.0 (0.0)	4.0 (1.0)	1.5 (0.4)
Apple Valley	251	5	NA§	NF	148.0	6.8 (4.6)	0.0 (0.0)	134.14 (90.6)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)
Boardman	747	25	NF	134.4	125.5	0.0 (0.0)	0.2 (0.1)	366.4 (109.2)	0.0 (0.0)	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Marina	947	25	288.0	335.0	343.7	98.7 (10.2)	47.4 (4.9)	789.6 (81.6)	71.0 (7.3)	9.0 (3.1)	25.3 (7.6)	36.2 (10.5)	23.1 (7.3)
Polson	1137	5	350.0	292.1	290.6	17.7 (1.6)	40.5 (3.6)	1052.5 (94.3)	1.5 (0.1)	1.2 (0.3)	0.0 (0.0)	0.0 (0.0)	0.4 (0.1)
Cedar Rapids	621	5	NF	NF	791.2	54.1 (2.8)	96.2 (5.0)	1725.5 (90.5)	26.9 (1.4)	NF	NF	21.0 (2.7)	12.2 (1.4)
Omaha	815	25	NF	561.4	474.5	86.8 (5.8)	43.3 (2.9)	1266.0 (85.0)	16.5 (1.1)	8.5 (1.4)	1.0 (0.2)	9.2 (1.9)	6.0 (1.1)
						Soil barrier							
Apple Valley	251	5	NA	NF	148.0	3.4 (2.3)	0.0 (0.0)	120.3 (81.2)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)
Albany	985	5	909.0 (909.0¶)	798.3 (996.2¶)	1447.8 (1560.0¶)	359.4 (9.9)	NA	2682.90 (73.7)	623.7 (17.1)	291.9 (32.1)	237.6 (23.8)	51.6 (3.4)	195.2 (17.1)
Cedar Rapids	621	5	NF	NF	791.2	79.6 (4.2)	29.5 (1.5)	1595.9 (83.7)	113.6 (6.0)	NF	NF	93.8 (12.0)	51.6 (6.0)

† Data not available for a full year.
‡ Percentages of precipitation are given in parentheses.
§ Not applicable.
¶ Total precipitation for Albany includes irrigation.

Table 2.4: Summary of water balance data for alternative covers (Albright et al., 2004).



Site	Duration	Slope	Total precipitation (1 July–30 June)				Surface runoff	Evapotranspiration	Percolation (1 July–30 June)					
			1999–2000	2000–2001	2001–2002	2002–2003			Total	1999–2000	2000–2001	2001–2002	2002–2003	Average
	d	%	mm						mm/yr					
							Monolithic barrier							
Altamont	781	5	NA†	NF‡	291.1	394.2	84.1 (9.3§)	770.1 (85.3)	4.0 (0.4)	NA	NF	1.5 (0.5)	2.5 (0.6)	1.5 (0.4)
Apple Valley	251	5	NA	NA	NF	148.0	0.0 (0.0)	79.5 (0.5)	0.0 (0.0)	NA	NA	NF	0.0 (0.0)	0.0 (0.0)
Boardman (1220 mm)	747	25	NA	NF	134.4	125.5	0.0 (0.0)	348.6 (103.9)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Boardman (1840 mm)							0.0 (0.0)	398.5 (118.8)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sacramento (1080 mm)	1228	5	517.9	356.6	277.1	245.1	105.5 (7.6)	1064.2 (77.1)	101.5 (7.4)	0.0 (0.0)	1.4 (0.4)	96.2 (34.7)	3.9 (1.7)	26.8 (7.4)
Sacramento (2450 mm)							66.9 (4.8)	1089.4 (78.9)	8.5 (0.6)	0.0 (0.0)	0.0 (0.0)	8.5 (3.1)	0.0 (0.0)	2.2 (0.6)
Albany	985	5	NF	909.0 (1078.5¶)	798.3 (1038.6¶)	1447.8 (1455.9¶)	18.5 (0.5)	3445.6 (92.0)	394.0 (10.5)	NF	134.1 (12.4)	3.1 (0.3)	218.3 (15.0)	123.3 (10.5)
Cedar Rapids	621	5	NA	NF	NF	791.2	59.9 (3.1)	1463.7 (76.8)	351.6 (18.4)	NA	NF	NF	157.1 (20.0)	159.6 (18.4)
							Capillary barrier							
Helena	1169	5	NF	180.9	265.2	252.0	50.1 (6.6)	680.2 (89.5)	0.0 (0.0)	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Marina	947	25	NF	288.0	335.0	343.7	0.0 (0.0)	902.5 (93.3)	159.9 (22.9)	NF	44.7 (15.5)	64.2 (19.2)	51.1 (14.9)	52.0 (16.5)
Monticello	872	5	NA	343.7	167.6	382.8	10.2 (1.2)	938.3 (104.7)	0.0 (0.0)	NA	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Omaha (1060 mm)	815	25	NA	NF	561.4	474.5	88.7 (6.0)	1258.9 (84.6)	155.3 (10.4)	NA	137.0 (22.5)	3.4 (0.6)	50.9 (10.7)	56.9 (10.4)
Omaha (1360 mm)							56.5 (3.8)	1311.9 (88.1)	90.7 (6.1)	NA	78.6 (12.9)	4.2 (0.7)	28.7 (6.0)	33.3 (6.1)
Polson	1137	5	NF	350.0	292.1	290.6	17.8 (1.6)	1133.2 (1.0)	0.2 (0.0)	NF	0.2 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

† Not applicable.
‡ Data not available for a full year.
§ Percentages of precipitation are given in parentheses.
¶ Total precipitation for Albany includes irrigation.

General conclusions and results from the ACAP are as follows[3]:

- The Polson, Montana site had a soil water storage which diminished more gradually because of lower temperature and less intense solar radiation. This resulted in less potential transpiration; therefore, slower water extraction.
- Precipitation occurring gradually leads to greater infiltration, less runoff, and higher peaks in soil water storage.
- Having water still stored in the cover after the dry season results in a smaller reservoir for soil water storage for the wetter season. This may lead to percolation events.
- Provided that the cover is designed to be adequately thick, percolation typically occurred within a very short time period for semi-arid regions. These percolation events usually occured towards the end of winter; therefore, only a short time period existed before the beginning of the growing season and the vegetation reduced the stored water in the soil.
- Having mature vegetation in humid climates is critical for the performance of ET cover systems because large volumes of water are required to be managed. Percolation rates can decline by more than a factor of 25 as trees (or vegetation) becomes established.
- Albright et al. (2010) stated that spring rain on snow can be a particularly challenging condition for ET covers to manage. This is a result of the snow limiting the ET while the snowmelt and rain is being directly applied to the cover system.

2.4.3.1 Marine Corps Logistic Base Albany Georgia Lysimeter Study[4]

Abichou et al. (2005) provided information, results, and conclusions on a conventional and alternative final cover system at the Marine Corps Logistic Base in Albany Georgia as part of ACAP. The cover systems were evaluated with the use of pan lysimeters, testing, and instrumentation consistent with ACAP (Figure 2.19). The alternative landfill cover system consisted of a 1,300-mm thick native clayey soil mixed with organic amendments (monolithic cover system) and vegetation with bermuda grass and hybrid

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[3] For clarity and brevity, ideas provided in this section are courtesy of Benson et al. (2002) unless otherwise noted.

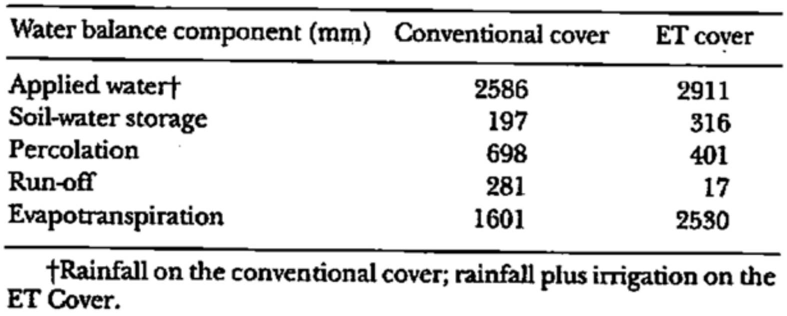
[4] For clarity and brevity, ideas provided in this section are courtesy of Abichou et al. (2005) unless otherwise noted.

poplar trees (Figure 2.18). The conventional cover system tested at this site consisted of a 150-mm thick erosion protection layer underlain by a 450-mm thick compacted clay layer (Figure 2.17). It should be noted that the alternative cover system (ET cover) was periodically irrigated throughout the monitoring period by a water drip line (adding 325-mm of water over 3-years) and the conventional cover system was not irrigated.

Water balance results for the conventional and alternative (ET) cover systems from this study is provided in Table 2.5, with percolation being 14% of the applied water for the ET cover system and 27% for the conventional cover. Immediately following construction of the conventional cover system, percolation was observed and was independent of short-term rainfall events. It was noted that this was likely due to the excess water used during construction and consolidation of the soil layer during compaction. Desiccation cracking likely occurred during the first drying period (7-week long drought) of the study and likely caused an increase in the rate of percolation. Post drought, preferential flow was suggested as the cause of percolation measured following rainfall events. Additionally, percolation increased from 8.9% of the applied water (prior to the drought) to 29.5% of the applied water (post drought) (Albright et al. 2005). The clay cover system was subjected to several wet-drying cycles during the monitoring period due to the infiltration of water from frequent precipitation events (fluctuations in water storage throughout the cover system was obsessive) (Albright et al. 2005).

For the ET cover system, continuous percolation was measured immediately following construction. The percolation during this period seemed to be independent of the rainfall and irrigation, which was likely a result of the cover system being at a near-saturated condition during construction and compaction causing consolidation of the clayey cover soil. An increase in soil water storage was observed during the first 4-months of monitoring, likely due to rainfall and minimal ET. Additionally, a substantial decrease in soil water storage was observed and likely caused by transpiration by the trees and severe desiccation. Drying of the cover system likely due to transpiration was observed during a period of rapid development of the trees. During the last period of monitoring, rainfall was measured just prior to the measurement of percolation. This percolation was likely due root channels and/or desiccation cracks penetrating through the entire cover system as a result of the prior drying period.

Table 2.5: Summary of water balance during the monitoring period (Abichou et al., 2005).



Water balance component (mm)	Conventional cover	ET cover
Applied water†	2586	2911
Soil-water storage	197	316
Percolation	698	401
Run-off	281	17
Evapotranspiration	1601	2530

†Rainfall on the conventional cover; rainfall plus irrigation on the ET Cover.

As indicated in Table 2.5, a greater amount of runoff was measured from the conventional cover when compared to the ET cover system. This was likely due to the establishment of greater amounts of vegetation on the ET cover system (trees and denser grass cover was present). The denser grass would result in more resistance to surface flow; therefore, less measured runoff. It should be noted that the majority of runoff for the ET cover system was measured prior to vegetation establishment.

2.4.3.2 Kiefer Landfill ET Cover Study[5]

Smesrud et al. (2012) provided information, results, and discussion on two (2) ET cover test sections at the Kiefer Landfill near Sacrament California. The Sacramento area has a semi-arid climate with an average annual precipitation of 17.6 inches with cool, wet winters; and warm, dry summers. Both of the ET cover sections were used to simulate a monolithic ET cover, and the primary difference was the thickness (the thicker section incorporated the planting of Oleander seedlings). Additionally, both were seeded with a mix of one annual and two perennial grass species (Figure 2.18). A sealed double ring infiltrometer (SDRI) and two stage borehole (TSB) permeameters were used to evaluate the saturated hydraulic conductivity (k_S) during the decommission of the lysimeter. Additionally, flexible wall permeameters was used on large-diameter (300-mm) undisturbed samples. Blue dye was added to the water during the SDRI testing to act as a tracer to document preferential pathways within the lysimeter. Vegetation composition within each test section was conducted prior to decommissioning the lysimeters (Figure 2.20). Additionally, two (2) model vegetation communities were implemented at the site and the

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[5] For clarity and brevity, ideas provided in this section are courtesy of Smesrud et al. (2012) unless otherwise noted.

water content and pressure potential profiles were obtained during the driest time of the year (Figure 2.21 and Figure 2.22).

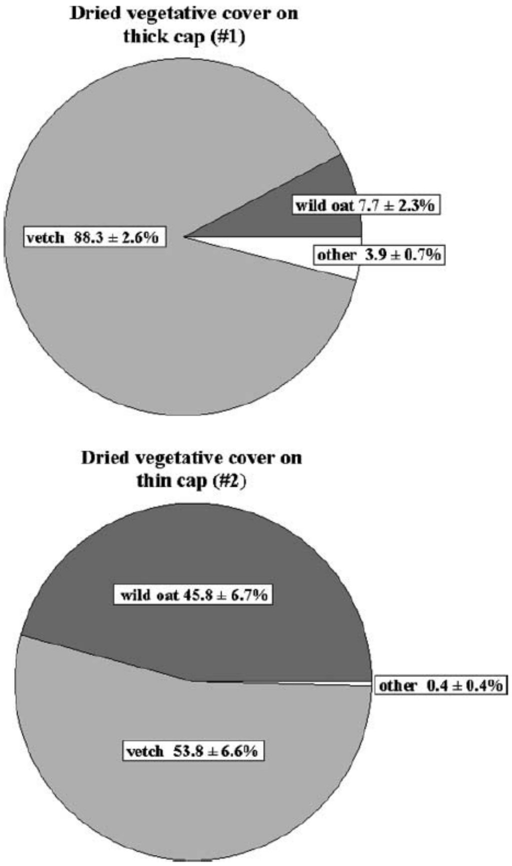

Figure 2.20: Vegetation composition prior to decommission of the test sections (Smesrud et al. 2012).

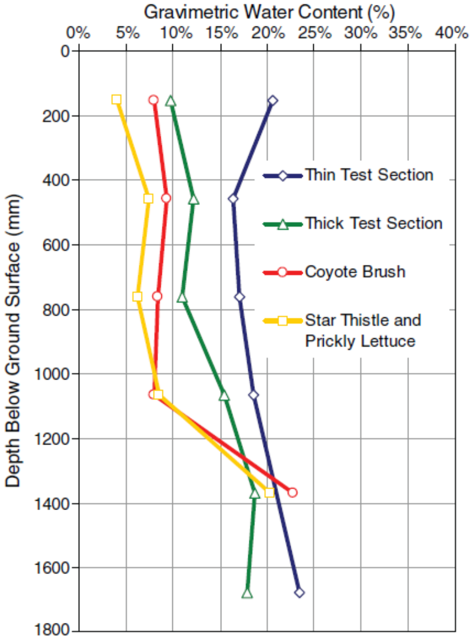

Figure 2.21: Soil water content profiles (Smesrud et al. 2012).

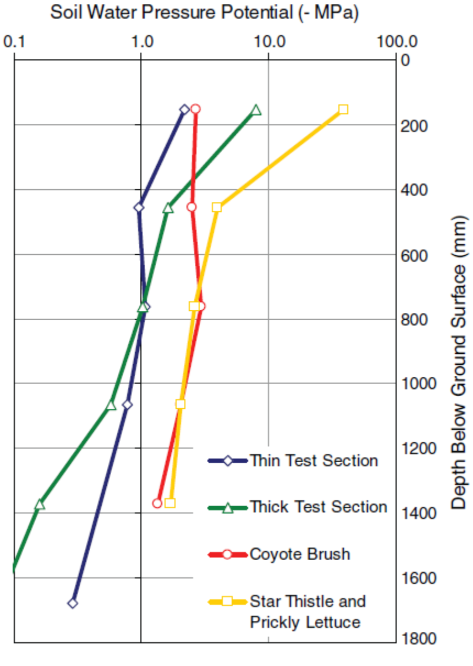

Figure 2.22: Soil water pressure potential profiles (Smesrud et al. 2012).

During decommissioning of the test sections, the saturated hydraulic conductivity of the soil from laboratory test results were lower than those during construction, indicating a more permeable soil over time. The tracer test that were conducted during the decommission revealed an absence of preferential flow pathways. Comparison between the construction and decommissioned SWCCs resulted in a decrease in lower air entry pressure and higher saturated water content over time. These results are indicative of a reduction in the soil density and the development of soil structure, and correspond to an increase in the available water storage capacity. As indicated by the vegetation study conducted during decommission (Figure 2.20), nearly all of the vegetation that was planted or seeded during construction of the test sections were replaced over the study period. Analysis of the water content and pressure potential profiles (Figure 2.21 and Figure 2.22) indicated that the naturally occurring vegetation (Star Thistle and Prickly Lettuce; Coyote Brush) were more effective at extracting deep stored soil moisture than the test section vegetation. Compaction of the cover at a high density can prevent the roots of the vegetation from penetrating throughout the cover. This may lead to a substantial decrease in the potential transpiration of the cover and could lead to percolation events and death or replacement of the selected vegetation.

2.4.3.3 Compacted Clay Cover Lysimeter Study[6]

Albright et al. (2005) provided information, results, and discussion on three (3) compacted clay landfill covers (located at Albany Georgia, Cedar Rapids Iowa, and Apple Valley California) as part of ACAP. Discussion on the compacted clay cover for the Albany Georgia site as provided in the previous section shall not be repeated. All three (3) cover systems were evaluated with the use of pan lysimeters, testing, and instrumentation consistent with ACAP (Figure 2.19). The conventional cover systems evaluated in this study are described in Figure 2.17. Water balance results for the three (3) compacted clay cover systems from this study are provided in Table 2.6.

The majority of percolation during the first 2-years in the compacted clay cover in Cedar Rapids was measured at a relatively uniform rate when the measured volumetric water content in the barrier was at or greater than the saturated volumetric water content measured in the laboratory. It was suggested that flow occurred through the soil matrix (i.e., not by preferential flow paths) during this relatively uniform rate of measured percolation. Following the monitoring period of relatively uniform rate of percolation, percolation was measured soon after snowmelt or precipitation events when the relatively low volumetric

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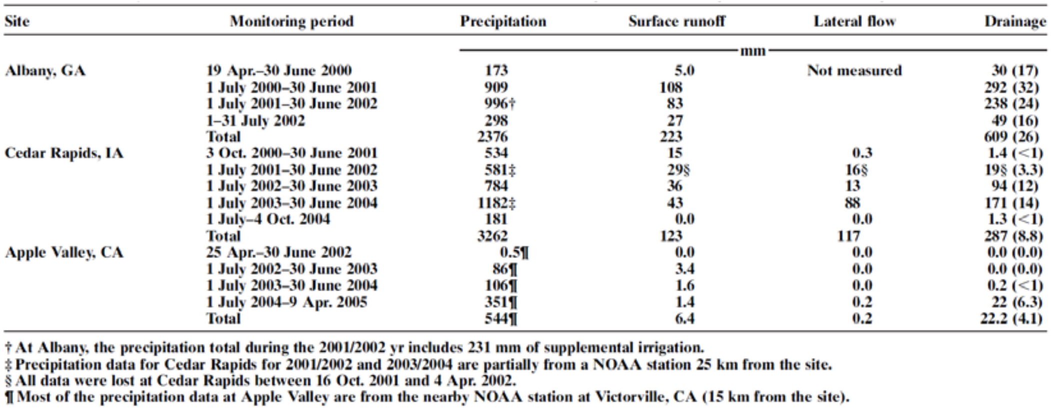
[6] For clarity and brevity, ideas provided in this section are courtesy of Albright et al. (2006) unless otherwise noted.

water contents in the soil layer was monitored. It was concluded by Albright et al. (2005) that this would suggest the occurrence of preferential flow.

Table 2.6: Summary of water balance data from the three test sections. Drainage as a percentage of precipitation is given in parentheses (Albright et al., 2005).



Site	Monitoring period	Precipitation	Surface runoff	Lateral flow	Drainage
		mm			
Albany, GA	19 Apr.–30 June 2000	173	5.0	Not measured	30 (17)
	1 July 2000–30 June 2001	909	108		292 (32)
	1 July 2001–30 June 2002	996†	83		238 (24)
	1–31 July 2002	298	27		49 (16)
	Total	2376	223		609 (26)
Cedar Rapids, IA	3 Oct. 2000–30 June 2001	534	15	0.3	1.4 (<1)
	1 July 2001–30 June 2002	581‡	29§	16§	19§ (3.3)
	1 July 2002–30 June 2003	784	36	13	94 (12)
	1 July 2003–30 June 2004	1182‡	43	88	171 (14)
	1 July–4 Oct. 2004	181	0.0	0.0	1.3 (<1)
	Total	3262	123	117	287 (8.8)
Apple Valley, CA	25 Apr.–30 June 2002	0.5¶	0.0	0.0	0.0 (0.0)
	1 July 2002–30 June 2003	86¶	3.4	0.0	0.0 (0.0)
	1 July 2003–30 June 2004	106¶	1.6	0.0	0.2 (<1)
	1 July 2004–9 Apr. 2005	351¶	1.4	0.2	22 (6.3)
	Total	544¶	6.4	0.2	22.2 (4.1)

† At Albany, the precipitation total during the 2001/2002 yr includes 231 mm of supplemental irrigation.
‡ Precipitation data for Cedar Rapids for 2001/2002 and 2003/2004 are partially from a NOAA station 25 km from the site.
§ All data were lost at Cedar Rapids between 16 Oct. 2001 and 4 Apr. 2002.
¶ Most of the precipitation data at Apple Valley are from the nearby NOAA station at Victorville, CA (15 km from the site).

Volumetric water content measured in the surface layer at the Apple Valley compacted clay cover system quickly responded to precipitation events and generally decreased during warmer months. High water contents were measured during the spring and a decrease through summer at deeper depths in the cover system (providing seasonal trends). Three (3) wet-drying cycles were measured in the cover system during the monitoring period. Percolation was measured quickly after precipitation events late in the monitoring period when volumetric water content was not at its peak, while no percolation was measured during times of peak volumetric water content. It was concluded by Albright et al. (2005) that this would suggest desiccation cracking developing preferential flow paths in the cover system.

The lack of a strong correlation between peak water content and an increase in percolation rate in compacted clay cover systems is a good indication of preferential flow occurring. It was noted by Albright et al. (2005) that larger precipitation events (greater than 10-mm) are more likely to result in preferential flow. Additionally, it was suggested that increases in water content does not cause the preferential flow paths to seal.

The effective field hydraulic conductivity (k_{cf}) was calculated for the three (3) sites by dividing the percolation volume (for a specific time period) by the test section area. The k_{cf} was compared to saturated hydraulic conductivity (k_s) measured in the laboratory and provided in Table 2.7. It was concluded by this study and others (e.g., Albrecht and Benson, 2001; Benson and Want, 1998) that large increases in hydraulic conductivity with time is not uncommon for clay layers. Additionally, the time required to develop desiccation cracks may increase with less frequency wet-dry cycles, and may result in small quantities of cracking and at shallower depths. The integrity of clay cover systems can be affected by weathering processes (i.e., wet-dry and freeze-thaw cycles) during relatively short periods of times. It was also suggested that preferential flow can be expected in these types of cover systems within relatively short time periods.

Table 2.7: Summary of effective hydraulic conductivities (k_{cf}) (Albright et al. 2005).

Site	K_{ef}		Ratio of K_{ef} from later period to other measures		
	Early period	Later period	K_{ef} in early period	As-built K_s† (laboratory)	Design standard
	cm s^{-1}				
Albany, GA	3.4×10^{-7}	3.6×10^{-5}	106	900	360
Cedar Rapids, IA	1.7×10^{-8}	1.3×10^{-5}	765	812	130
Apple Valley, CA	No drainage‡	3.9×10^{-6}	NA‡	229	39

† Saturated hydraulic conductivity.
‡ There was no drainage during the early period at Apple Valley, thus K_{ef} was not determined.

2.4.4 A 7-year ET Cover Lysimeter Study[7]

Nyhan (2005) monitored and evaluated the water balance of four (4) 1-m by 10-m ET cover test plots with slopes of 5%, 10%, 15%, and 25% during a 7-year period at Los Alamos National Laboratory. All of the test plots were un-vegetated and utilized a 2.02-m by 0.76-m metal pan for percolation collection. The ET cover system utilized in all of the test plots is provided in Figure 2.23.

Seasonal trends in the soil water inventory was observed during the study. Large soil water inventories were measured (typically) in the topsoil and crushed tuff in the spring with a gradual decrease to a minimum observed in the fall. It was noted that as the upper portions of the soil profile dried, the ET induced gradients caused the soil stored in the soil to move upward (towards the atmosphere/soil boundary) (Hillel, 1971; Suleiman and Ritchie, 2003). This phenomenon was observed during the study as a downward moving drying front in the soil profile. Large changes in the soil water storage were observed in the crushed tuff layer in all of the ET cover test plots. The test plots with slopes of 15% and 25% showed slightly smaller stored water when compared to the test plots having slopes of 5% and 10%. An annual trend for evaporation to decrease with a decrease in slope was observed. Nyhan et al. (1997) suggested

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[7] For clarity and brevity, ideas provided in this section are courtesy of Nyhan (2005) unless otherwise noted.

that this was likely because large slopes can intercept greater amounts of solar radiation when compared to shallower slopes.

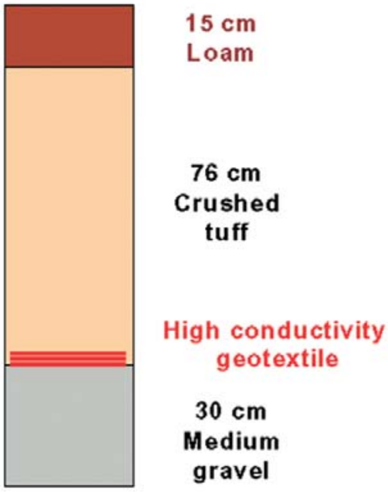

Figure 2.23: Descriptions of soil layers in the ET cover design at the Protective Barrier Landfill Cover Demonstration (modified from Nyhan, 2005).

Insignificant or no percolation was observed in all four (4) of the test plots during the 7-year study (Table 2.8). Therefore; a relationship of daily percolation with time could not be made. Snowmelt and rainfall events resulted in runoff being observed throughout the monitoring period on all of the test plots. As shown in Table 2.8, an increase in the quantity of runoff with an increase in cover slope was observed. Runoff represented 1% to 4% of the precipitation measured during the 7-year study. As a result of the measured water balance data from the study, a ET landfill cover slope between 10% to 15% was recommended.

Table 2.8: Water balance data for ET cover design as a function of slope from 1992 through 1998. Total precipitation for this time period was 311.14 cm (Nyhan, 2005).

	Water balance parameter					
Landfill cover slope	Evaporation	Interflow	Seepage	Runoff	Change in soil water inventory	Evaporation/ precipitation
%	cm					
5	273.77	16.22	5.25	4.25	11.65	0.88
10	280.50	18.35	1.33	7.57	3.39	0.90
15	296.13	10.57	1.32	8.58	−5.46	0.95
25	287.40	8.82	0.64	11.79	2.49	0.92

2.4.5 *Grand Junction Colorado Lysimeter Study*[8]

This study monitored and evaluated two (2) identical test sections utilizing ACAP style monitoring methods at the Grand Junction, Colorado Disposal Site. One of the test sections was used as a control (constructed with the same design and materials as the existing disposal cell) (Figure 2.24), and the other test section was renovated from the control section. The renovation included ripping and mixing the rock, bedding, and protective layers to blend the fine-textured soil and overlying riprap. Additionally, native shrubs were planted in the rip rows of the renovated test section. The goal of the renovation (ripping) was to create a blockier structure in an effort the enhance permeability, plant health, and root development. Monitoring in this study was conducted from November 15, 2007 to October 24, 2010 with a precipitation total of 620-mm and average annual precipitation of 207-mm.

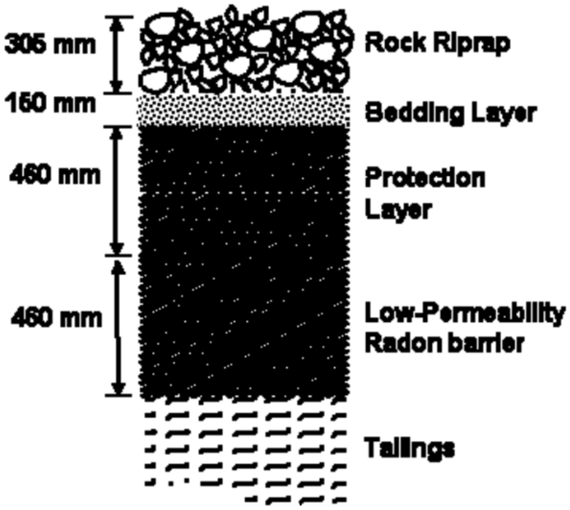

Figure 2.24: Profile of Grand Junction Disposal Cell cover (Benson et al., 2011).

During the monitoring period, very small amounts of percolation and runoff were measured (percolation measured less than 4% of precipitation). Deterioration for both of the cover systems monitored was indicated by the measured percolation following an intermittent or stair-step pattern. This would tend to indicated the development of preferential flow paths in the cover systems. Relatively large variations in soil water content were measured in the bedding layer and upper portion of the protection layer. It was

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[8] For clarity and brevity, ideas provided in this section are courtesy of Benson et al. (2011) unless otherwise noted.

indicated that this was a response to the infiltration from rainfall events and evaporation. For both test sections, subtle changes in water content was measured in the radon barrier. Additionally, the water content for both of the test sections behaved essentially the same.

Chapter 3

Methodology

3.1 Introduction

This chapter includes construction and design considerations of evapotranspiration (ET) cover system monitoring systems and monitoring climatological and ET cover system performance parameter in an effort to accomplishes research objectives outlined in Chapter 1.

The City of Denton Municipal Solid Waste Landfill is located on the southeast side of Denton Texas. The landfill is the first within the local area to conduct this type of study and may serve as a standard for similar meteorological and vegetation conditions. The location of the study area is indicated on Figure 3.1. This location was selected because it is at the top of existing waste (intermediate cover), incorporates top section and sideslope, is readily accessible, and shall not disturb normal landfill activities during the study period.

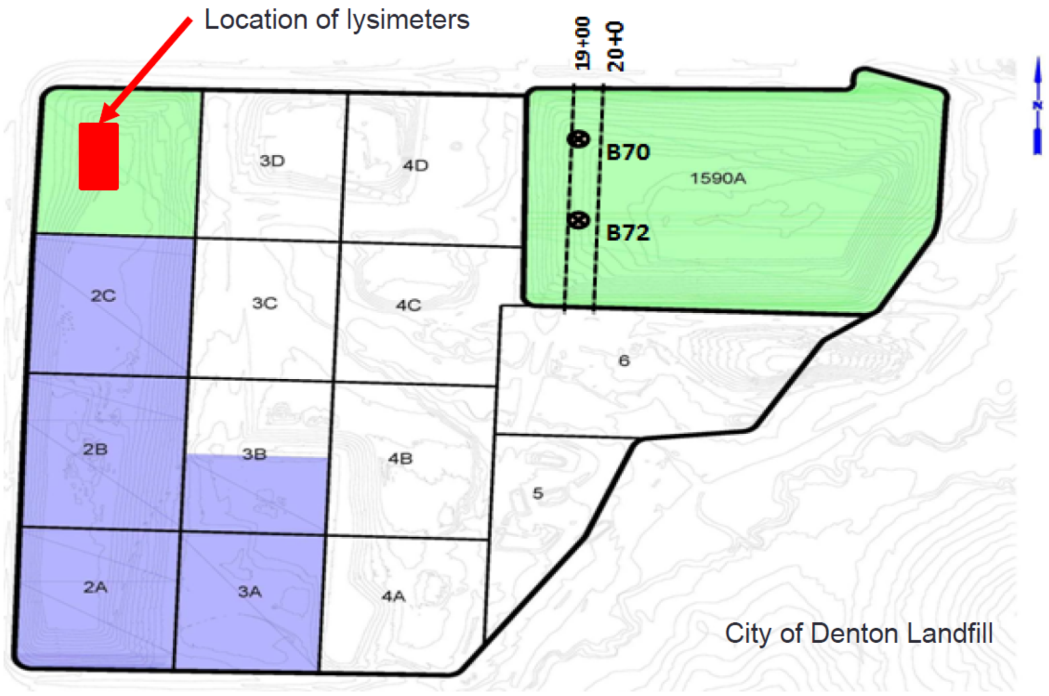


Figure 3.1: City of Denton Municipal Solid Waste Landfill and study location

3.2 Construction and Design Considerations of Evapotranspiration Cover System Monitoring Systems

3.2.1 *Introduction*

Pan lysimeters (lysimeters) were selected to monitor the performance of the ET cover systems because they can provide a direct measurement of percolation and are typically utilized to measure moisture fluxes through soil.

The construction of a lysimeter can be a complicated and costly endeavor and should be designed in such a manner that replicates the procedure that will be used for the actual cover system. There are several critical components which must be considered within the design of a large-scale pan lysimeter:

- Base and walls,
- Drainage layer and sump,
- Surface and percolation collection and measurement systems,
- Root barrier (optional),
- Cover soil, and
- Location.

The base and the wall of a large-scale lysimeter are required to entrap and collect the infiltrated water from within the cover soil. Therefore, geomembranes such linear low density polyethylene (LLDPE) are typically used (such as the case for the ACAP). Use of LLDPE or similar geomembranes allows for flexibility to allow a transition between the vertical walls and floor and for the geomembrane to conform to gradation changes (Benson et al. 2002). Additionally, holes in the geomembrane can cause errors in the percolation measurements so puncture resistance of the geomembrane is a critical issue.

The drainage layer allows for the collection of percolated water through the entire cover and directed to the no-storage sump. Typically, a geonet sandwiched between two (2) non-woven geotextiles (geocomposite) is used because it allows for the rapid transition of water to the sump with little storage (Benson et al. 2002). The water that is collected by the geocomposite and transmitted to the sump is then directed to the percolation collection and measurement system.

This percolation collection and measurement system (along with the surface collection and measurement system) is required to efficiently transmit the collected water from the lysimeter into a basin, where the collected water can be reliably and accurately measured. It is beneficial to design measurement systems that rely on redundancy to accurately and reliably measure the collected water. An example of such a design is from ACAP, where a tipping bucket, pressure transducer, and dosing siphon with a float switch allowed for redundancy in the measured volume of collected water and the basin to be automatically emptied (Benson et al. 2002). It should be noted that the surface runoff measurement system did not include a tipping bucket, due to the high frequency at which the capacity of the tipping bucket is exceeded (Benson et al. 2002). Additionally, berms were placed along the edges of the lysimeter and above and below the lysimeter to prevent water from flowing into or out-off the lysimeter area (Albright et al. 2002).

The inclusion of a root intrusion barrier within the cover soil layer may address several of the concerns associated with using drainage layers (Albright et al. 2002). Several of these concerns are (Albright et al. 2002):

- The capillary break affect causing an increase in the water storage capacity of the cover soils, and
- An issue with monolithic covers where the additional water created by the capillary break is transpired by the roots.

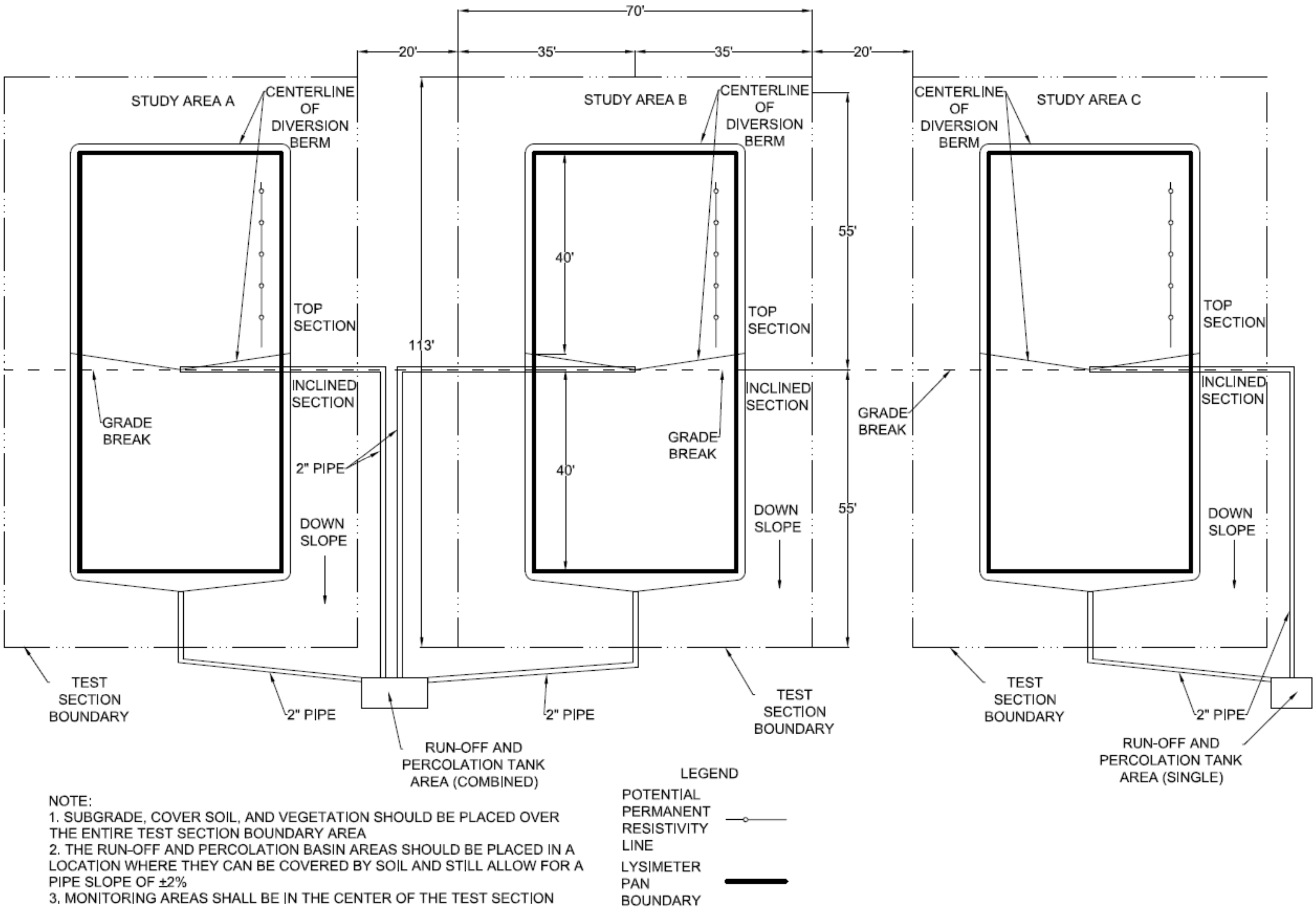
The inclusion of a root barrier prevents the root system from representing actual cover conditions and probably results in the transpiration of less water (Albright et al. 2002).

Based upon these considerations, a lysimeter design and construction sequencing (Figure 3.3) was selected for the proposed lysimeters, and is discussed subsequently. As is common during construction, changes were made to this lysimeter design and sequencing as discussed in Chapter 4.

3.2.2 *Construction Preparation*

The proposal for the six (6) 40-ft x 40-ft lysimeters to measure the effectiveness of ET cover systems and sequence is provided in Figure 3.2 and Figure 3.3. General details regarding the lysimeters and monitoring systems is provided as follows:

- Separate lysimeters shall be constructed at the top and inclined sections of the landfill (Figure 3.2). Incorporating two (2) separate lysimeters at the top and inclined sections for each test section should allow for separate monitoring for each of the main landfill cover components (inclined and relatively flat cover systems).
- The lysimeters encompass a relatively large area [two (2) 40 x 40-ft lysimeters in each test section]. As discussed previously, large lysimeters are recommended in an effort to accurately represent and replicate full-scale landfill covers (i.e., account for preferential flow through macrofeatures, spatial variability, and construction techniques).
- Placement of the runoff and percolation tank areas outside of the test section areas (Figure 3.2). Placing the runoff and percolation tank areas outside of the test section areas should allow the tanks to be properly buried while maintaining an adequate pipe slope (discussed further in Construction Step 2).
- Berms at the lower ends of each lysimeter shall be constructed to funnel runoff and percolated water into a collection point. Constructing the earthen and diversion berms to direct water into the collection points should prevent the storage of percolation water through the cover at the lysimeter bottom and on the soil surface. Additionally, directing the runoff and percolated water into the collection points should allow for an accurate measurement of such factors.



NOTE:
1. SUBGRADE, COVER SOIL, AND VEGETATION SHOULD BE PLACED OVER THE ENTIRE TEST SECTION BOUNDARY AREA
2. THE RUN-OFF AND PERCOLATION BASIN AREAS SHOULD BE PLACED IN A LOCATION WHERE THEY CAN BE COVERED BY SOIL AND STILL ALLOW FOR A PIPE SLOPE OF ±2%
3, MONITORING AREAS SHALL BE IN THE CENTER OF THE TEST SECTION

Figure 3.2: Original proposal layout of the ET cover test sections.

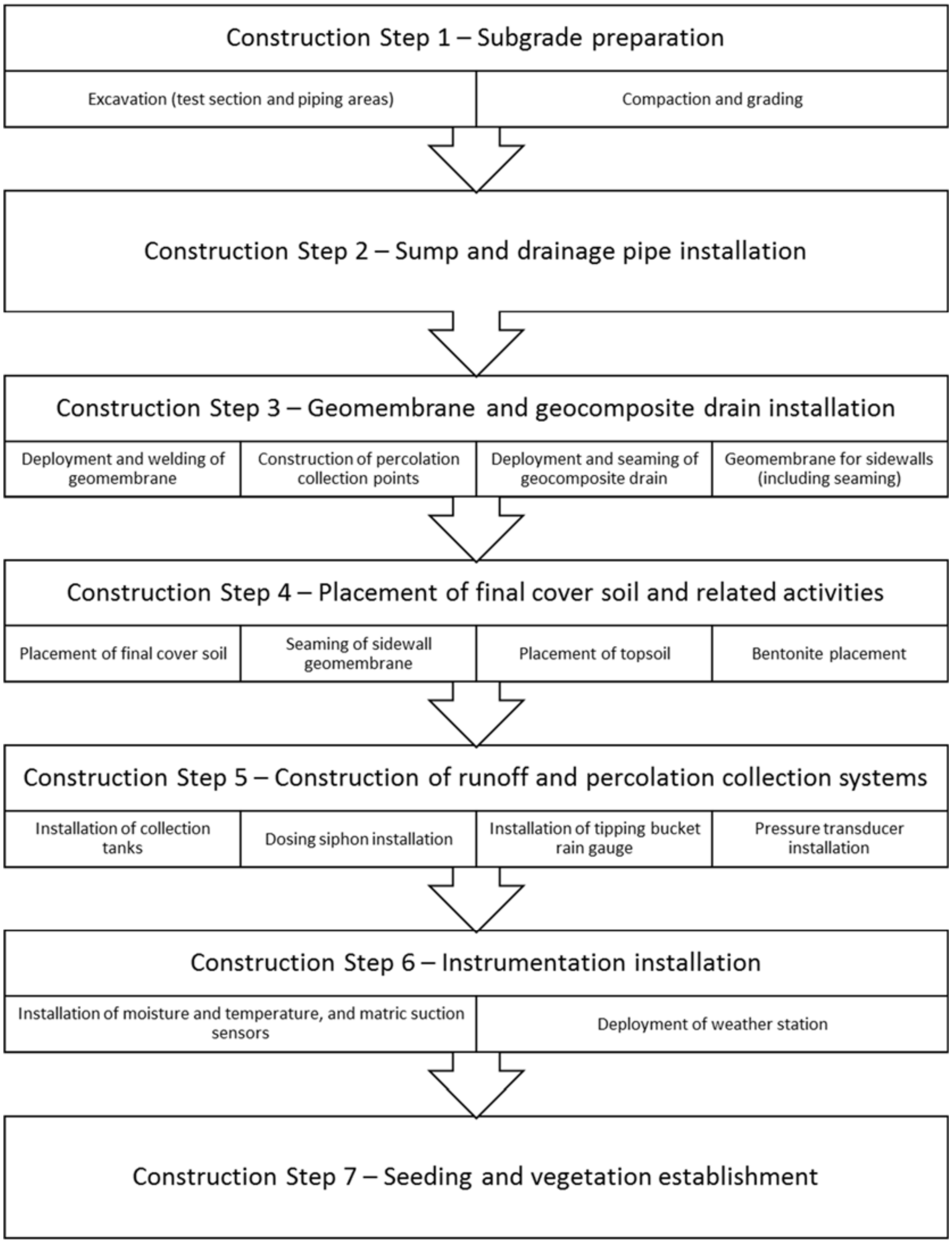


Figure 3.3: Proposed construction sequence.

3.2.3 *Construction Step 1 – Subgrade and Sidewall Preparation*

The first step for the construction of the ET cover test sections is the subgrade and sidewall preparation. Subgrade and sidewall preparation shall involve the following procedure to be completed:

1. An embankment shall be constructed overlying the existing intermediate cover to facilitate excavation for the lysimeters.
2. Excavation of the existing soil over the entire test section (Figure 3.4) and percolation pipe locations. Excavating the entire test section area shall allow the placement of cover soils and vegetation throughout the test section area. This will enable the vegetation monitoring to be conducted outside the lysimeter area and prevent unnecessary disturbance to the vegetation within. Additionally, placing the same cover system inside and outside the lysimeter area should create similar (if not the same) conditions for vegetation growth throughout the test section, which will not be achieved if the soil system differs between the inside and outside of the lysimeter area. The trenches for the piping shall be constructed from the lysimeter sumps (Construction Step 2) to the percolation tank (Construction Step 5) locations; and graded at a ±2% slope, draining towards the percolation tanks.
3. Compaction and grading as shown in Figure 3.5. The subgrade exposed after the excavation process shall be compacted and prepared to provide an adequate surface which can avoid settlement and damage to the geomembrane [i.e., replacing inferior soil and removing large particles (≥ 0.5-inches)]. Additionally, grading shall be conducted as shown in Figure 3.5 to permit routing of the percolated water into the lysimeter sumps without storage. An earthen berm shall be constructed of subgrade material along the perimeter of the lysimeter in an effort to prevent percolated water from lingering along the lysimeter edges (Figure 3.5 and Figure 3.6).

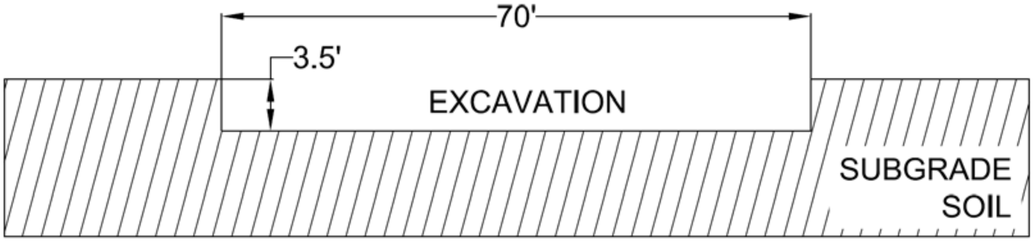


Figure 3.4: Schematic showing the excavation of a test section.

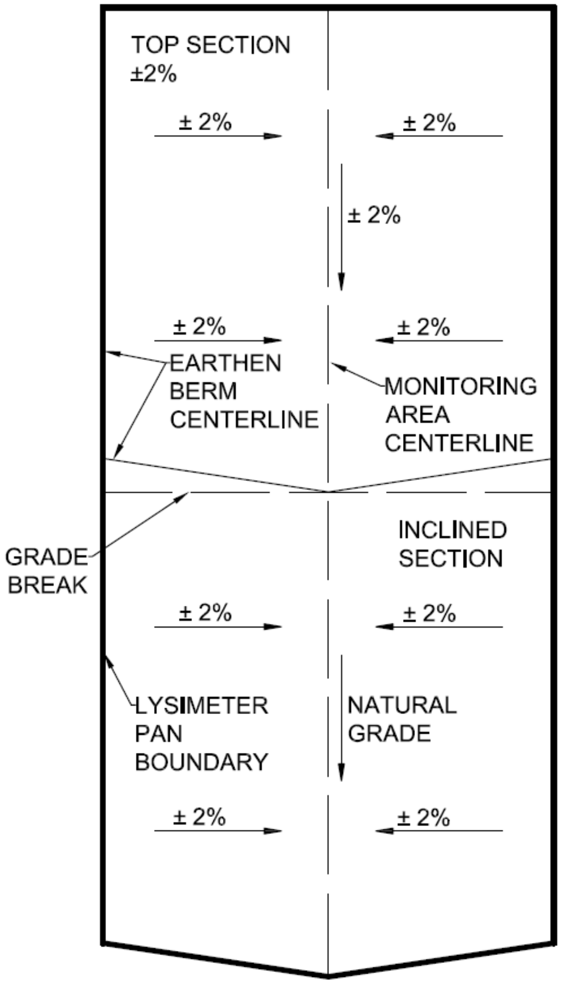


Figure 3.5: Schematic showing the original proposal for grading within the lysimeter of a text section.

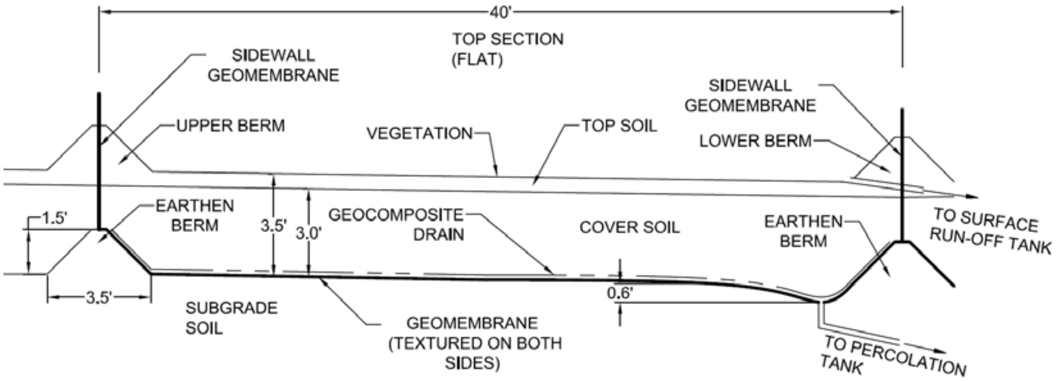


Figure 3.6: Cross-section of test section (top section only).

3.2.4 *Construction Step 2 – Sump and Drainage Pipe Installation*

The second construction step of the ET cover test sections is the installation of the sumps and drainage pipes. Completion of the sumps and drainage pipes shall incorporate the following:

1. Installation of two (2) sumps [one (1) for the top section and one (1) for the inclined section] within each test section (Figure 3.7). Installation of the sump in both the top and inclined sections of each of the test sections should allow for separate monitoring of the percolation; therefore, permit a comparison between varying slopes and vegetation mixes. Additionally, the sumps could provide an easy transition for the percolated water between the geocomposite (Construction Step 3) and percolation piping system, and minimize the water stored at the lysimeter base. The factory manufactured boot shall be welded to the geomembrane (Construction Step 3) and positioned to allow percolation to easily flow into the piping system.
2. Drainage pipe installation from each of the sumps to the corresponding percolation tanks. Installation of drainage pipes from each sump should allow for the percolated water to be transferred from the test section to a percolation tank (Construction Step 5), where the percolation quantity is to be measured. The drainage pipes shall be placed in trenches prepared during Construction Step 1 and shall be positioned at a ±2% slope, draining towards the percolation tanks.

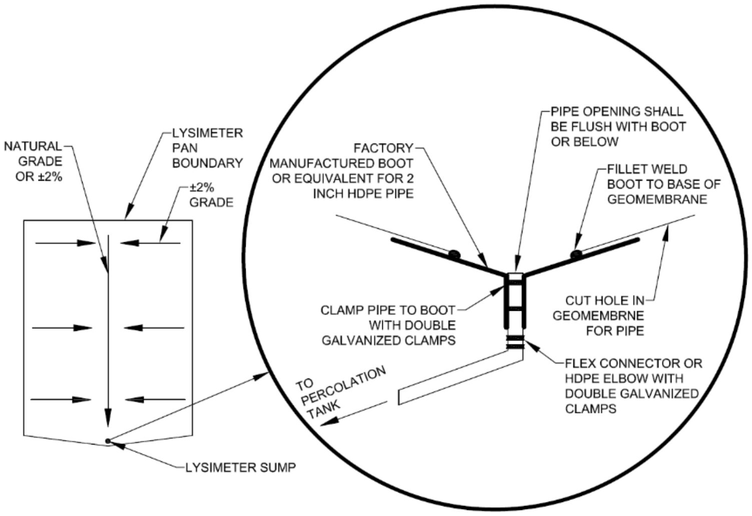


Figure 3.7: Schematic of a lysimeter sump.

3.2.5 *Construction Step 3 – Geomembrane and Geocomposite Drain Installation*

The third construction step of the ET cover test sections is the installation of the geomembrane and geocomposite drain. Installation of the geomembrane and geocomposite drain shall incorporate the following:

1. Placing the geomembrane upon the prepared subgrade (Construction Step 1) in the lysimeter area (Figure 3.8). Placement of the geomembrane at the lysimeter bottom should allow for collection of percolated water from the cover soils and can prevent infiltration into the underlying subgrade soil and waste mass. Cover soils outside of the lysimeter area shall be placed prior to the geomembrane and geocomposite drain installation (discussed in greater detail in the Construction Step 4 section). At least 7.5-ft of geomembrane shall be placed vertical along the edges of the lysimeter to allow for a vertical wall passing through the cover soil, diversion berms, and an additional 2-ft above the top of the diversion berms (Figure 3.8). The geomembrane shall be overlapped and welded for the prevention of percolated water from infiltrating into the underlying subgrade soil and waste mass. Additionally, it is recommended to test the welds and inspect/repair any defects in the geomembrane for infiltration prevention insurance.
2. Installation of geocomposite drains overlaying the geomembrane within the lysimeter (Figure 3.8). Installation of the geocomposite drain should allow routing of the percolated water towards the lysimeter sump for measurement, and to prevent the storage of water at the lysimeter bottom. The geocomposite drain shall be placed only at the lysimeter bottom and side of the subgrade berms, as shown in Figure 3.8.

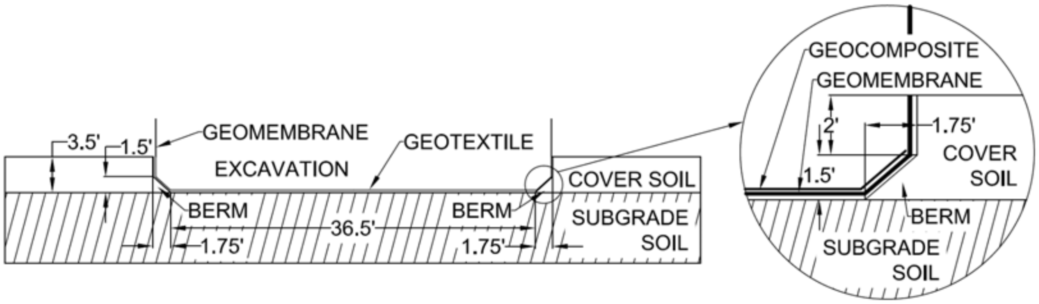


Figure 3.8: Schematic showing the excavation with geosynthetic placement.

3.2.6 *Construction Step 4 – Placement of Final Cover Soil and Related Activities*

The forth construction step of the ET cover test sections is the placement of the final cover soils and other related activities. Placement of the final cover shall incorporate the following:

1. Placing 3-ft of cover soil in accordance to the Texas Commission on Environmental Quality (TCEQ) rules and regulation, and shall be placed over the entire test section area (i.e., inside and outside of the lysimeter area). Placement of 3-ft of cover soil is designed to prevent large quantities of water from infiltrating into the underlying subgrade soil and waste mass. Additionally, the cover soil shall be placed over the entire test section area to allow vegetation analysis to be conducted (as previously discussed in the Construction Step 1 section). The soil shall be compacted and placed with the same (or similar) procedure as is planned for the full-scale cover in an effort to accurately replicated full-scale cover construction and soil conditions. Special precautions should be made to prevent damage to the geomembrane and geocomposite drain layers. Samples shall be collected and testing conducted to ensure conformity to TCEQ rules and regulations, and for monitoring and evaluation purposes (i.e., nuclear density tests, grab samples, block samples, and/or Shelby Tube samples).
2. Seaming of the sidewall geomembrane. Seaming of the sidewall geomembrane shall be completed in an effort to contain the infiltrated and runoff water within the lysimeter area. Special compaction effort shall be implemented near the sidewall geomembrane to prevent damage, ensure adequate compaction, and provide an acceptable interface between cover soil and geomembrane sidewall (i.e., using jumping-jack or vibrating plate compactors).
3. Bentonite placement in narrow trenches along the sidewall geomembrane. Placement of bentonite in narrow trenches along the sidewall geomembrane should prevent the development of preferential flow along the sidewalls, possibly resulting in unrealistic quantities of percolation.
4. Placement of 1-ft of topsoil overlaying the 3-ft of cover soil. Placing 1-ft of topsoil at the surface of the test sections is necessary in an effort to support plant growth for the removal of infiltrated water by evapotranspiration (ET). The topsoil shall be placed with the same procedure as is planned for the full-scale cover in an effort to accurately replicate full-scale cover conditions.

5. Construction of diversion berms with topsoil (Figure 3.9 and Figure 3.10) along the peripheral of the lysimeter (Figure 3.2 and Figure 3.6). Placing diversion berms along the peripheral of the lysimeter should allow for the collection and quantification of the runoff within (and only within) the lysimeter. A 2-ft high diversion berm for the lower side of the lysimeter (Figure 3.10) is designed to prevent the overflow of runoff water from a 25-year storm event in Denton. The two (2) lower berms within each test section incorporate a runoff collection point at the centerline and lowest point of the lysimeter surface (Figure 3.10). Collection of runoff within each test section and from the top and inclined sections should allow the quantification of ET and the evaluation of vegetation performance to be conducted. The runoff collection piping shall be installed with the same procedure as the percolation piping system (Construction Step 2).

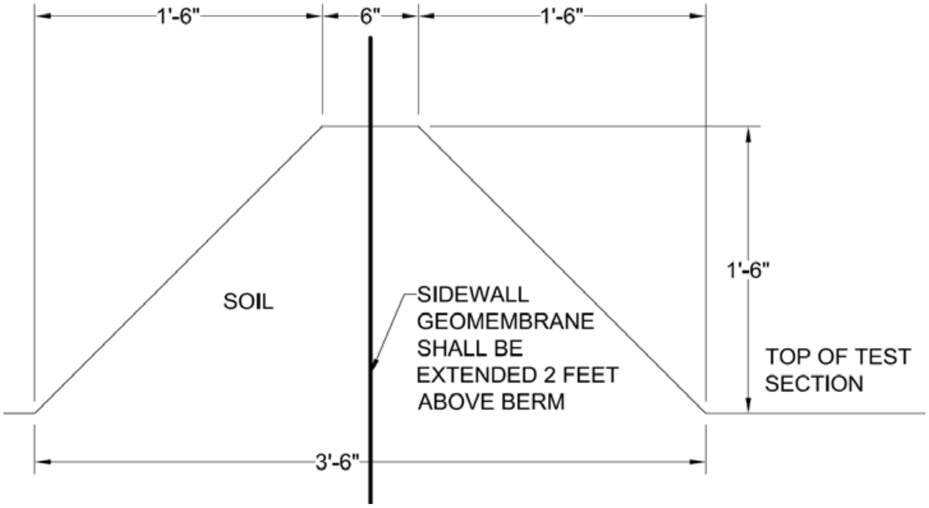
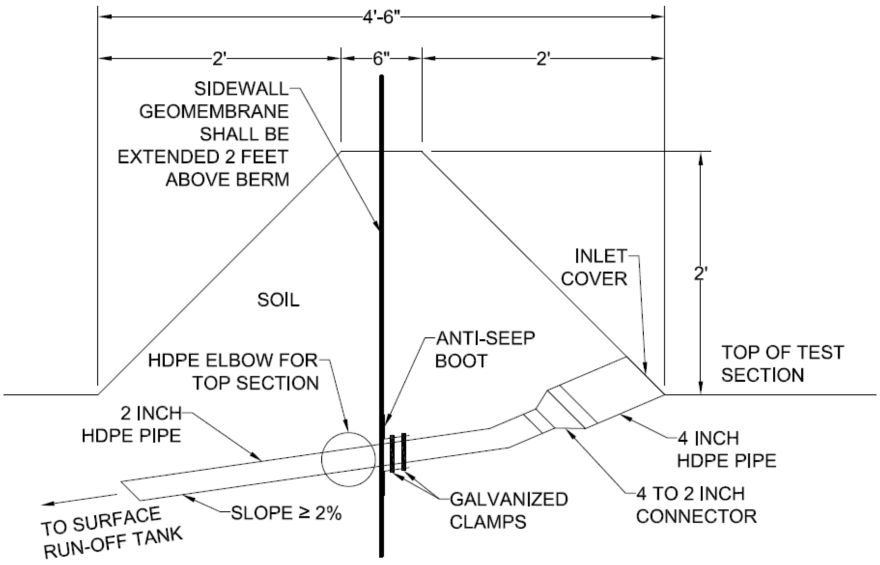


Figure 3.9: Schematic of Diversion Berms.



NOTE:
1. SLOPE SWELL IN LOWER BERM TO COLLECTION PIPE
2. COVER OPENING OF COLLECTION PIPE WITH 10 BY 10 mm GALVANIZED WIRE MESH OR GEONET
3. ENSURE INVERT OF 4 INCH PIPE IS AT THE LOWEST POINT IN SWALE
4. WELD ANTI-SEEP BOOT. SEAL BOOT-PIPE CONNECTION SILICON CAULK BEFORE CLAMPING
5. THESE NOTES SERVE AS A GUIDELINE FOR ALL THREE ET COVER TEST SECTIONS

Figure 3.10: Schematic for runoff collection and diversion berm.

3.2.7 *Construction Step 5 – Construction of Runoff and Percolation Collection Systems*

The fifth construction step of the ET cover test sections is the construction of the runoff and percolation collection systems. Construction of these runoff and percolation collection systems shall incorporate the following:

1. Installation of the runoff and percolation collection tanks (Figure 3.11 and Figure 3.12). Installing individual runoff and percolation collection tanks connected to the percolation and runoff piping from each test section and slope should enable the measurement and quantification of runoff, percolation, and ET from the lysimeter. This shall be implemented in an effort to evaluate each vegetation mix and to make a recommendation of an effective cover system. The tanks shall be placed in a location that allows the piping systems to slope down-gradient at least ±2% from the test sections and such that the final water elevation is below frost level. The tanks shall be large enough to encase the dosing siphon and tipping bucket rain gauge, along with the inflow and

outflow piping. Collection tanks shall be placed on a compacted base to prevent settlement or movement, possibly resulting in monitoring issues.

2. Installation of the dosing siphon in all of the runoff and percolation collection tanks (Figure 3.11 and Figure 3.12). Installing a dosing siphon within each tank should prevent overflow and are equipped with dosing counters to quantify the discharge quantity (designed to measure the runoff or percolation quantities). Testing of the dosing siphon shall be conducted following installation to ensure the volume of water removed from the tank from each discharge event (flush).
3. Installation of the pressure transducer in only the runoff collection tanks (Figure 3.11). Installing a pressure transducer in each runoff collection tank could allow for precise measurements of the runoff quantity from each test section and verify runoff quantities measured by the dosing siphon.
4. Installation of the tipping bucket rain gauge in only the percolation collection tanks (Figure 3.12). Installing a tipping bucket rain gauge within each percolation collection tank should allow for precise measurements to be obtained of the percolation quantity from a test section (large quantities of runoff could overwhelm the tipping bucket if incorporated into the runoff collection system, resulted in an ineffective method of measurement). Additionally, the tipping bucket rain gauge will allow for percolation quantity verification of the dosing siphon.

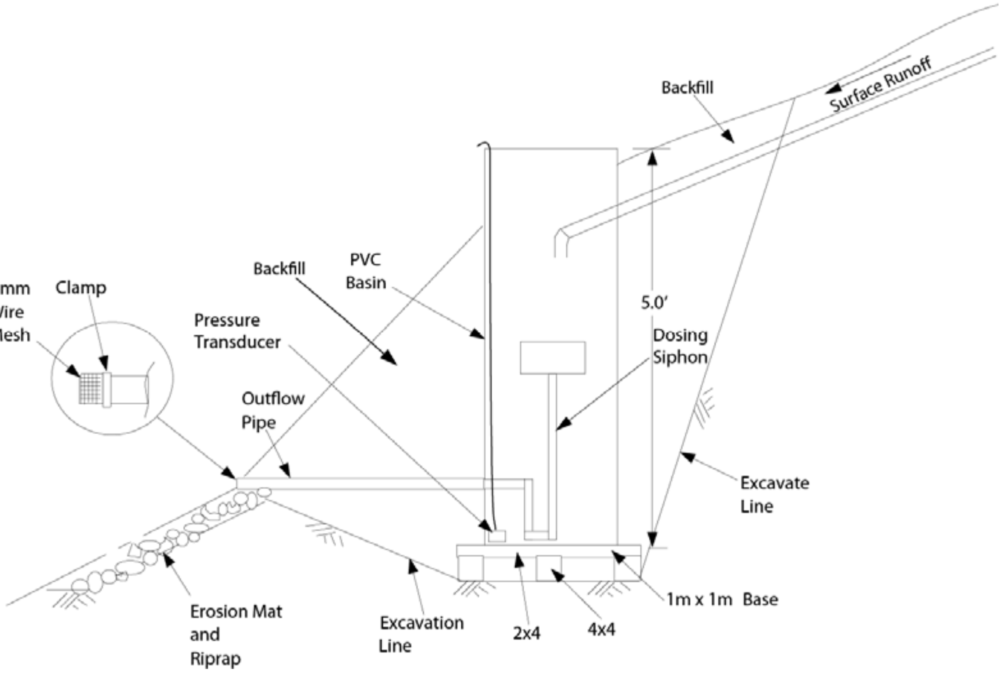


Figure 3.11: Collection tank and monitoring systems for the surface runoff.

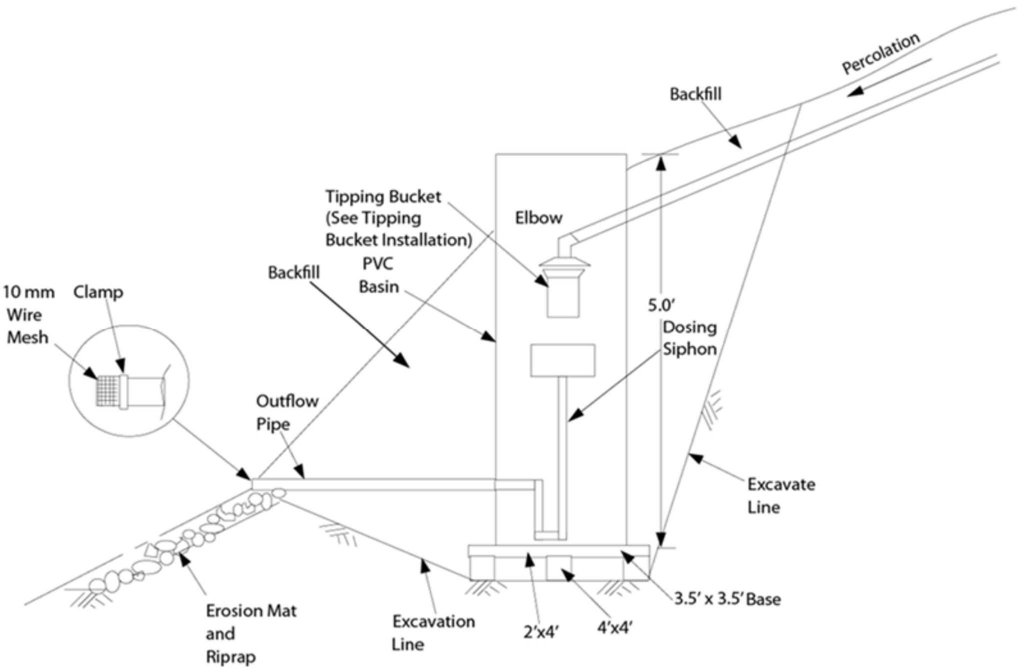


Figure 3.12: Collection tank and monitoring systems for percolation.

3.2.8 *Construction Step 6 – Instrumentation Installation*

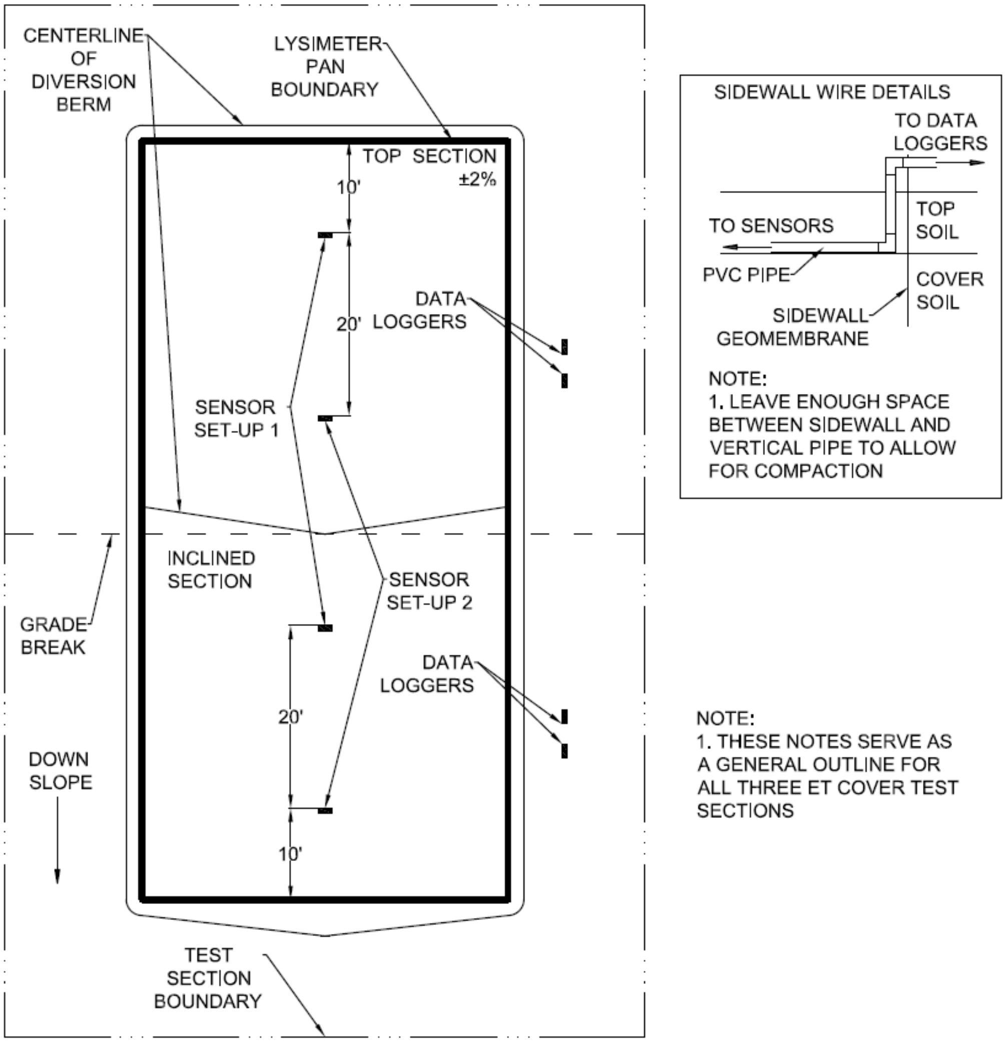
The sixth construction step of the ET cover test sections is the instrumentation installation. Installation of the instrumentation shall incorporate the following:

1. Installation of four (4) sensor nests in each test section (Figure 3.13), and incorporates two (2) distinct sensor set-ups (Figure 3.14 and Figure 3.15). These sensor nests will be vital to measure the quantity of infiltrated water within the cover soil and should enable the estimation of ET within each test section (as discussed in the next section). These sensors shall be installed following the placement of topsoil and cover soil; this should allow for the cover soil over the entire test section to be placed by machinery. Cables from the senor nests shall be routed to the data loggers outside of the lysimeter area to avoid unnecessary disturbance to the soil and vegetation within the lysimeter (Figure 3.13). An anti-seep collar shall be placed along the wires in the excavated area to prevent preferential flow of water (Figure 3.14 and Figure 3.15).
2. Deploying the weather station outside, but in the vicinity of the test sections. Implementing a weather station near the test section areas can allow climatic conditions (critical to the cover evaluation process) to be measured during the monitoring period (as discussed in the next section).

3.2.9 *Construction Step 7 – Seeding and Vegetation Establishment*

The seventh and final construction step of the ET cover test sections is the seeding and vegetation establishment. Seeding and vegetation establishment process shall incorporate the following:

1. Seeding with distinct vegetation for each of the test sections. Seeding with distinct vegetation should allow a variety of vegetation mixes to be analyzed during the monitoring period. Seeding shall be conducted with the same procedure as what is planned for the full-scale cover.
2. Erosion blankets or mulching. If erosion before vegetation establishment is of concern, erosion blankets or mulching can be employed in an effort to minimize or eliminate erosion from the test sections.
3. Irrigation (could be implemented if climatic conditions prevent vegetation establishment). Irrigation should allow for the establishment of the vegetation within the test sections during dry or drought conditions. Many irrigation methods are available to apply water to the test sections; however, the quantity of water applied within each lysimeter should be measured to ensure accurate calculation of ET.



NOTE:
1. LEAVE ENOUGH SPACE BETWEEN SIDEWALL AND VERTICAL PIPE TO ALLOW FOR COMPACTION

NOTE:
1. THESE NOTES SERVE AS A GENERAL OUTLINE FOR ALL THREE ET COVER TEST SECTIONS

Figure 3.13: Instrumentation nests and data logger locations.

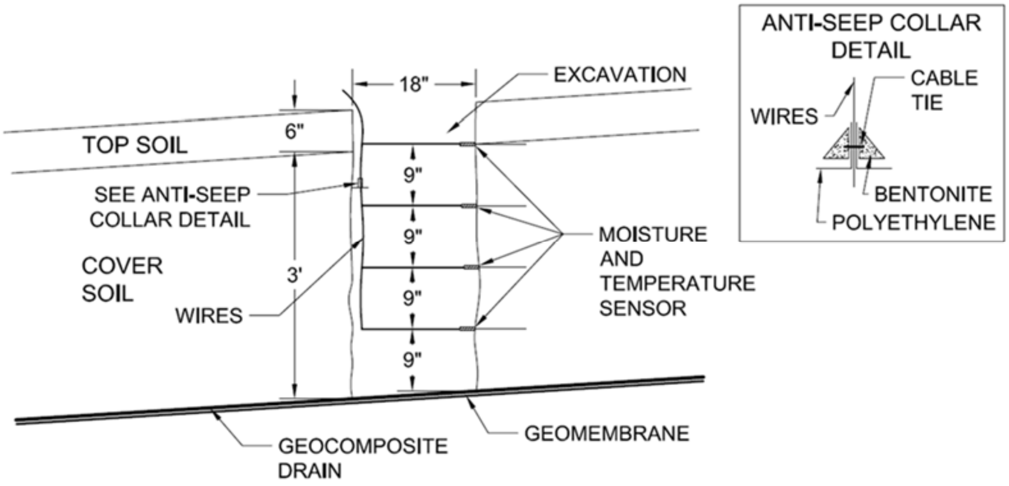


Figure 3.14: Sensor set-up 1.

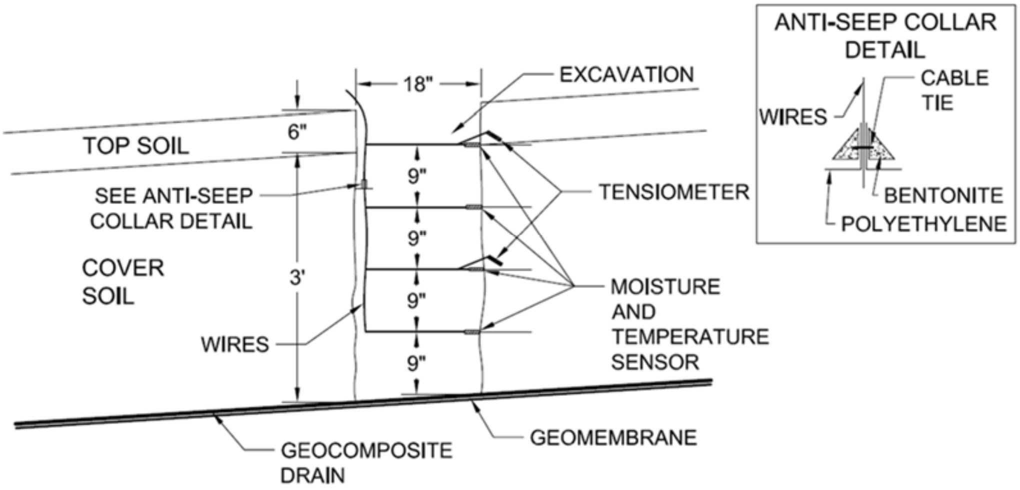


Figure 3.15: Sensor set-up 2.

3.3 Monitoring Climatological and Evapotranspiration Cover System Performance Parameters

As discussed previously (Chapter 2), many factors can have an effect on the performance of ET cover system (percolation, runoff, soil water storage, and ET) including: Climatological (quantity and intensity of precipitation, air temperature, relative humidity, and wind speed), cover slope, vegetation, rodent burrows, etc. To obtain a thorough understanding of the performance of ET cover sections, it is vital to monitor and/or evaluate as many of these factors as possible. Therefore, an instrumentation and ET cover performance assessment program was developed and described in this section. A summary of important

ET cover performance parameters and proposed method of measurement/control is provided in Figure 3.16, which can generally be divided into the following four (4) basic groups:

- Geometry of the ET cover sections;
- Meteorological parameters;
- Soil properties and soil moisture; and
- Vegetation properties.

Maintaining the same geometry of the ET cover sections and lysimeters is critical to the evaluation and comparison of the ET cover systems in this study. Small changes in the size of the lysimeter and/or soil depth between lysimeters could result in additional variability to be accounted for when assessing the performance and conducting comparisons of the ET cover systems. Therefore, construction quality control is proposed during the construction process to minimize or eliminate these changes.

A weather station capable of obtaining site specific quantities for rainfall, barometric pressure, temperature, relative humidity, wind speed and direction, and solar radiation is proposed to be placed at the site (close to the lysimeters). A weather station capable of meeting these requirements is the Davis Vantage Pro2 (Figure 3.17), with accuracy and range for each parameter provided in Table 3.1. The weather station shall incorporate a data collection system which will allow for collection of recorded data during routine site visits.

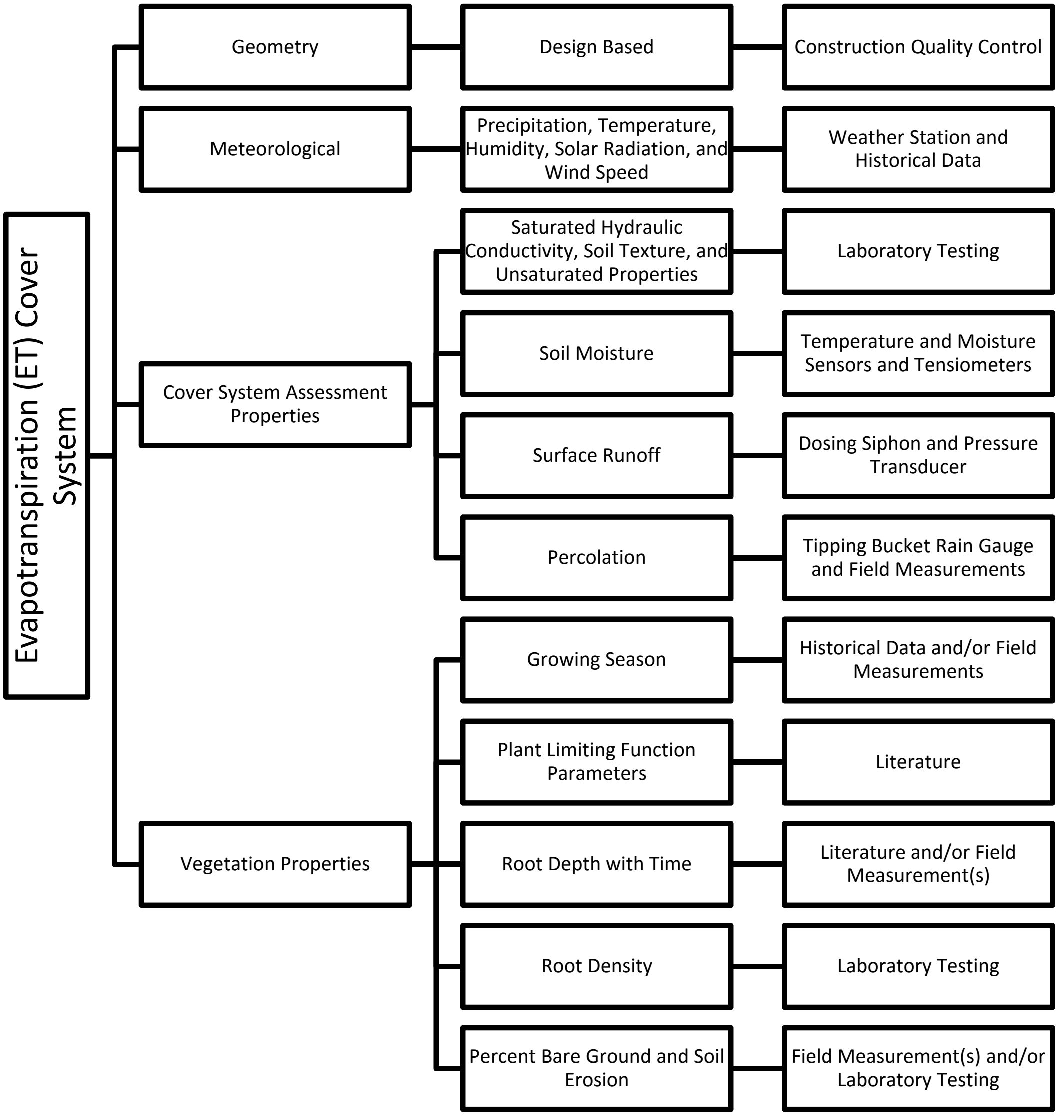


Figure 3.16: Hierarchy chart symbolizing important properties of the ET cover and purposed methods of obtainment.

Figure 3.17: Weather station (Davis Vantage Pro2).

Table 3.1: Parameter, accuracy, and range for the Davis Vantage Pro2.

Parameter	Accuracy	Range
Temperature	1°F	-40 to 150°F
Relative Humidity	±3%	0 to 100%
Wind Speed	±5%	2 to 150 mph
Wind Direction	±3°	0 to 360°
Precipitation	±4%	0 to 99.99 inch

Monitoring the soil water storage, percolation, and runoff of each of the ET cover systems is essential to conduct performance assessment. Therefore; an instrumentation and evaluation program has been developed as follows:

- Saturated and unsaturated hydraulic conductivity, soil texture, and unsaturated soil properties can be evaluated in the laboratory.
- Moisture, temperature, and water potential can be monitored by utilizing 48 moisture and temperature sensors (Decagon Devices – 5TM, Figure 3.18) and 12 tensiometers (Decagon Devices – MPS-2, Figure 3.19) placed within the storage layer as shown in Figure 3.14 and Figure 3.15. The moisture sensors can be utilized to provide an understanding of the quantity of water stored within the ET cover systems, and the tensiometers shall be utilized to understand how dry

or wet the soil is (unsaturated or saturated conditions). Integrating the moisture content provided by the moisture sensors over the depth of the cover can provide an estimated soil water storage. These sensors can provide hourly readings with data stored in data loggers, which can be gathered during routine site visits.

- Surface runoff can be collected as previously indicated in this Chapter and routed to collection tanks (Figure 3.11). The quantity of runoff in each of these tanks can be measured by a dosing siphon (Omega – OSI214F, Figure 3.20) and pressure transducer (Campbell Scientific – CS451, Figure 3.21). To provide individual results for each ET cover system, each system can have a separate runoff collection system and tank [total of six (6)]. The dosing siphon can include a counter registering flushes, which will be read during routine site visits. The pressure transducer can provide continuous readings of the water depth in the runoff collection tanks and shall be attached to a data logger. This data can be collected during routine site visits.
- Percolation through the cover systems shall be collected as previously indicated in this Chapter and routed to percolation collection tanks (Figure 3.12). A rain gauge (Texas Electronics – TE525, Figure 3.22) can be placed in each of the percolation collection tanks [total of six (6)] to measure small amounts of percolation anticipated. The rain gauge can allow for small quantities of percolation to be measured and be attached to a data logger. This data can be collected during routine site visits. Additionally, the quantity of percolation can be measured by the level of water in the collection tanks during the routine site visits.
- ETgage™ manufactured by ETgage Company can directly measure evapotranspiration by utilizing a ceramic evaporator that responds similar to a leaf does to sunlight and the climate. A ETgage™ (Figure 3.23) can be placed on the inclined and top sections near the lysimeters in an effort to measure micro-climate variations in evapotranspiration. This data provided by the ET gages can be collected during routine site visits.

Figure 3.18: Moisture and temperature sensor (Decagon Devices – 5TM).

Figure 3.19: Tensiometer (Decagon Devices – MPS-2).

Figure 3.20: Dosing siphon (Omega – OSI214F).

Figure 3.21: Pressure transducer (Campbell Scientific – CS451).

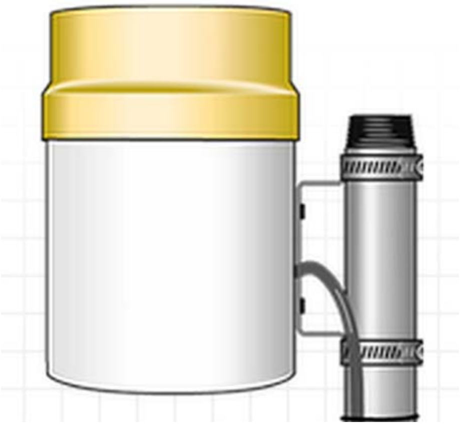


Figure 3.22: Rain gauge (Texas Electronics – TE-525).

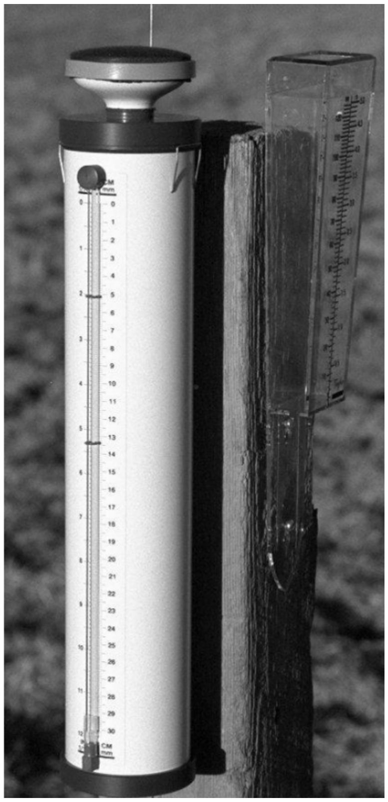
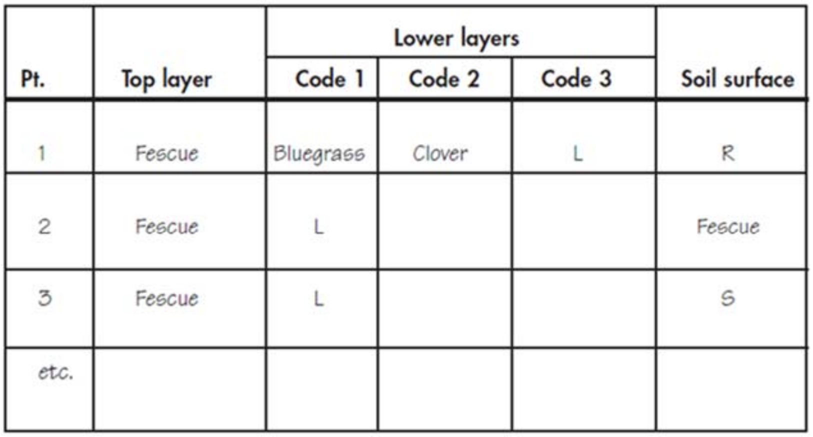


Figure 3.23: ET Gage™ (ETgage Company – Model A).

Monitoring of vegetation in ET cover systems is essential to understanding the performance as transpiration is designed to remove water stored in the cover system prior to it becoming percolation. Therefore, vegetation properties and parameters can either be obtained from literature or field measurements. Several proposed vegetation evaluation field measurements are provided and described as follows:

- The Line-point Intercept method can allow for quantitative monitoring of the performance of vegetation and soil cover with respect to time and changes in weather conditions. It is a relatively simple, quick, and accurate method that may or may not require the establishment of permanent points to repeatedly conduct the Line-point Intercept method. Changes in the vegetation and soil cover are monitored by placing a measuring tape and anchoring it into the ground, and then a pin is dropped vertically along the measuring tape (transit) at predetermined intervals. The vegetation, rocks, mosses, and others or lack thereof, is recorded with each drop of the pin and the overall height and type of vegetation can be recorded as shown in Figure 3.24 (Herrick et al. 2009a and Herrick et al. 2009b). This process should be conducted along multiple transects within each ET cover test section.



Pt.	Top layer	Lower layers			Soil surface
		Code 1	Code 2	Code 3	
1	Fescue	Bluegrass	Clover	L	R
2	Fescue	L			Fescue
3	Fescue	L			S
etc.					

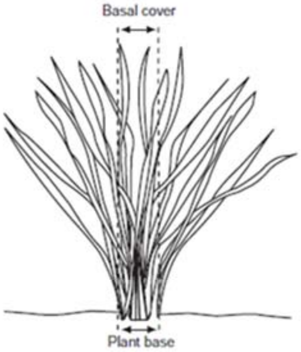
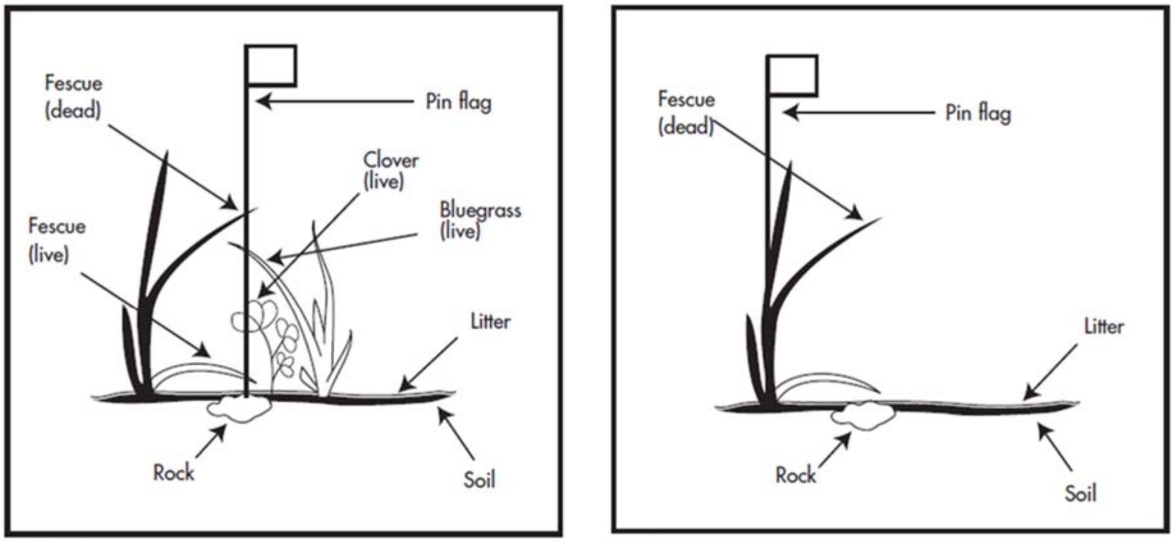


Figure 8. Area defined as plant base and included as basal cover.



Point 1 **Point 2**

Figure 3.24: Sample data form for examples illustrated below. Points 1 and 2 show the first two points on a line. In Point 1, the pin flag is touching dead fescue, live bluegrass, clove, live fescue, litter, and a rock. Record fescue only once, even though it intercepts the pin twice. In Point 2, the flag touches fescue, and then touches litter and finally the fescue plant base. The table shows how to record these two points on the data form (Herrick et al. 2009).

- The Gap Intercep t method can provide quantitative measurements on the proportion of each transect that is covered by large gaps between plants. It is a relatively simple and quick method that can be conducted in conjunction with the Line-point Intercept method along the same transects. This method is important because large gaps between plant canopies can be an indicator of potential wind erosion and/or weed invasion, while large gaps between plant bases can indicate problems with runoff and water erosion. A measuring tape is placed in the same manner as the Line-point Intercept method and the gaps between plant canopies and plant bases are measured as shown in Figure 3.25, **Error! Reference source not found.**, Table 3.2, and **Error! Reference source not found.** (Herrick et al. 2009a and Herrick et al. 2009b). Similar to the Line-point Intercept method, this process should be conducted along multiple transects within each ET cover test section and established ET cover.

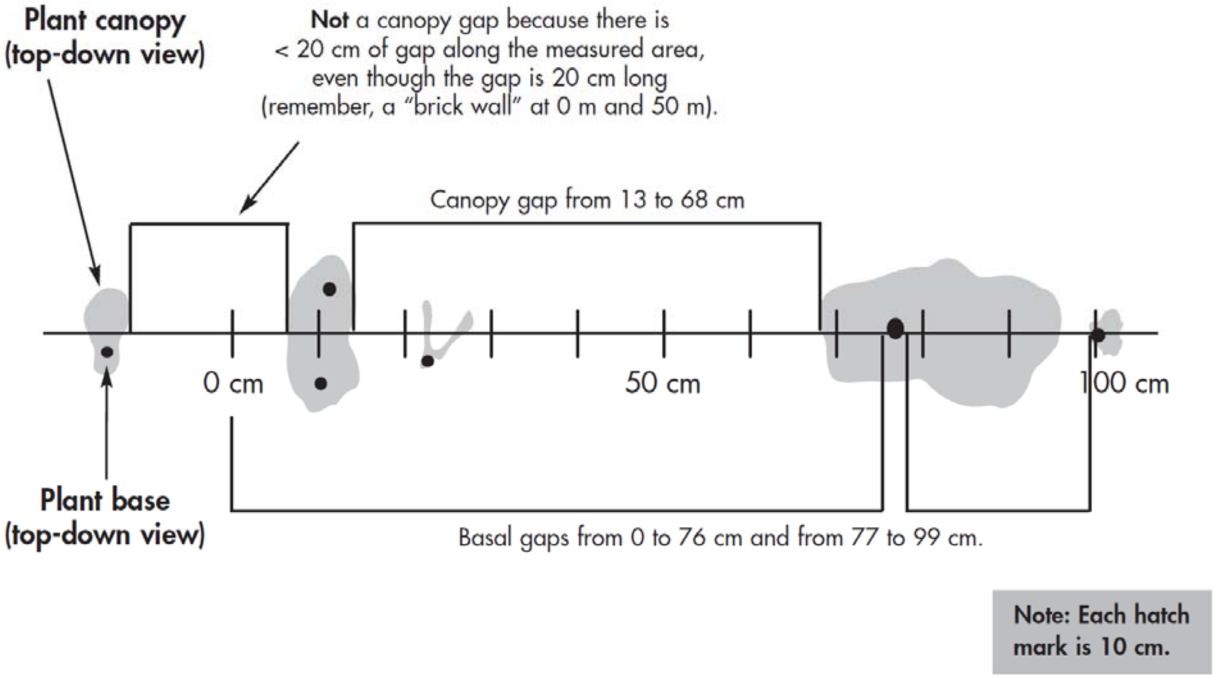
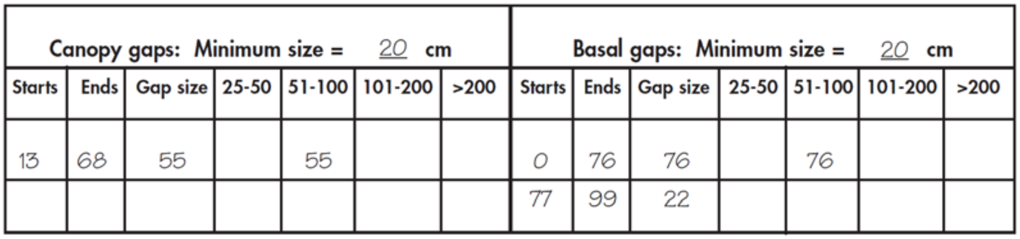


Figure 3.25: Example of canopy gap intercepts (above the line) and basal gap intercepts (below the line) for 1-m (100-cm) of a 50-m line. Canopy gaps: look at the plant canopy intercept between the 20 and 30-cm marks on the transect. Because each canopy intercept covers less than 50% of the 3-cm segment of the line, it does not count as canopy (Herrick et al. 2009).

Table 3.2: Gap intercept data form example associated with Figure 3.25 (Herrick et al. 2009).



Canopy gaps: Minimum size = 20 cm							Basal gaps: Minimum size = 20 cm						
Starts	Ends	Gap size	25-50	51-100	101-200	>200	Starts	Ends	Gap size	25-50	51-100	101-200	>200
13	68	55		55			0	76	76		76		
							77	99	22				

- Portable ET chambers have been used to measure evapotranspiration (ET) from bare soil and sparsely vegetated plant communities (Stannard 1988; Stannard and Weltz 2006), from distinct vegetation types within mixed species communities (Stannard 1988), and from cultivated alfalfa field (Reicosky et al. 1983). These ET chambers measure the water vapor exchange between the atmosphere and the Earth's surface within a small area (Dugas et al., 1997). This is completed by enclosing a known volume of a plant canopy and/or soil surface, and measuring the increase in the vapor density within the ET chamber (Garcia et al., 2008). A typical porable ET chamber is shown in Figure 3.26.

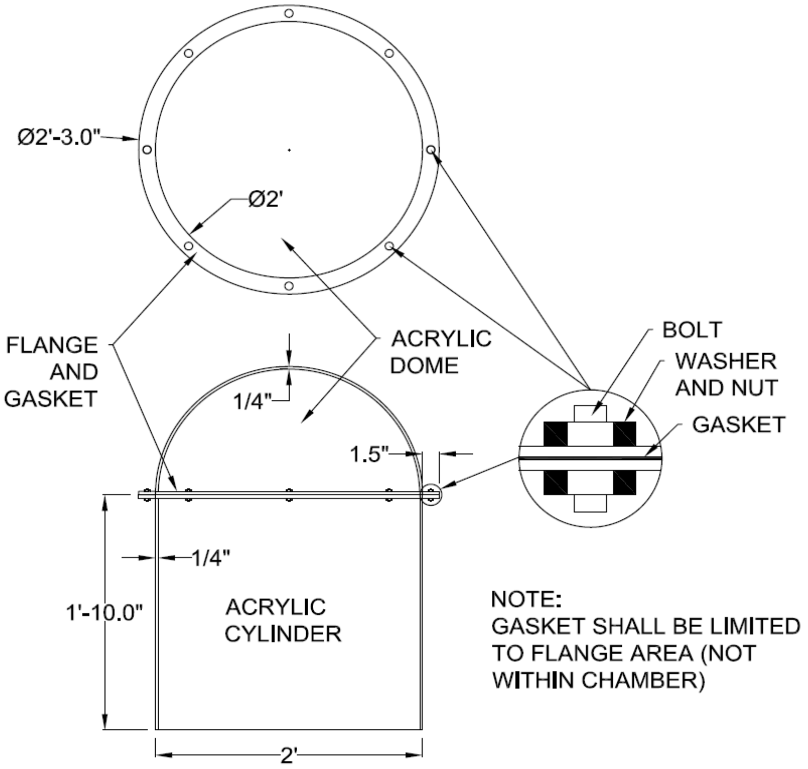
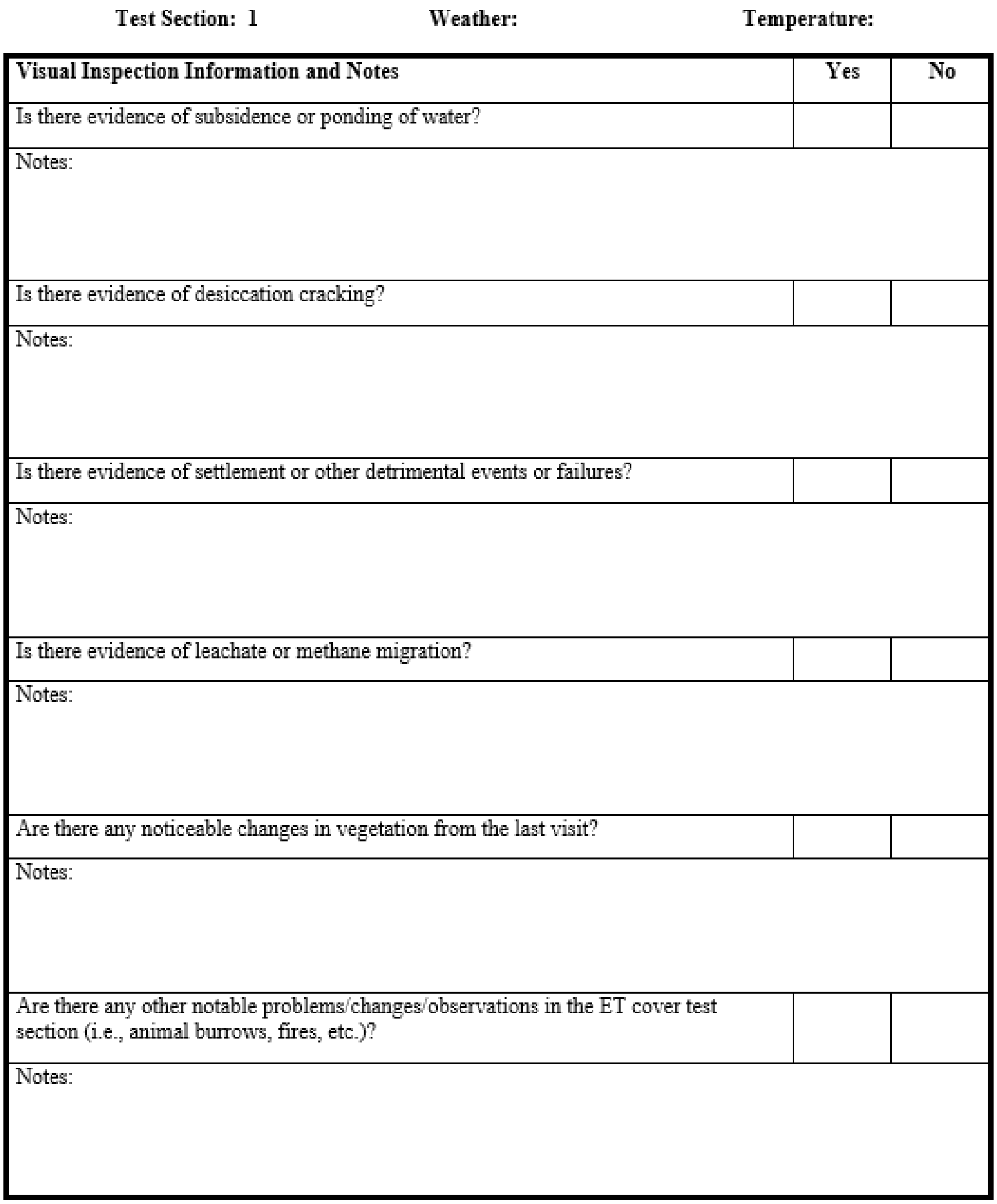


Figure 3.26: Schematic of ET chamber.

- The Soil Stability Test method can provide quantitative measurements on the degree of soil erosion resistance and structural development. It is a relatively simple and quick method that can be conducted in conjunction with the Line-point Intercept and Gap Intercept method. This method is important because it measures the soil's stability when subjected to rapid wetting. It is important to limit the comparison of testing results to similar textured soils, since the results of the Soil Stability Test is affected by the soil texture. This process should be conducted multiple times within each ET cover test section and established ET cover.

Other problems or notable changes in the ET cover systems could have a large effect on the performance; therefore, monitoring these problems and/or changes is critical to performance assessment of the cover systems. These items include animal burrows, ponding of water, subsidence, cracking, etc. A visual inspection document has been created to be completed during routine site visits as outlined in Figure 3.27.



Test Section: 1 **Weather:** **Temperature:**

Visual Inspection Information and Notes	**Yes**	**No**
Is there evidence of subsidence or ponding of water?		
Notes:		
Is there evidence of desiccation cracking?		
Notes:		
Is there evidence of settlement or other detrimental events or failures?		
Notes:		
Is there evidence of leachate or methane migration?		
Notes:		
Are there any noticeable changes in vegetation from the last visit?		
Notes:		
Are there any other notable problems/changes/observations in the ET cover test section (i.e., animal burrows, fires, etc.)?		
Notes:		

Figure 3.27: Visual inspection and notes.

Chapter 4

Lysimeter and Evapotranspiration Cover System Construction

4.1 Introduction

Construction of six (6) lysimeters was a time-consuming process which required a number of tasks (with multiple steps associated with each task) to be completed (15 step process). As is common during construction activities, deviations from the original plans (see Chapter 3) were made throughout the construction process. Construction of the lysimeters started June 17th, 2014 and was completed November 1st, 2014 [a span of four (4) and a half months]. The tasks which were completed during the construction of the lysimeters are provided in Figure 4.1, and discussed subsequently. Additional details of the construction process and daily activity reports are provided in Appendix A.

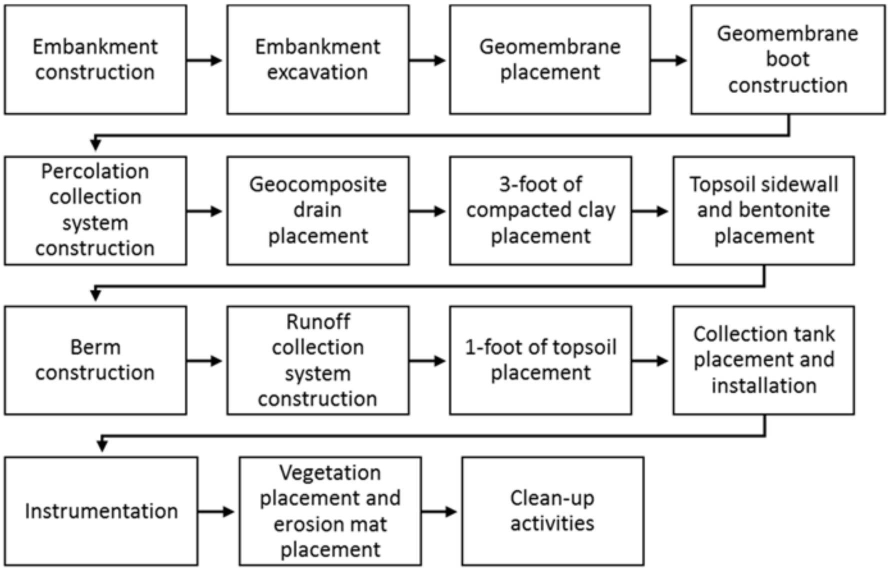


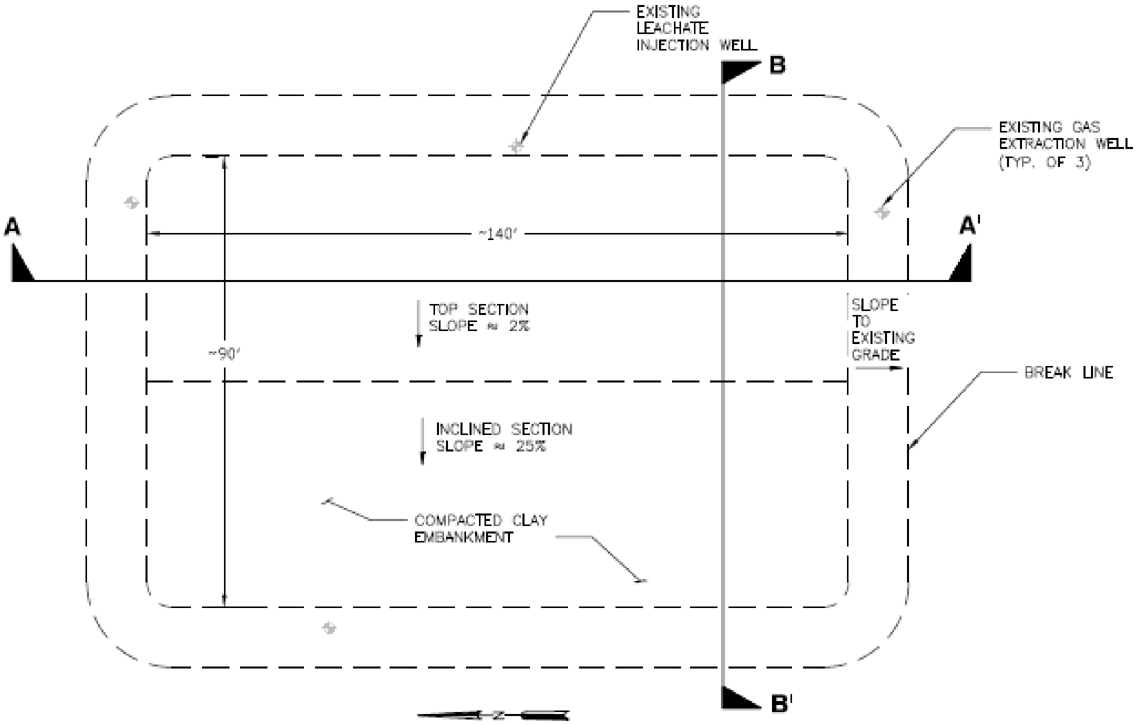
Figure 4.1: Lysimeter Construction Sequencing

4.2 Lysimeter and Evapotranspiration Cover System Construction

4.2.1 *Step 1 – embankment construction*

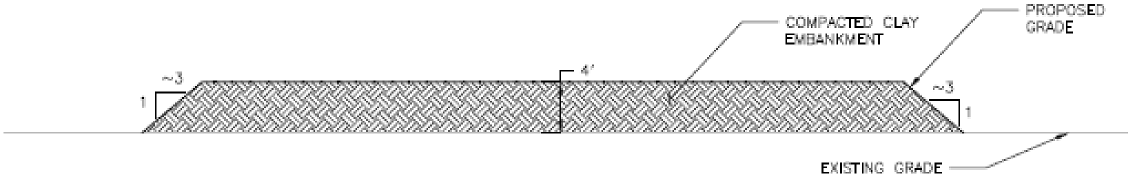
A 4-foot tall embankment was constructed of clay by contractors, so the lysimeter pits could be excavated without contacting the underlying waste mass. The embankment encompassed an area greater than the cumulative size of the six (6) lysimeters, and was constructed in lifts. The boundary provided a buffer zone between the outside of the lysimeters and the embankment sideslope to existing grade. The topsoil was stripped and markers/stakes were placed near gas wells prior to construction of the embankment. The embankment was compacted in an effort to allow for excavation of the lysimeter pits (Step 2) without excessive sidewall failure. Water was applied during each lift placement and a bulldozer was used in an effort to achieve compaction. Existing structures (leachate injection wells and gas collection wells) were present near/within the embankment and resulted in coordination challenges. Clayey soil was obtained from an on-site borrow source. It was noted that it may be beneficial to create an embankment to a height that is equal to or greater than the height of the subgrade, storage layer, and topsoil. Details of this construction procedure are provided in Figure 4.2, and the University of Texas at Arlington (UTA) provided construction inspection and resolved any problems that arose. General details of the constructed embankment (end of Step 1) are provided in Figure 4.3.

Figure 4.2: Embankment construction a) construction by bulldozer, b) water application for compaction purposes, and c) transportation of soil to the site.



PLAN VIEW

NTS



SECTION A-A'

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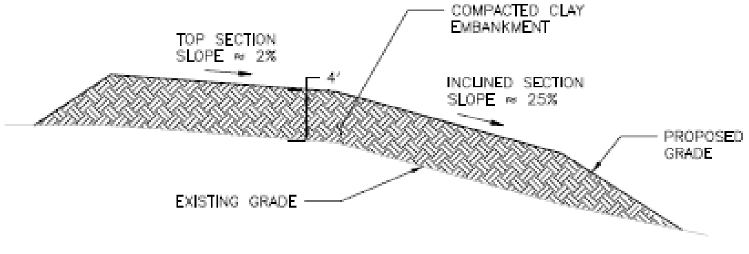

SECTION B-B'

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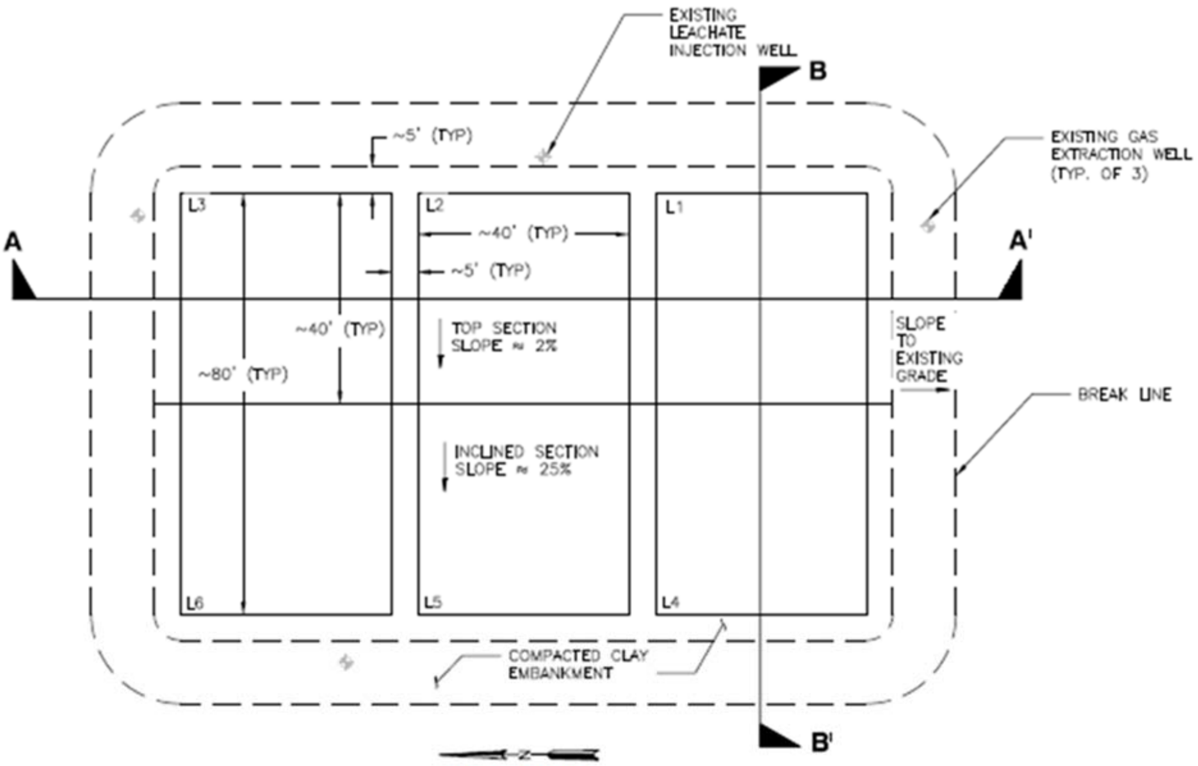
Figure 4.3: Step 1 - general construction details.

4.2.2 *Step 2 – embankment excavation*

Post embankment construction, soil was excavated in the lysimeter locations by the contractor. The excavation areas were approximately 12 x 12-m (40 x 40-ft) wide and approximately 0.9-m (3-ft) deep. Subgrades of the excavated areas were compacted to provide an adequate surface to place geomembrane and ensure minimal hydraulic conductivities below the geomembrane (k = 1x10^{-7} cm/sec). It was discovered that sloping the sidewalls of the excavation minimized sidewall failure and allowed for easier geomembrane sidewall placement (Step 3). Additionally, the subgrade of the three (3) top sections were slightly sloped for water collection purposes (±2%), and the inclined sections constructed with an approximate slope of 25%. A string line was placed around the perimeter of the lysimeters to help ensure correct dimensions (40-ft by 40-ft). For ease of construction, the top three (3) lysimeters were constructed first (up to Step 7), followed by the inclined sections. Critical steps in the embankment excavation task are presented in Figure 4.4, and UTA provided construction inspection and solved any encountered problems. General details of the embankment excavation (end of Step 2) are provided in Figure 4.5.

Figure 4.4: Lysimeter excavation a) excavation in preparation for a lysimeter, b) finalizing the lysimeter subgrade and compaction by a skid-steer, and c) subgrade slope and height verification.



PLAN VIEW

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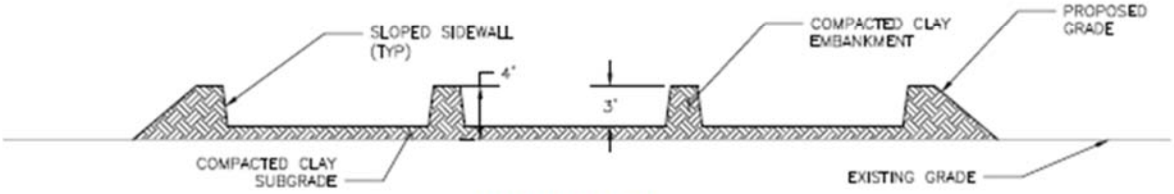

SECTION A-A'

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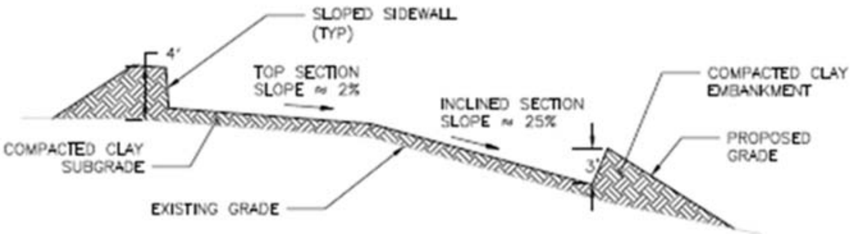

SECTION B-B'

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Figure 4.5: Step 2 - general construction details.

4.2.3 *Step 3 – geomembrane placement*

Geomembrane (60-mil) was placed on the subgrade and along the sidewalls of the excavations. Three (3) geomembrane sheets were placed downslope [two (2) overlaying the subgrade and one (1) cut into half and placed on the sidewalls]. Prior to geomembrane placement, soil clots and other debris were removed from the subgrade to provide a smooth surface and to prevent holes from developing in the overlaying geomembrane. The geomembrane sheets were welded together along the seams by a hand welder (Figure 4.6a). It was noted that a thinner geomembrane (especially along the sidewalls) may be used an allow greater flexibility and easier construction around corners and sidewalls. Sandbags and tires were placed on the geomembrane on the top of the embankment to avoid wind related issues. It was noted that summer related heat expansion of the geomembrane caused wrinkles, and it may have been beneficial to place the geomembrane during colder times of the year. Substantial amounts of time and effort were expended by UTA and the City of Denton (COD) staff to complete this task, and details are provided in Figure 4.6. General details of the geomembrane placement (end of Step 3) are provided in Figure 4.7.

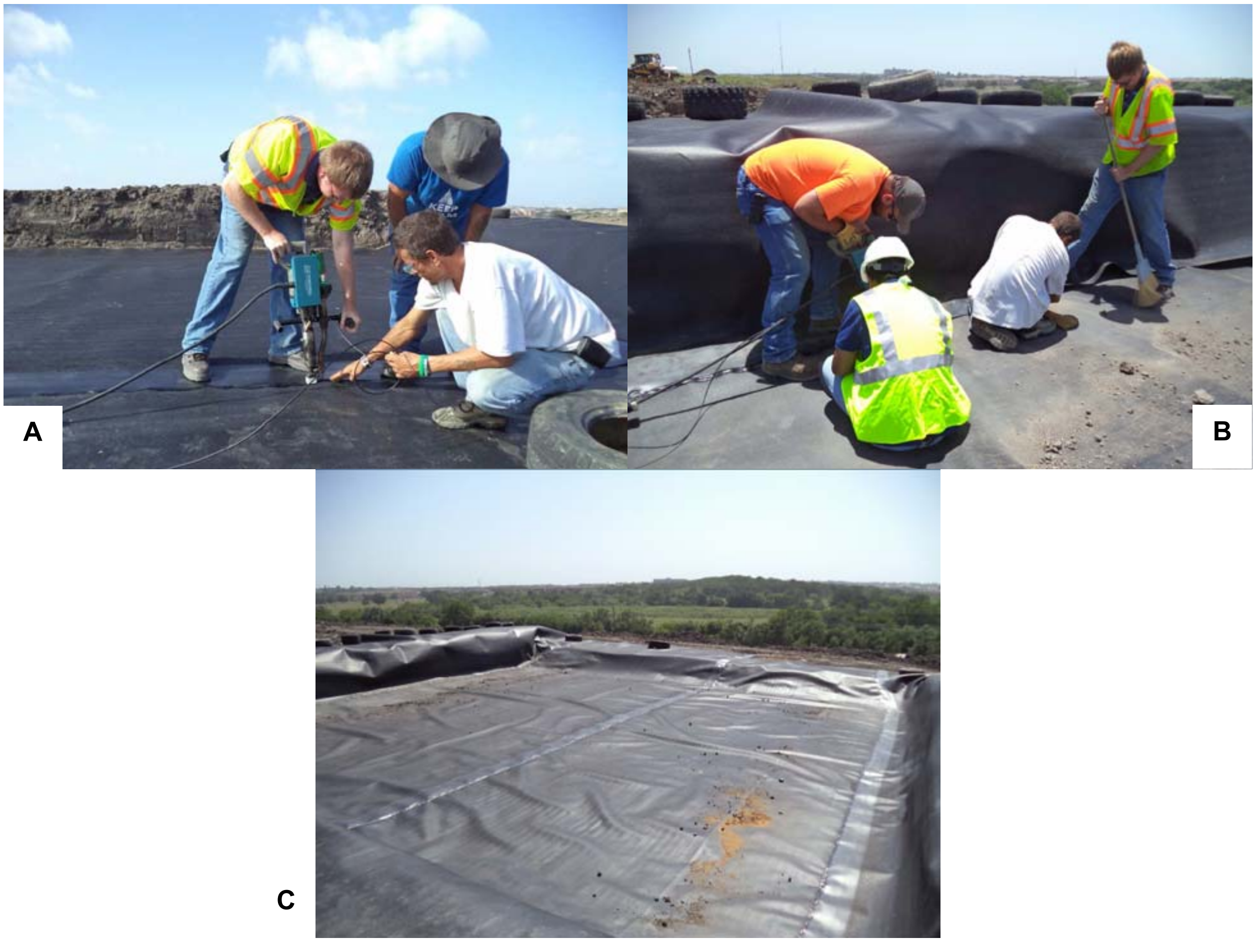
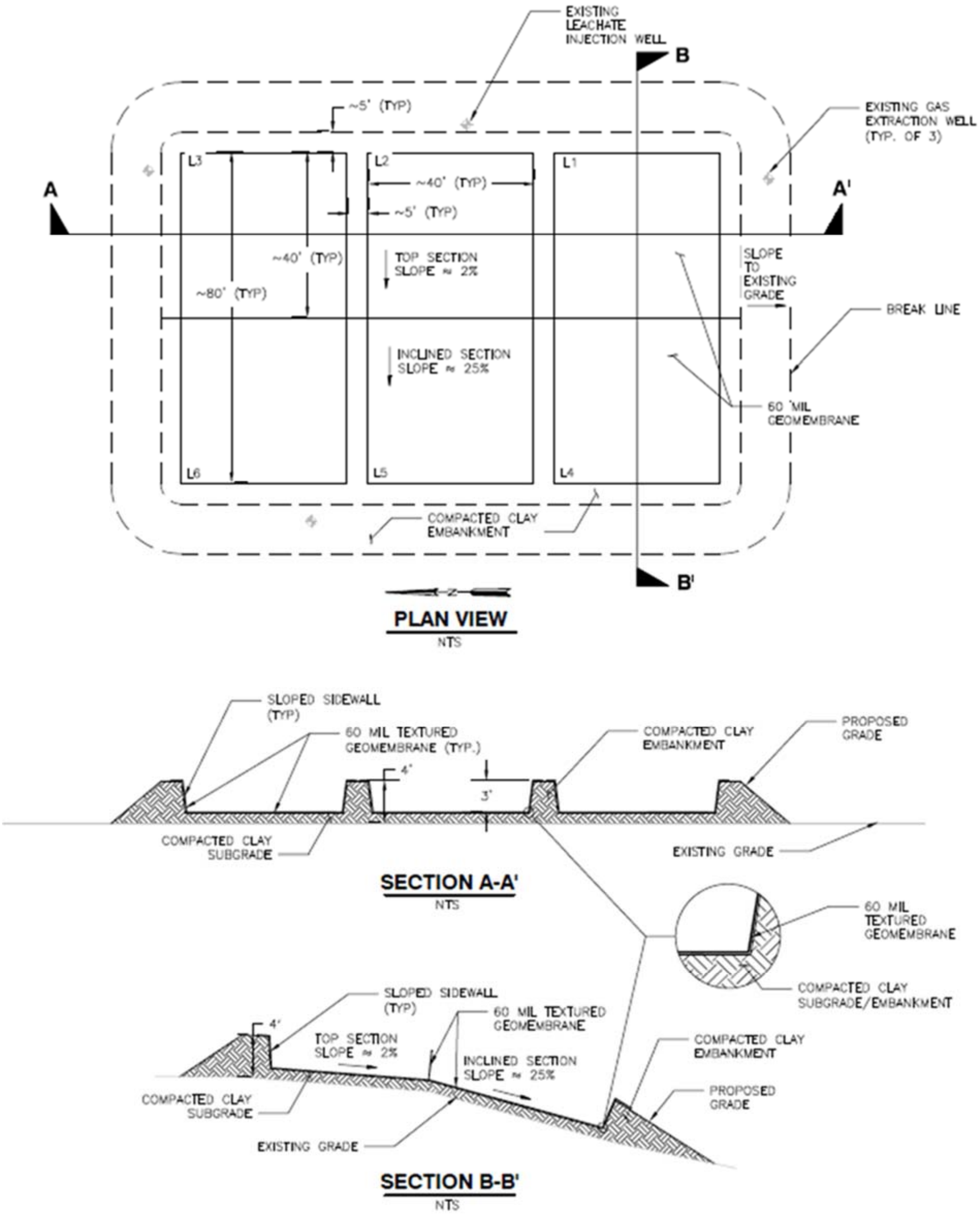


Figure 4.6: Geomembrane placement a) welding the geomembrane, b) sidewall geomembrane welding, and c) finished with the geomembrane in a lysimeter.



PLAN VIEW
NTS

SECTION A-A'
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SECTION B-B'
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Figure 4.7: Step 3 - general construction details.

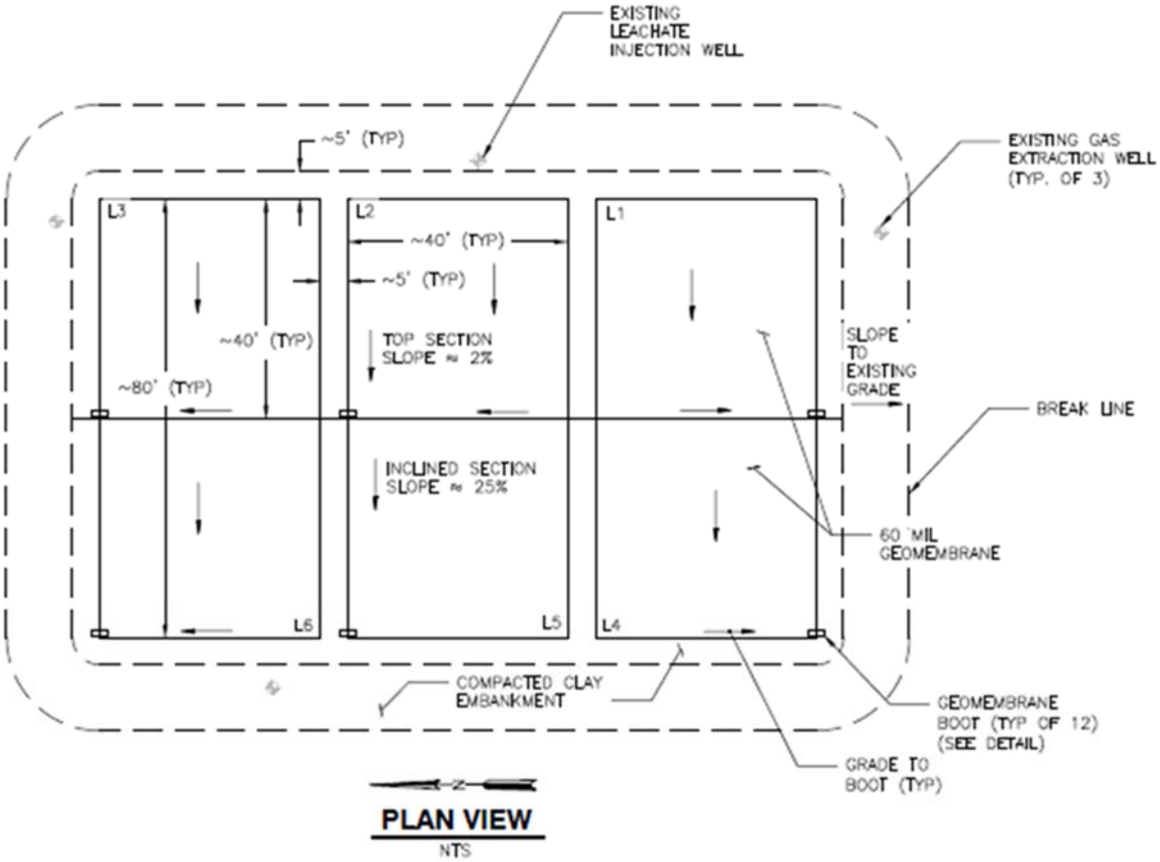
4.2.4 *Step 4 – geomembrane boot construction*

A total of twelve (12) geomembrane boots were constructed to be placed in the lysimeters [six (6) to attach to percolation collection pipes and six (6) connected to the runoff collection pipes]. Manufactured boots were not able to be found; therefore, they were constructed by COD and UTA. This process required a number of steps as follows:

1. A small geomembrane sheet was cut to approximately 1.5- by 1.5-feet,
2. The 4-inch HDPE pipe was used to trace a circle in the geomembrane sheet (Figure 4.8a),
3. The circle was cut-out in preparation for the 4-inch HDPE pipe to be inserted (Figure 4.8b),
4. The 4-inch HDPE pipe was inserted into the hole in the geomembrane sheet and this was placed into the 6-inch HDPE pipe in preparation for welding (Figure 4.8c),
5. The 4-inch HDPE pipe was heated to properly weld the geomembrane sheet to the HDPE pipe (Figure 4.8d),
6. The pipe and geomembrane sheet were welded together with the welding gun (Figure 4.8e),
7. The pipe and sheet were flipped over and welded for an adequate seal, and
8. This process was repeated for the remaining eleven (11) boots, with the resulting boot shown in Figure 4.8f.

These geomembrane boots were placed in the lowest point in the each lysimeter (just above the geomembrane) for percolation collection and the lowest point above the storage layer for runoff collection. Locations and details of the geomembrane boots (end of Step 4) in the lysimeters are provided in Figure 4.9.

Figure 4.8: Geomembrane boot construction a) tracing the pipe to cut the hole in the geomembrane sheet, b) cutting a 4-inch hole in the geomembrane, c) placing the geomembrane sheet and 4-inch pipe in a 6-inch pipe in preparation of welding d) heating the 4-inch HDPE pipe for welding preparation, e) welding the geomembrane to the HDPE pipe, and f) results of the welding procedure.



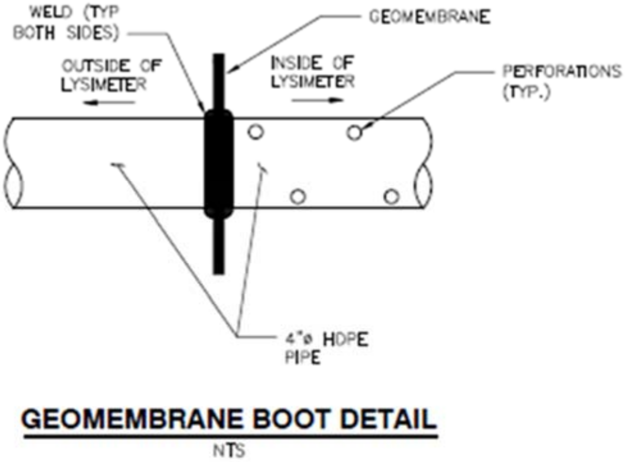


Figure 4.9: Step 4 - general construction details.

4.2.5 *Step 5 – percolation collection system construction*

To effectively collect the percolated water through the ET cover system, a percolation collection system was installed along the lowest side of each lysimeter. This would allow for water to flow from the geocomposite drain along the entire length of the lysimeter and be directed to a percolation collection tank. Considerable amounts of time were required of UTA and COD staff to place these percolation collection systems. The following procedure was followed during the construction of each collection system:

1. The embankment was excavated near where the HDPE pipe will pass through the lysimeter,
2. Joining adjacent HDPE pipes [a perforated pipe was attached to the geomembrane boot within the lysimeters and another (non-perforated) pipe attached to the boot outside of each lysimeter] (Figure 4.10a),
3. The boot was attached to the sidewall at the lowest point in each lysimeter (highly time-consuming process) (Figure 4.10b),
4. Geocomposite drain and pea-gravel was placed around each perforated pipe within the lysimeters (Figure 4.10d), and
5. The geocomposite drain was zip-tied together to encompass the percolation collection pipes and pea-gravel (Figure 4.10e).

General details of the percolation collection system (end of Step 5) are provided in Figure 4.11.

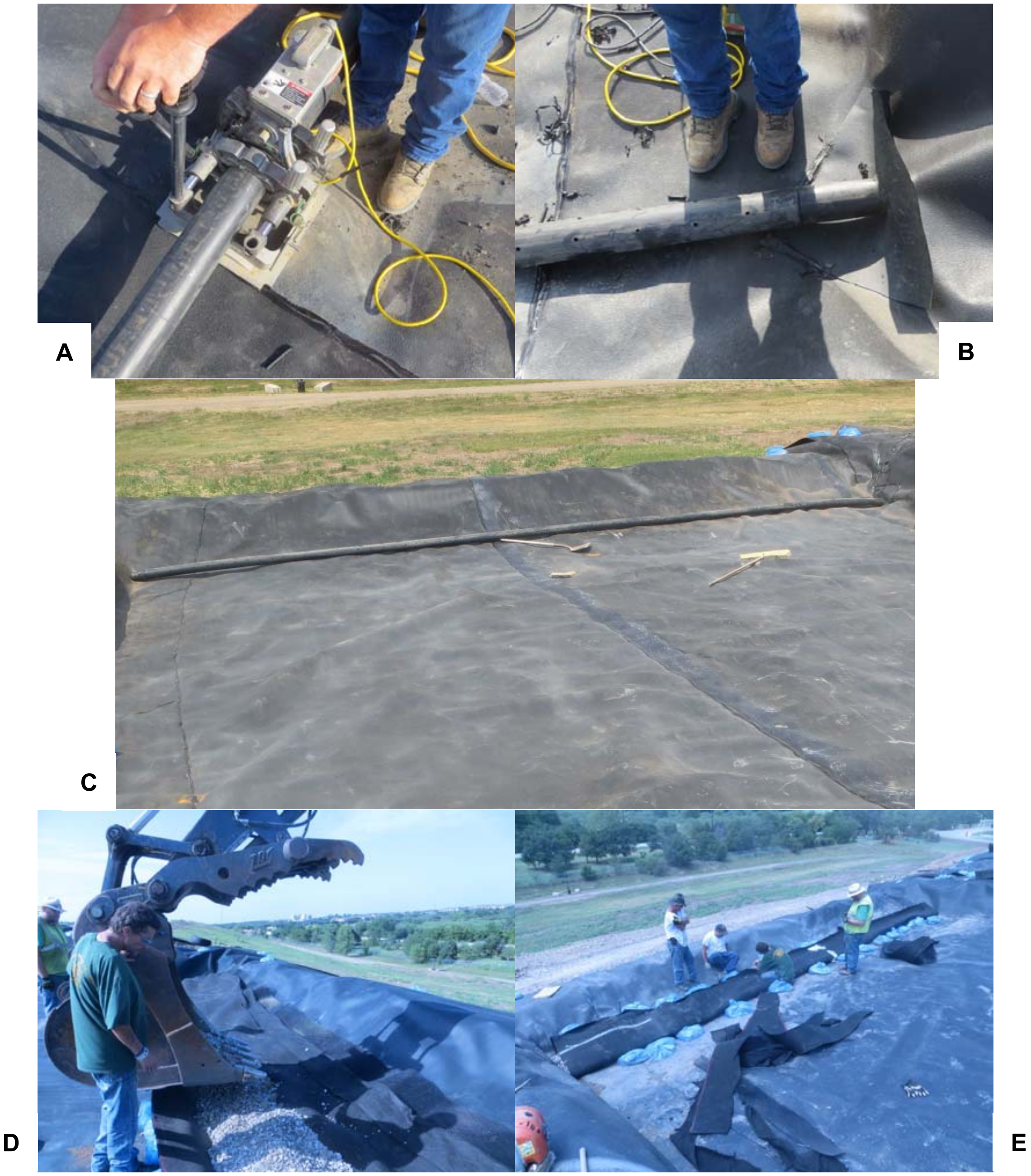


Figure 4.10: Percolation piping system construction a) cutting the HDPE pipe to join adjacent pipes, b) boot placement within a lysimeter, c) percolation collection pipe placed in a lysimeter, d) pea-gravel placed in the percolation piping system, and e) placing zip-ties to join the geocomposite drain.

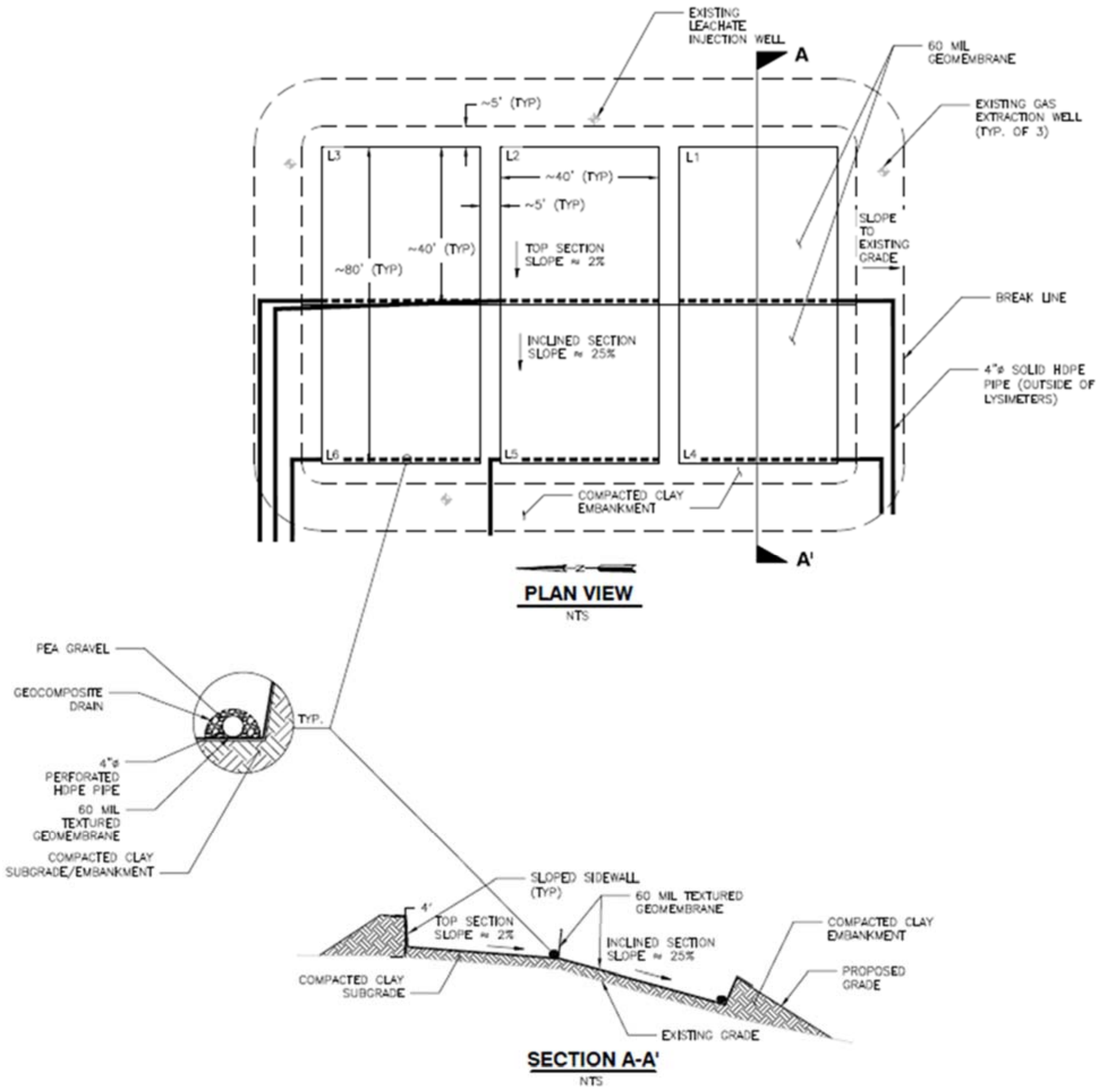


Figure 4.11: Step 5 - general construction details.

4.2.6 *Step 6 – geocomposite drain placement*

Geocomposite drains were placed overlaying the geomembrane at the bottom of the lysimeters, and geotextile was placed along the sidewalls. The geocomposite drain was placed at the bottom of each lysimeter to collect and direct water percolation through the ET cover systems to the percolation collection system. A preferential flow pathway would have been created if the geocomposite drain was placed along the sidewalls; therefore, only geotextile was placed along sidewalls. The geotextile along the sidewall was placed in an effort to protect the geomembrane sidewall during subsequent soil placement. This step was relatively less time consuming for UTA and COD to complete than the previous several tasks; however, the geocomposite drain and geotextile tended to stick (similar to Velcro) to the geomembrane. Adjacent sheets of geocomposite drain and geotextile were connecting by zip-ties at approximately 0.5-m (1.5-ft) intervals (Figure 4.12a and Figure 4.12b). General details of the geocomposite drain within the lysimeters (end of Step 6) are provided in Figure 4.13.

Figure 4.12: Geocomposite drain placement a) joining adjacent geocomposite drains, b) joining geocomposite drain and geotextile (located on the sidewall), and c) finished with geocomposite in a lysimeter.

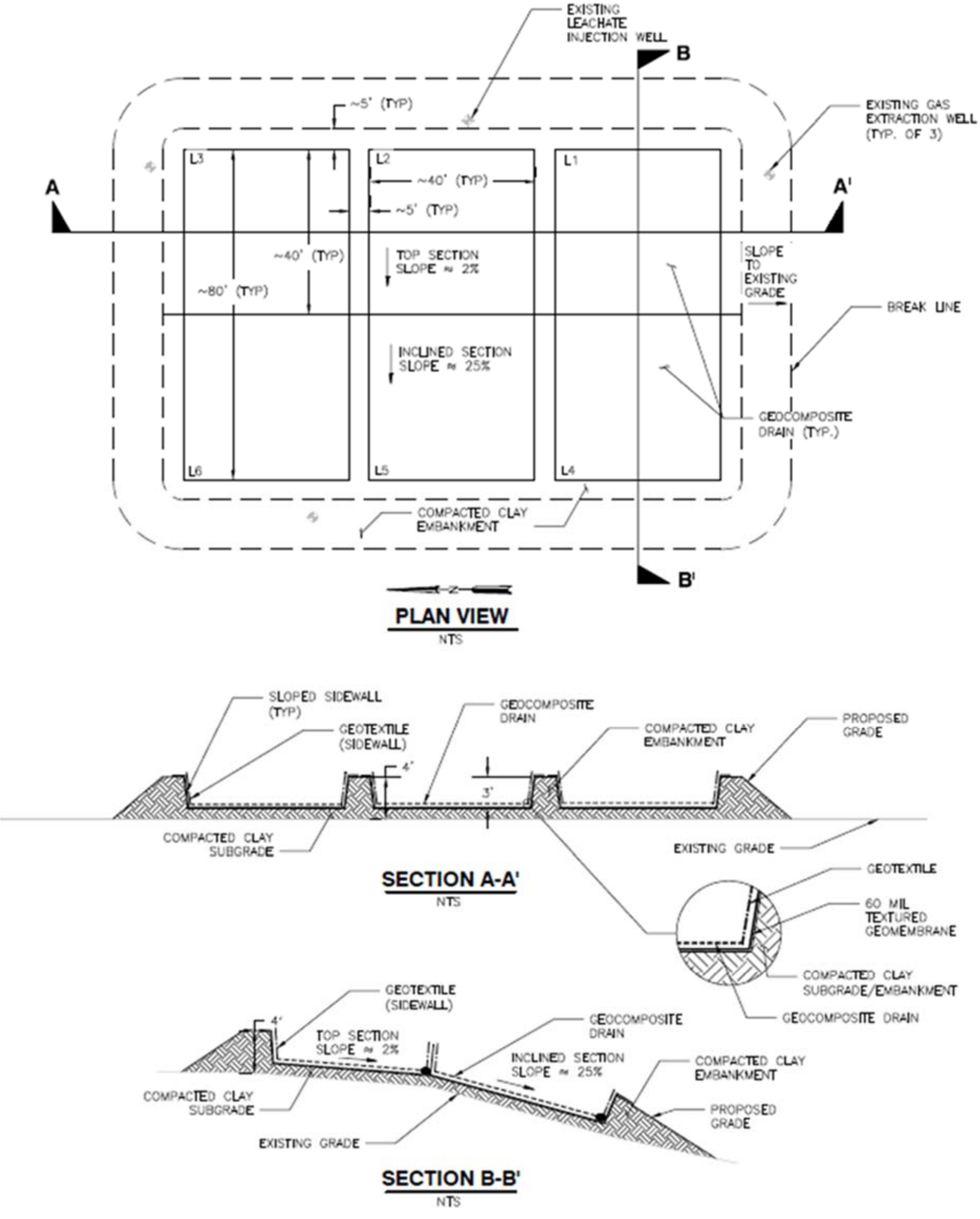


Figure 4.13: Step 6 - general construction details.

4.2.7 *Step 7 – 3-foot of compacted clay placement*

Compacted clay [0.9-m (3-ft)] was placed in each lysimeter in approximately 0.2-m (8-inch) lifts by the contractor. In an effort to obtain the required 95% maximum dry density requirement, the soil was wetted and compacted with a sheep-footed compactor (Figure 4.14b and Figure 4.14b). The density and moisture content of each lift within each lysimeter was tested by a nuclear density gauge (results provided in Appendix A). A 8-inch un-compacted loose lift was used for each layer and the height of each lift was indicated on the sidewall in several locations. The 1st soil layer was critical to not damaging the geomembrane liner system and for percolation collection; therefore, special precautions were taken (e.g., avoiding wrinkles in the geomembrane while placing the soil, avoiding running equipment on the liner, and avoiding sharp turning of equipment). Desiccation cracks observed at the top of soil layers were removed by either scarifying the surface or removing the top several inches prior to placement of the subsequent soil layer. Soil samples were taken from each lift for laboratory analysis, with the results provided subsequently. It was noted that excessively wet compacted clay can cause sliding of equipment during soil placement in inclined sections. UTA was present throughout the soil placement to ensure quality control and resolve any construction and design problems. General details of the compacted clay within the lysimeters (end of Step 7) are provided in Figure 4.15.

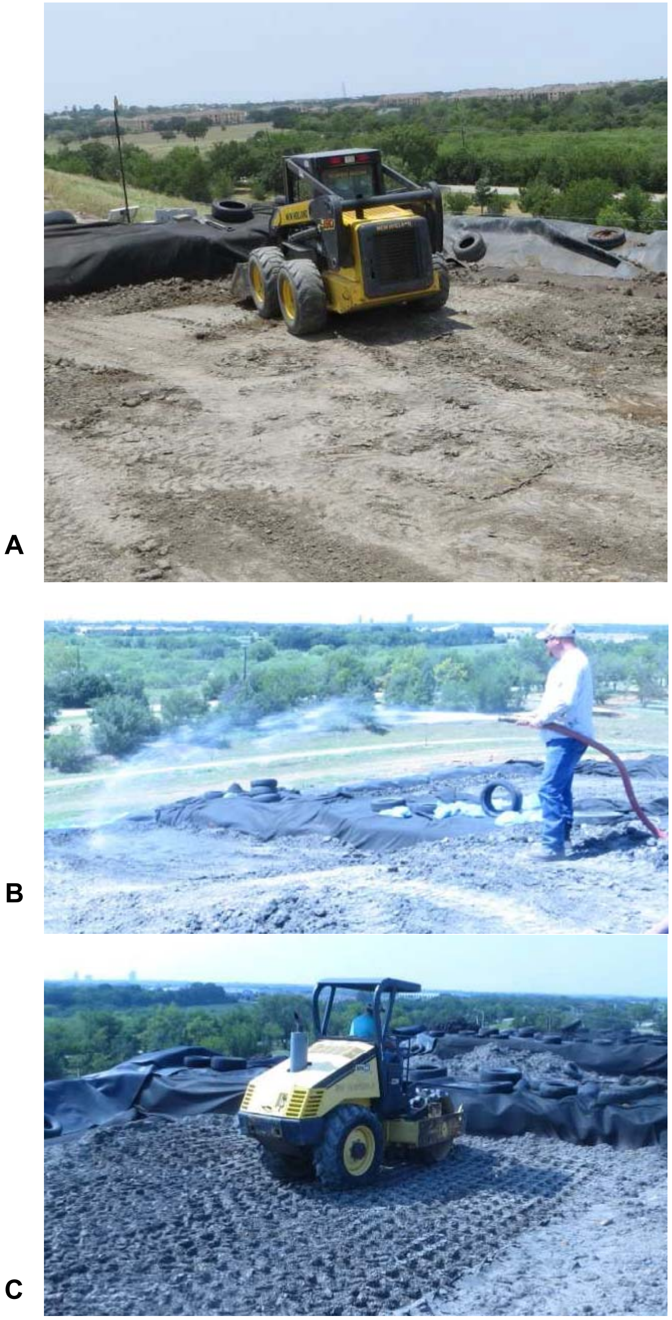


Figure 4.14: Compacted clay placement a) placement of clay by a skid-steer, b) water application for compaction purposes, c) sheep-footed compactor utilization.

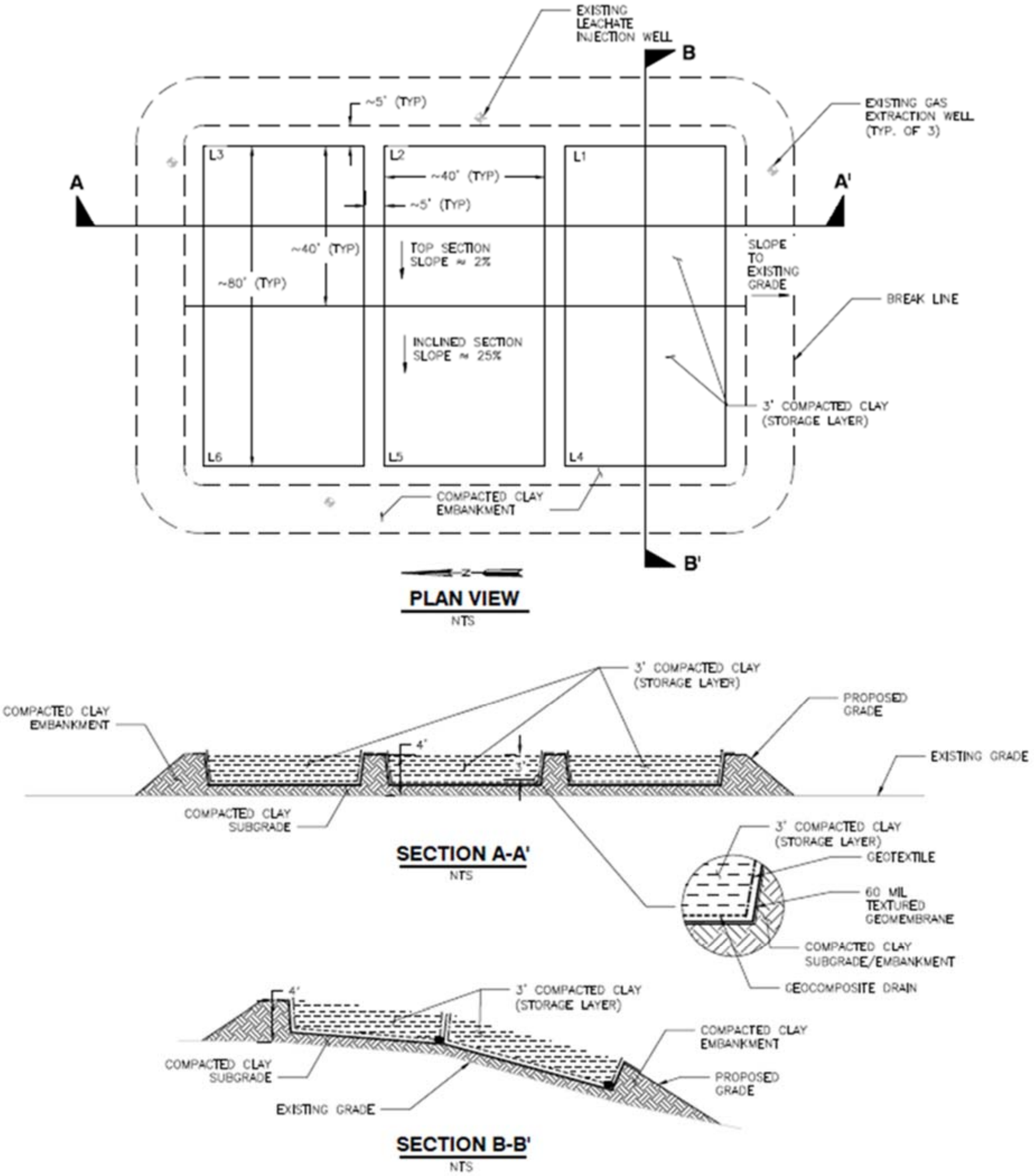


Figure 4.15: Step 7 - general construction details.

Laboratory analysis was conducted on the soil samples obtained during construction of the clay storage layer[9]. The particle size distribution was determined for samples by sieve analysis (wet sieve). For the inclined ET cover sections over 90% (fine content) of the soil passed through the No. 200 sieve, and 80 to 90 passed through the No. 200 sieve for the top cover sections (Table 4.1). Additionally, the Atterberg Limit test was conducted on the soils, with results provided in Table 4.1.

Table 4.1: USCS Soil Classification of the Test Samples

Approx. Slope	Lysimeter No. And Sample Location	Liquid Limit	Plastic Limit	Plasticity Index	Fine Content (%)	Soil Classification (USCS)	Soil Description
2%	L1, Top Lift	51	21	30	81.39	CH	High Plastic Clay
2%	L2, Top Lift	46	22	24	82.55	CL	Medium Plastic Clay
2%	L3, Top Lift	47	24	23	84.65	CL	Medium Plastic Clay
25%	L4, First Lift	50	22	28	97.37	CH	High Plastic Clay
25%	L5, First Lift	56	26	30	95.22	CH	High Plastic Clay
25%	L6, First Lift	53	25	28	92.20	CH	High Plastic Clay

The Standard Proctor test has been conducted on the same samples to obtain the optimum moisture content (OMC) and the max dry unit weight of the soil. Similar results were obtained from all of the soils tested (Figure 4.16 and Table 4.2). Max dry unit weight ranges between 108 to 111 pound per cubic feet and optimum moisture content ranges between 17 to 19%.

The SWCC of the soil utilized in the storage layer was estimated based upon results from moisture and tensiometer sensors measuring soil moisture content and suction in the field. The moisture content at field capacity (33 kPa) and wilting point (1,500 kPa) can be estimated as 0.34 and 0.25, respectively.

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[9] Laboratory testing was not conducted by the Author, but by other UTA students; however, soil data is included to provide a complete understanding of the ET cover systems installed.

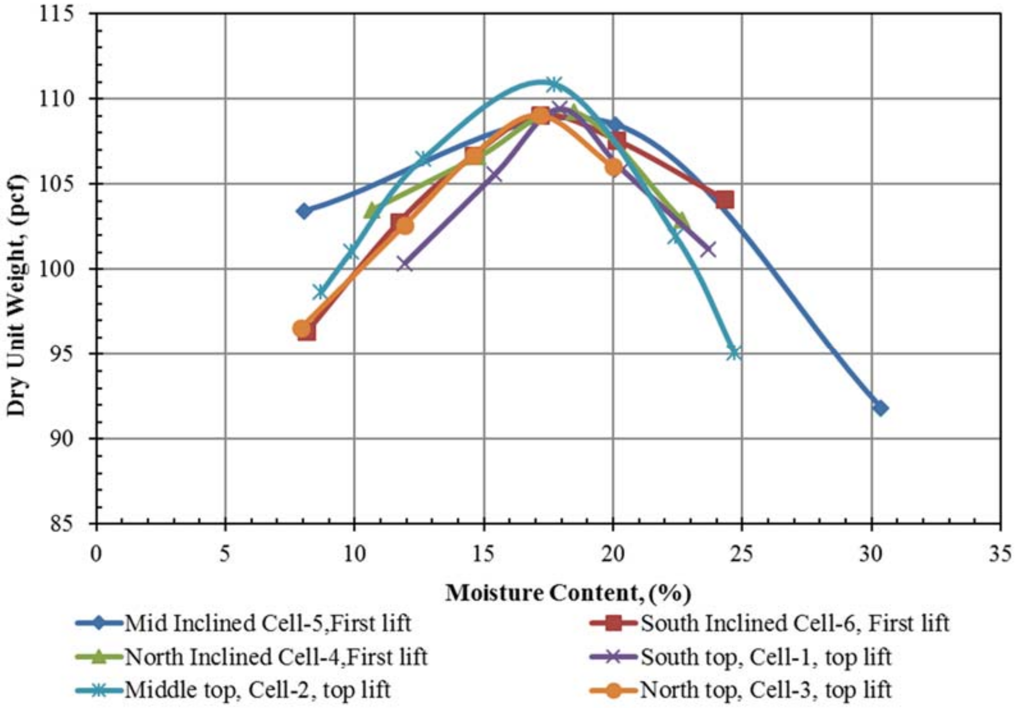


Figure 4.16: Standard Proctor Test Results

Table 4.2: Standard Proctor Test Results

Approx. Slope	Lysimeter No. And Sample Location	Max Dry Unit Weight (lb/ft^3)	OMC (%)
2%	L1, Top Lift	109.5	17.9
2%	L2, Top Lift	111	17.3
2%	L3, Top Lift	109.2	17.2
25%	L4, First Lift	109.1	17.3
25%	L5, First Lift	108.9	18.5
25%	L6, First Lift	109.6	18

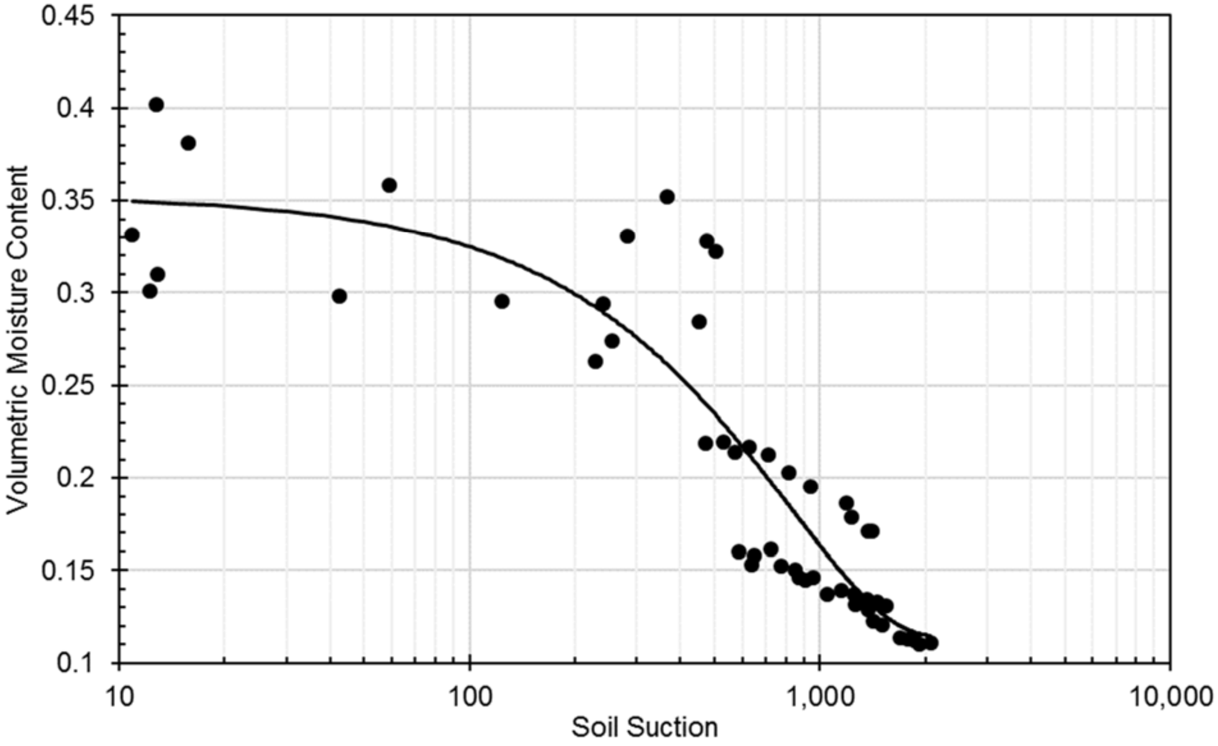


Figure 4.17: SWCC from field moisture and tensiometer sensors.

4.2.8 *Step 8 – topsoil sidewall placement and bentonite placement*

In an effort to limit the water to within the lysimeters, the geomembrane liner was vertically placed approximately 0.9-m (3-ft) from the top of the compacted clay (storage layer). This allowed the placement of a 0.9-m (3-ft) high berm along the lysimeter perimeter. Excess soil was removed around the lysimeter perimeters and bentonite placed in those locations by UTA and COD staff (Figure 4.18a and Figure 4.18c). A substantial amount of bentonite was placed in an effort to prevent preferential flow along sidewalls. General details of the topsoil and bentonite place (end of Step 8) are provided in Figure 4.19.

Figure 4.18: Top of sidewall preparation a) removal of excess soil around the lysimeter perimeters, b) results of placing geomembrane vertical, and c) placing bentonite along the lysimeter perimeters.

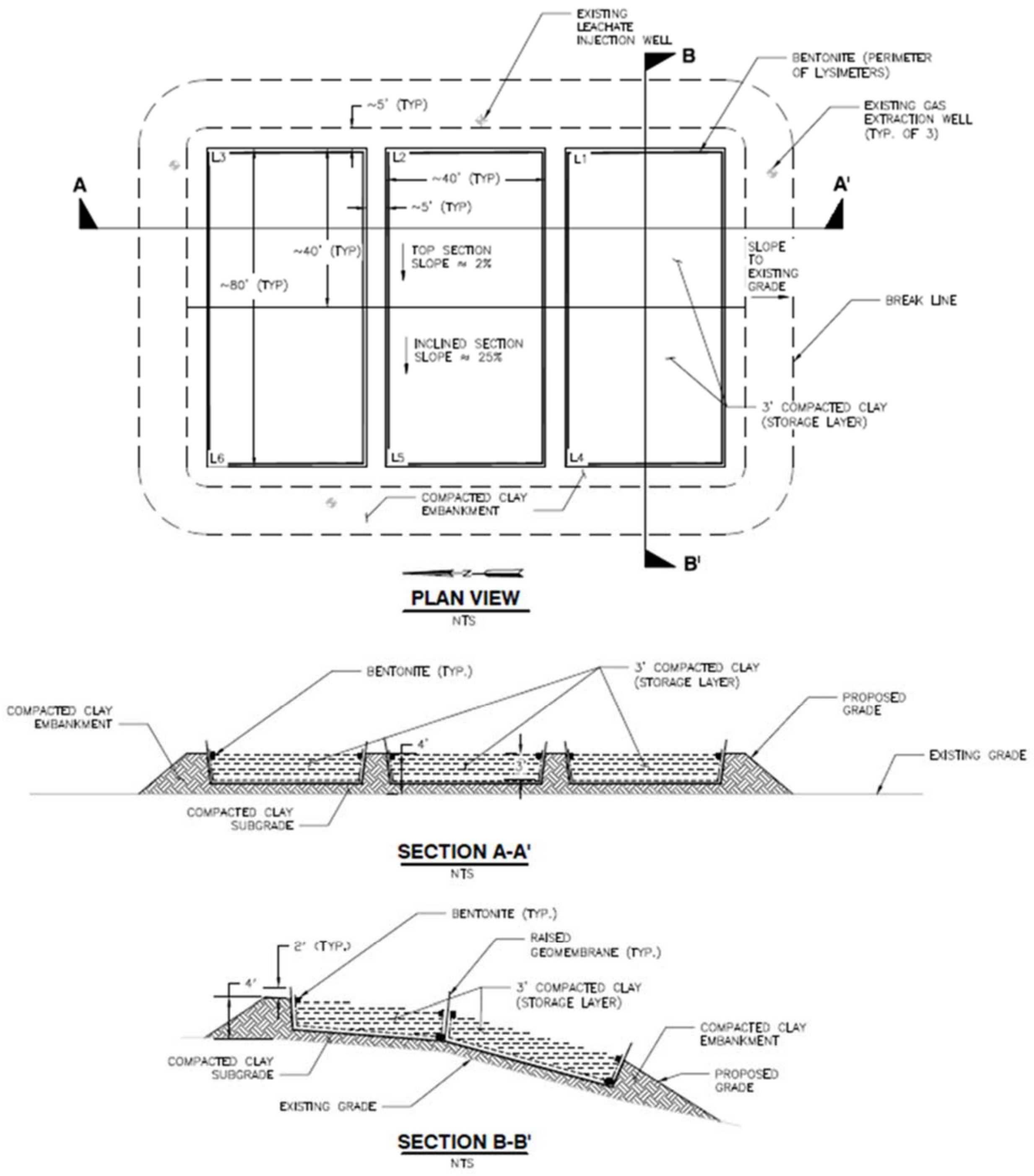


Figure 4.19: Step 8 - general construction details.

4.2.9 *Step 9 – Berm construction*

Clay berms were installed on both sides of the exposed vertical geomembrane along the lysimeter perimeters [all four (4) sides]. Berms were compacted by a skid-steer in an effort to avoid settlement during the monitoring period and were constructed approximately 2- to 3-ft tall. The berms were placed by COD and UTA, and were installed to limit the runoff from flowing into or out of the lysimeters. Construction details of the berm are provided in Figure 4.20. General details of the berm within the lysimeters (end of Step 9) are provided in Figure 4.21.

Figure 4.20: Berm construction a) between two (2) lysimeters and b) within a lysimeter.

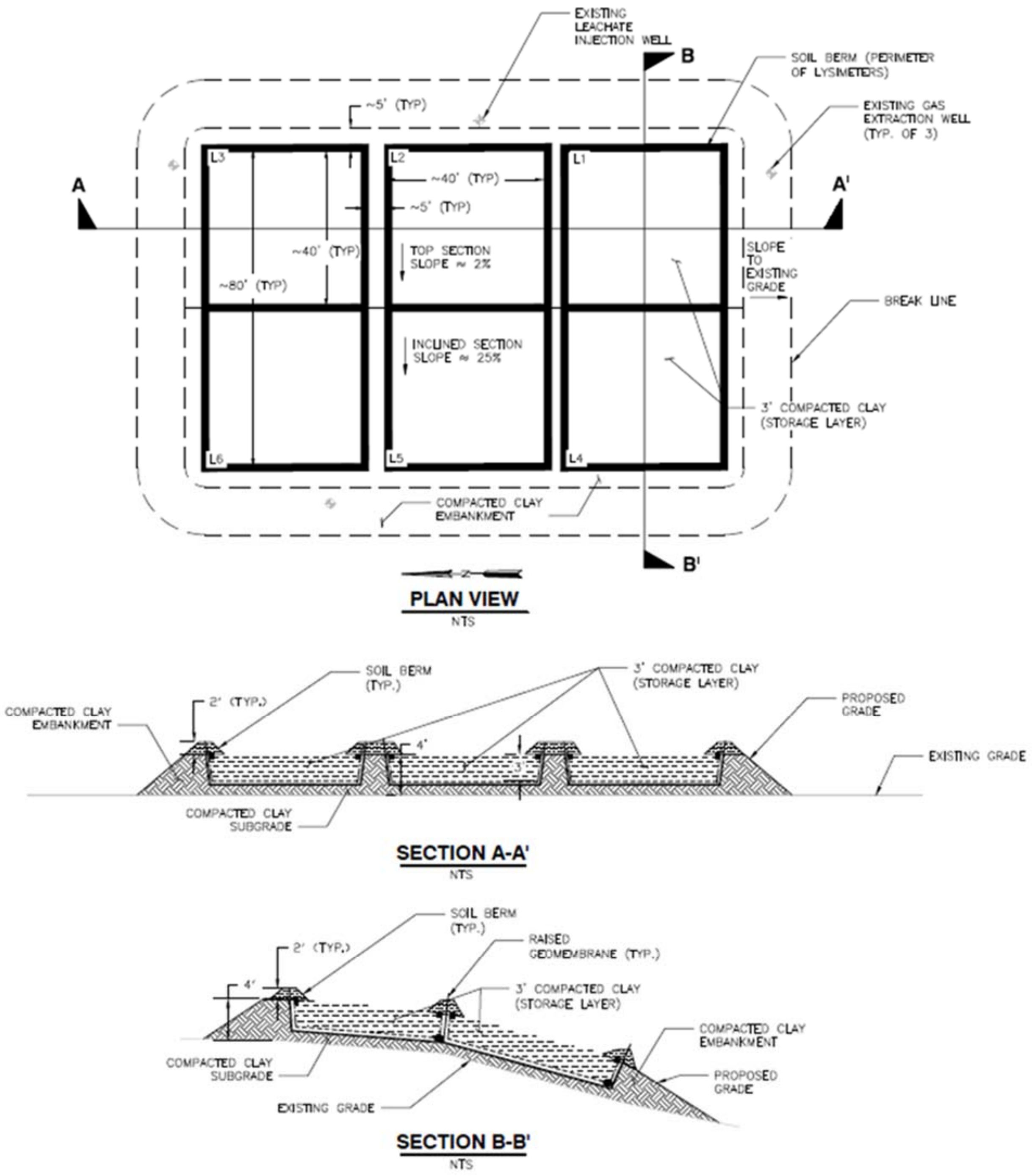


Figure 4.21: Step 9 - general construction details.

4.2.10 *Step 10 – runoff collection system construction*

The runoff collection systems were constructed with a similar procedure as the percolation collection systems, and were completed by COD and UTA staff. A slight grade was incorporated into the runoff collection system to direct collected runoff towards the geomembrane boot and to the runoff collection tanks. Each lysimeter had its own runoff collection system. The following procedure was followed:

1. Geomembrane with overlaying geocomposite drain was placed along the lowest lysimeter side (Figure 4.22a),
2. Adjacent perforated pipes were welded together and the geomembrane boot was welded to the sidewall (same procedure as the percolation collection systems) (Figure 4.22b),
3. Pea-gravel was placed around the perforated pipes (Figure 4.22c), and
4. The geocomposite drains were zip-tied to encompass the perforated pipes and pea-gravel to form a “burrito-wrap” (Figure 4.22d).

A geomembrane liner was placed below the runoff collection system in an effort to avoid runoff from passing through the “burrito wrap” and infiltrating into the cover system prior to collection. General details of the runoff collection systems (end of Step 10) are provided in Figure 4.23.

Figure 4.22: Runoff collection system a) geomembrane and geocomposite drain placement, b) welding geomembrane boot, c) runoff collection pipe and pea-gravel placement, and d) placing zip-ties to join the geocomposite drain.

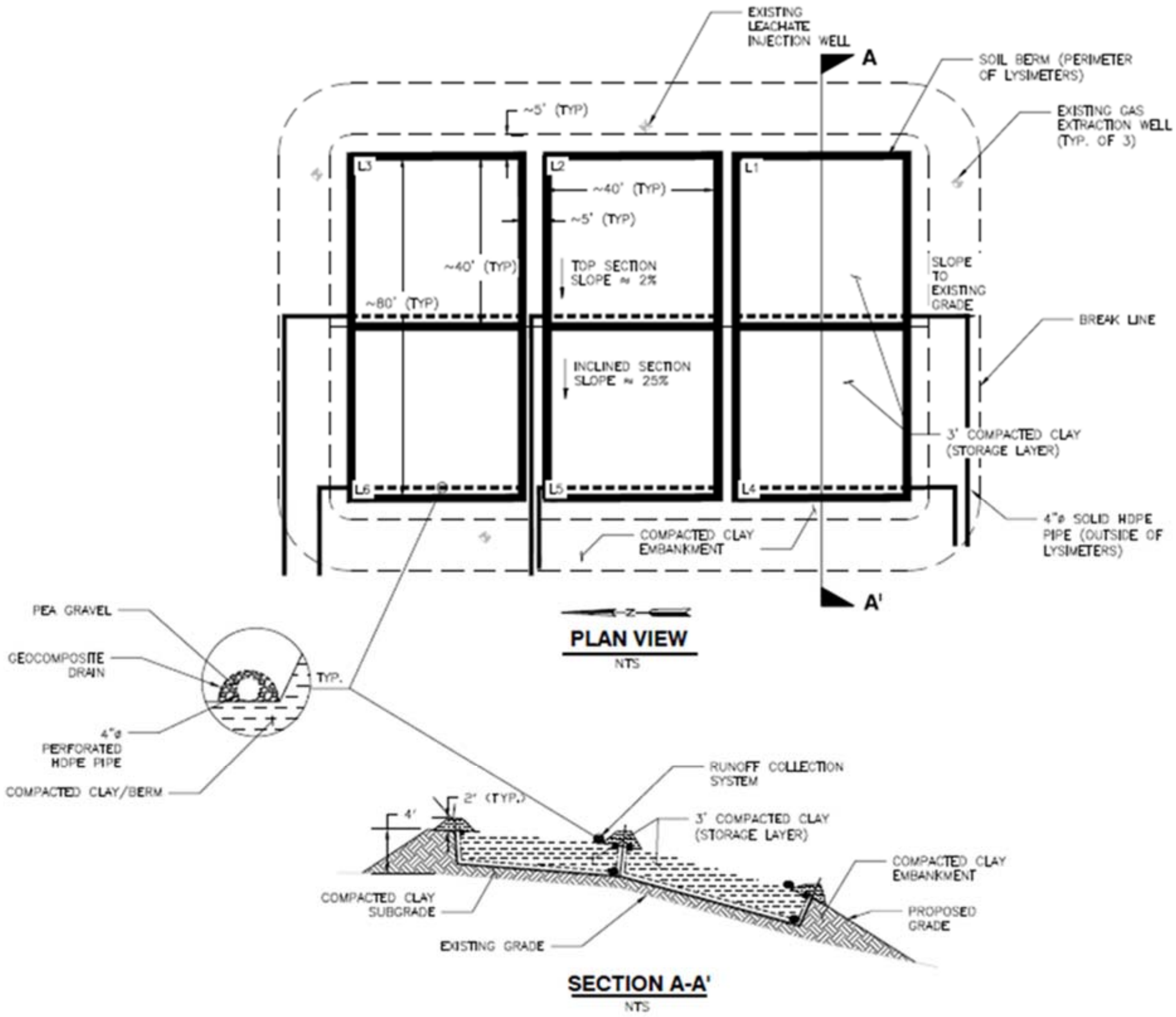


Figure 4.23: Step 10 – general construction details.

4.2.11 *Step 11 – 1-foot of topsoil placement*

Topsoil [approximately 0.3-m (1-ft)] was placed overlaying the compacted clay layer and berms in each lysimeter. The topsoil was placed in an effort to allow vegetation growth, and was not compacted. Stakes were placed at the corner and center of each lysimeter and marked at 1-ft to in an effort to ensure a correct depth of topsoil. Placement of the topsoil was conducted by the COD and overseen by UTA. Details of this construction process are provided in Figure 4.24. General details of the topsoil placement within the lysimeters (end of Step 11) are provided in Figure 4.25.

Figure 4.24: Topsoil placement a) placing the topsoil above compacted clay and b) 1-foot of topsoil placed.

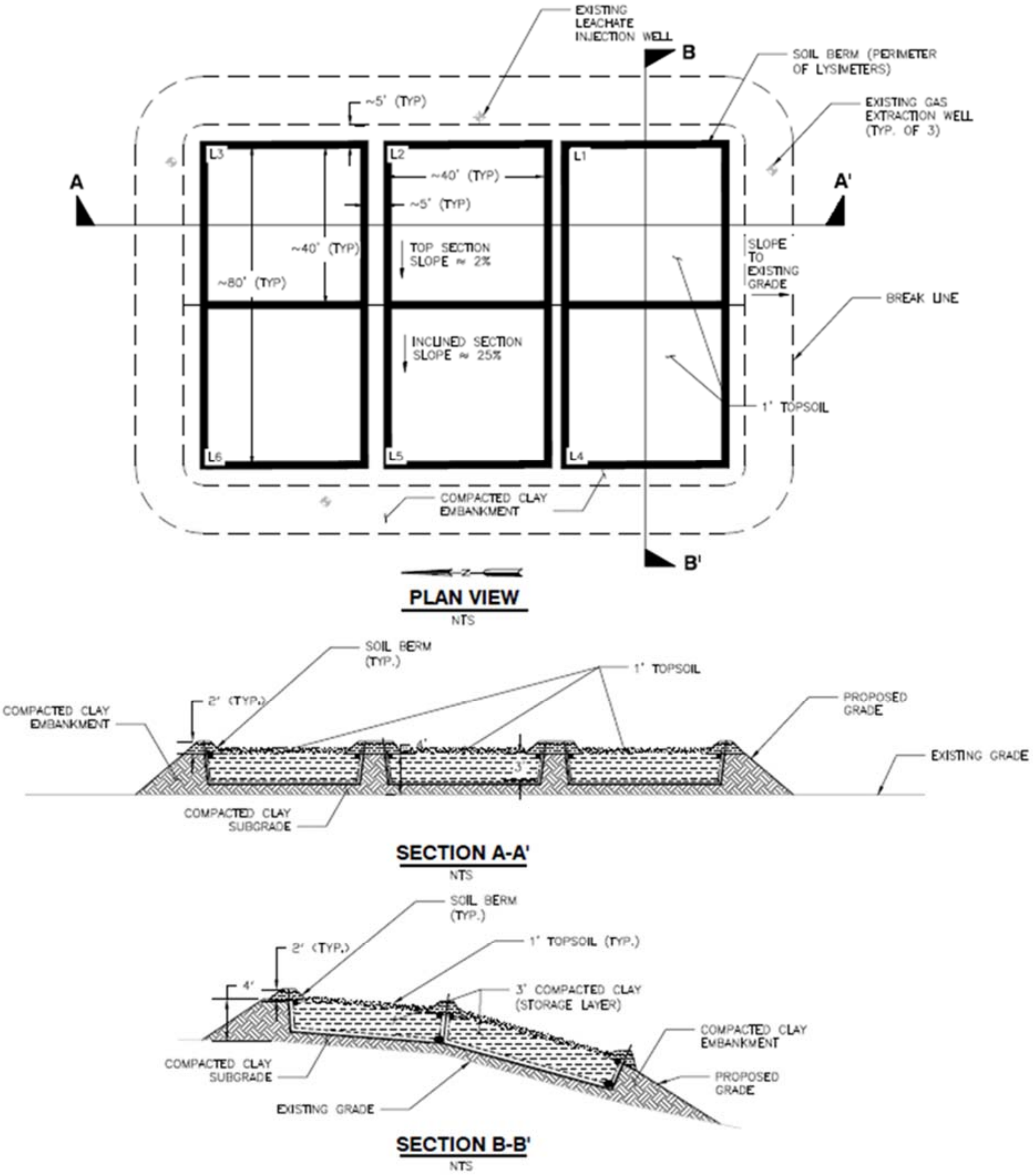


Figure 4.25: Step 11 - general construction details.

4.2.12 *Step 12 – collection tank placement and installation (percolation and runoff)*

Details of this step are provided in Section 4.3; however, General details of the collection tank placement and installation (percolation and runoff) (end of Step 12) are provided in Figure 4.26.

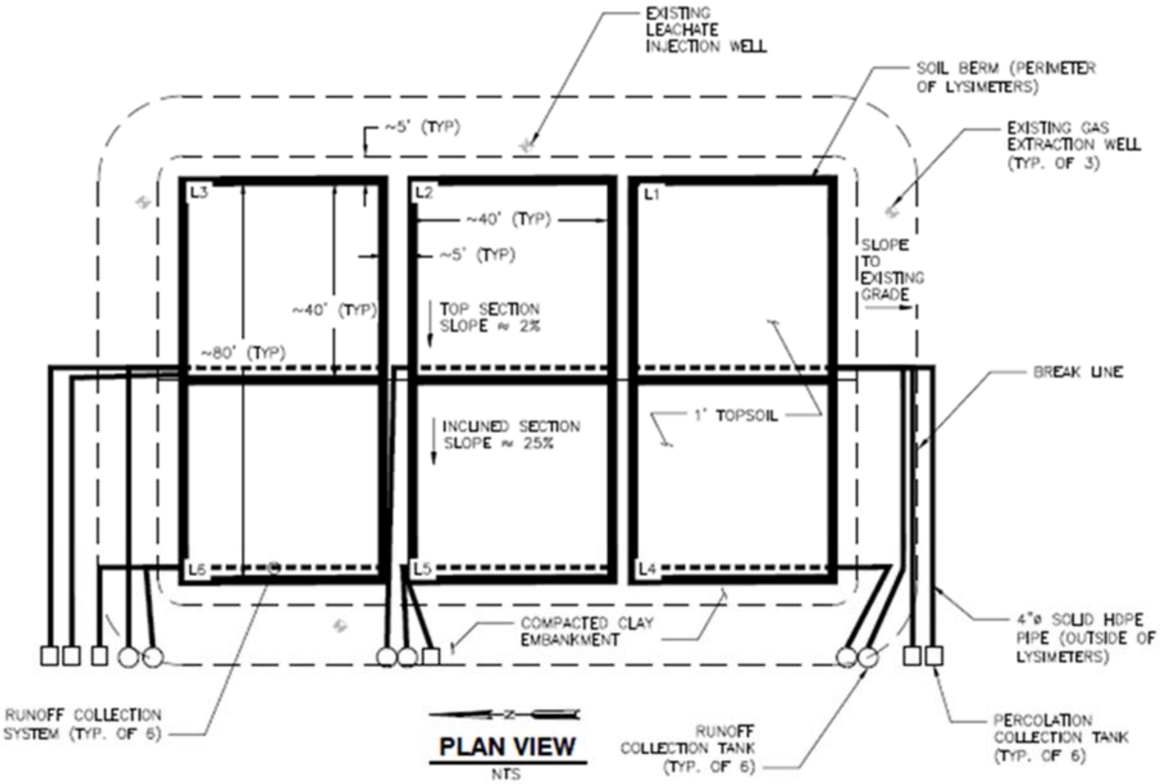


Figure 4.26: Step 12 - general construction details.

4.2.13 *Step 13 – instrumentation (within soil, near/within collection tanks, and weather station)*

Details of this step are provided in Section 4.3.

4.2.14 *Step 14 – vegetation placement and erosion mat placement*

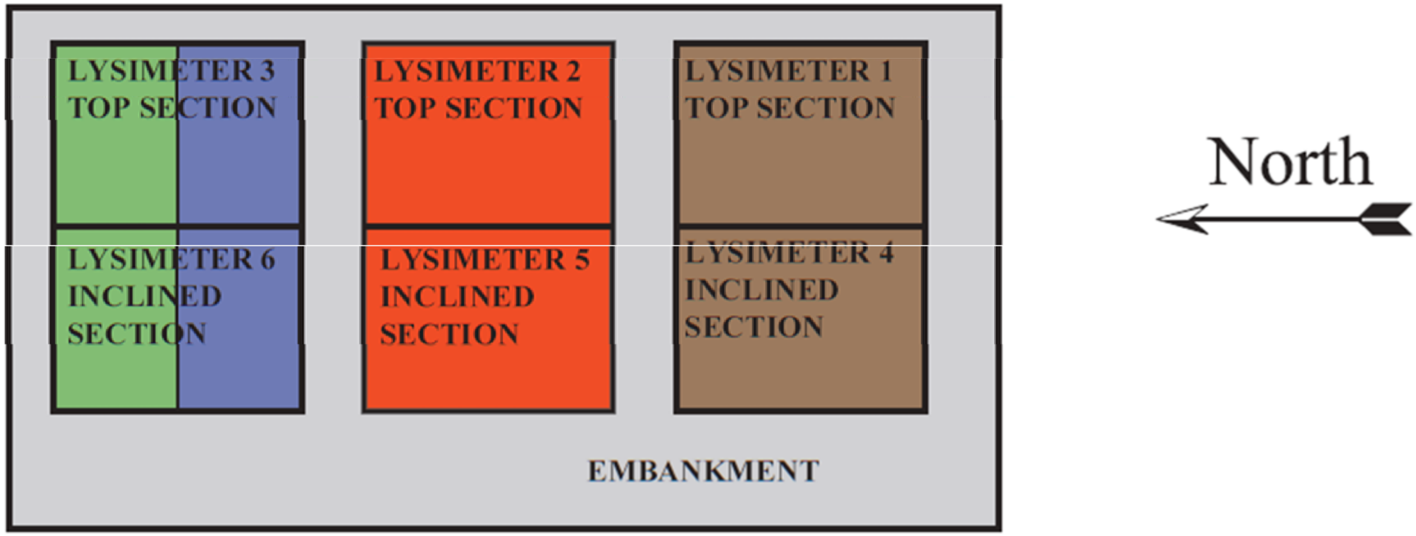
Seeds and sod to establish vegetation were placed overlying the topsoil in accordance to Table 4.3 and Figure 4.27. The vegetation was selected because the vegetation is either native which have evolved to thrive in the research location, or have the ability to thrive in the area (i.e., bermuda grass). These vegetation mixes were also selected because they are readily available in the area and likely to provide transpiration throughout the year. Additionally, the vegetation mixes were selected as to not have to rely on yearly seeding. It was determined to sod (bermuda grass) half of two (2) of the ET cover sections with seed the remain half with bermuda grass. This was conducted to analyze the performance of the sod versus seeded of the same vegetation species, as sodding a landfill is associated with substantial cost. Additionally, Lysimeters 1, 2, 4, and 5 were planted with similar vegetation mixes which only varied by planting upland switchgrass in Lysimeters 2 and 5, and planting a mix of native trail in Lysimeters 1 and 4. This was done in an effort to evaluate the difference that switchgrass and native trail have on the performance of the cover.

The vegetation placement was conducted by UTA and COD; and the following procedure was used:

1. Seeds were placed within the lysimeters [with the exception of half of two (2) lysimeters where sod was placed] (Figure 4.28a),
2. The seeded areas were rolled to place the seeds within the topsoil (Figure 4.28b),
3. Erosion mat was placed and stapled into place over the seeded areas (Figure 4.28c),
4. Switchgrass bulbs were placed within two (2) lysimeters (Figure 4.28d), and
5. Sod was installed in half of two (2) lysimeters (Figure 4.28e).

Table 4.3: Vegetation mix details.

Vegetation Type	Vegetation Details	Extent of Vegetation
1	Common Bermuda Grass	50% of Lysimeters 3 and 6
	Hulled Common Bermuda Grass (Grade 90/80)	50% of Lysimeters 3 and 6
2	Mix of Upland Switchgrass, Perennial Wildflower Mix, and Caliche	100% of Lysimeters 2 and 5
3	Mix of Native Trail, Perennial Wildflower Mix, and Caliche	100% of Lysimeters 1 and 4



LEGEND:

🟩 Sod

🟦 Hulled Common Bermuda Grass (Grade 90/80)

🟧 Mix of equal portions of Upland Switchgrass, # 2511, Perennial Wildflower Mix (of Scourched Earth Recovery Mix, #1816), and Caliche, # 2860 Mix

🟫 Mix of equal portions of Native Trail, # 1811 (or Texas #1001) Mix, Perennial Wildflower Mix and Caliche # 1 Mix

⬜ Coal

PLANTING DETAILS:

1. Seeding details shall be in accordance to the application methodology provided by the local supplier.
2. Erosion control blanket shall be placed within each lysimeter, except where sod is located.

Figure 4.27: Vegetation details.

Figure 4.28: Vegetation placement procedure a) seed placement, b) rolling topsoil/seeds, c) erosion mat placement, d) switchgrass planting, and e) sod placement.

4.2.15 *Step 15 – clean-up activities*

Various clean-up activities encompassed the final construction task. These activities were completed by UTA and COD and included the following:

- Construction of a wall near a lysimeter to allow access to a gas collection well (Figure 4.29a),
- Placement of a water tank to efficiently provide the vegetation water (Figure 4.29b), and
- Placement of erosion mats on the embankment (Figure 4.29c).

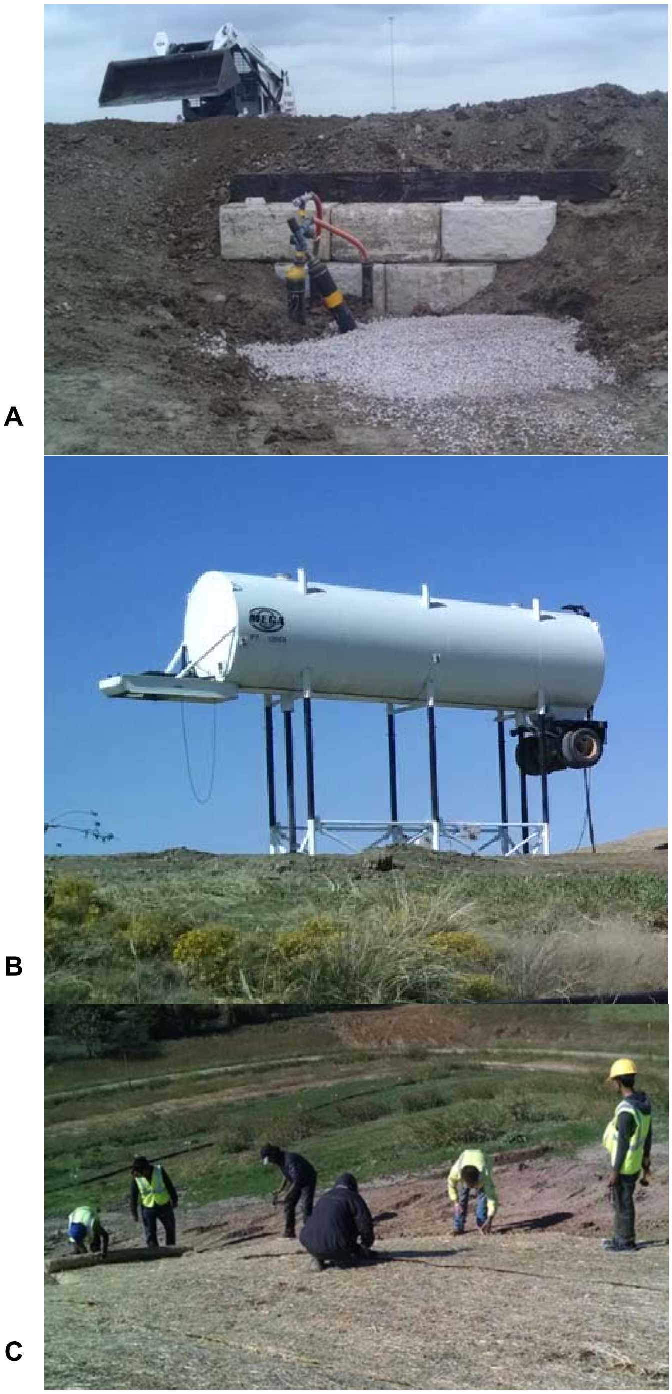


Figure 4.29: Clean-up activities a) gravity wall construction b) water tank placement c) erosion mat placement outside of lysimeters.

4.2.16 *Completed lysimeters and evapotranspiration cover systems*

Results of the time-consuming and effort intensive construction process previously discussed are provided Figure 4.30, Figure 4.31, and Figure 4.32.

Figure 4.30: Finalized construction of a) a top section, b) an inclined section, c) west embankment and collection tanks, and d) north embankment and collection tanks.

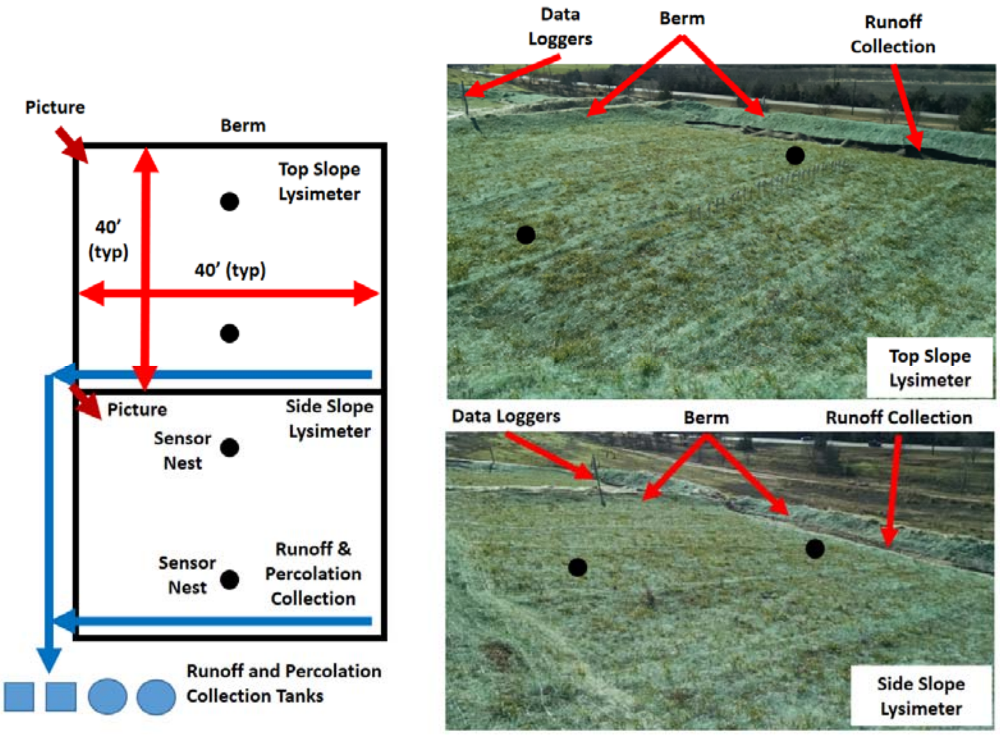


Figure 4.31: General details of the complete lysimeters and ET cover sections.

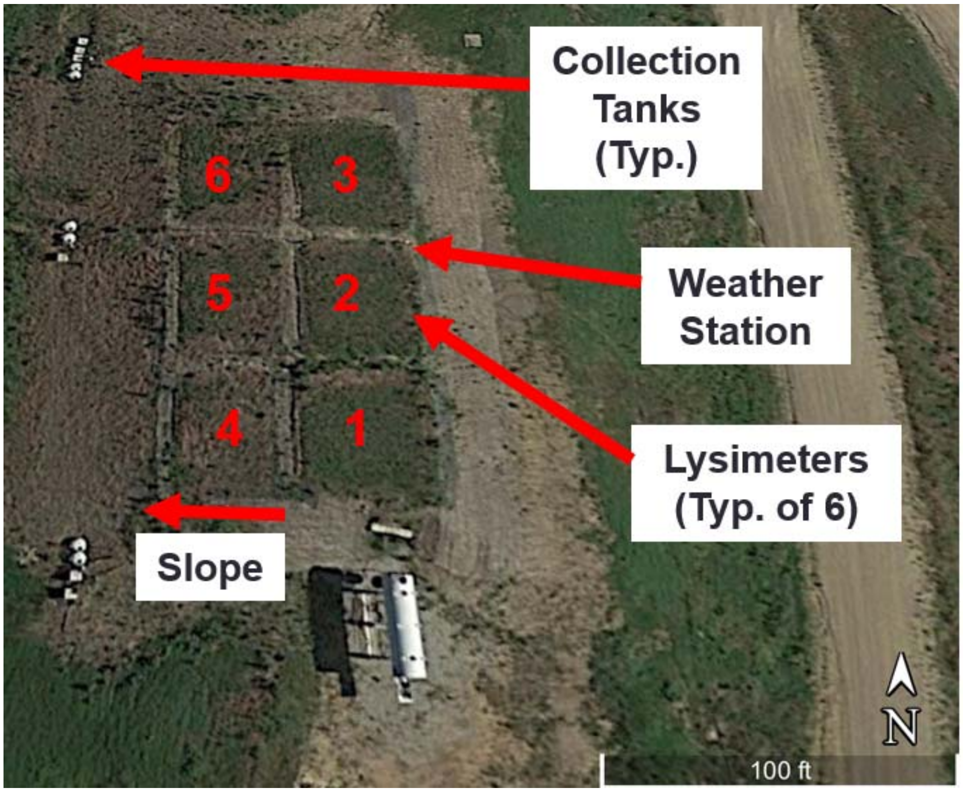


Figure 4.32: Completed lysimeters – Google aerial view

4.3 Instrumentation Installation

A plethora of sensors and instrumentation were installed to effectively measure and analysis critical parameters of the ET cover systems (as discussed in Chapter 3). Sensors and instrumentation was placed within each ET cover system, runoff collection tanks, and percolation collection tanks; and provided individual results for each cover system. A motorized auger (6-inch diameter) was utilized to excavate the soil for placement of sensors within the cover systems. Due to the high compaction rate of the cover soil that was installed, drilling with the motorized auger was difficult and required four (4) people. One (1) runoff and one (1) percolation collection tank were installed for each of the lysimeters. This allowed for individual monitoring of runoff and percolation for each of the ET cover systems. As discussed in Chapter 3, the subgrade of the collection tanks was compacted in an effort to prevent differential settlement. As shown in Figure 4.35, relatively large cylindrical tanks were utilized for collection of runoff (large amounts of runoff was anticipated). The percolation collection tanks were smaller than the runoff tanks and were obtained from onsite (recycled). The percolation tanks incorporated a ball valve at the bottom for when/if water was required to be discharged, and volume markers for percolation volume measurement during site visits. Other details of the runoff and percolation collection tanks generally conform to those shown in Chapter 3.

The sensor and instrumentation utilized, and other pertinent information are provided as follows:

- Moisture and temperature sensor (quantity: 48) – multiple sensors were installed (Figure 4.33 and Figure 4.34) in groups (nests) in an effort to effectively measure the moisture content within the compacted clay at varying depth. As shown in Figure 4.31, two sets of senor nests were placed in each lysimeter. Trenches were dug into the topsoil for the wires of the sensors and extend to data loggers just outside of each lysimeter. The sensors were placed throughout the storage layer (cover soil) in an effort to obtain an accurate representation of water stored within each of the cover system. Additionally, a buffer (9-inch) was incorporate between the bottom sensor and the geomembrane to prevent drilling through the liner system.
- Tensiometer (quantity: 12) – multiple sensors were installed (Figure 4.33 and Figure 4.34) to try to measure the soil matric potential within the compacted clay. The tensiometers were placed in one (1) of the nests in each ET cover system. The cords for the tensiometers were routed in the trenches and to the same data loggers as the moisture and temperature sensors.

- Dosing siphon (quantity: 6) – this instrument was placed within each runoff collection tank (Figure 4.35) to attempt to measure the quantity of runoff from the lysimeter and avoid overflow of the collection tank.
- Pressure transducers (quantity: 6) – placed within the runoff collection tank (Figure 4.35) in an effort to measure the time dependent quantity of runoff from each lysimeter.
- Rain gauge (quantity: 6) – installed within each percolation collection tank (Figure 4.35) to try to obtain an accurate measurement of the quantity of the percolation through the ET cover system.
- Weather station (quantity: 1) – can obtain site specific quantities for rainfall, barometric pressure, temperature, relative humidity, wind speed and direction, and solar radiation. The weather station was placed between lysimeter 2 and 3 at the top of the embankment (Figure 4.32).
- ETgage™ (quantity: 2)[10] – in an effort to directly measure ET on the inclined and top sections, and directly and reliably evaluate differences in ET between the two locations, these instruments have been placed on the site, one (1) on the inclined section between Lysimeters 4 and 5, and another on the top section between Lysimeter 1 and 2 (Figure 4.36 and Figure 4.37).

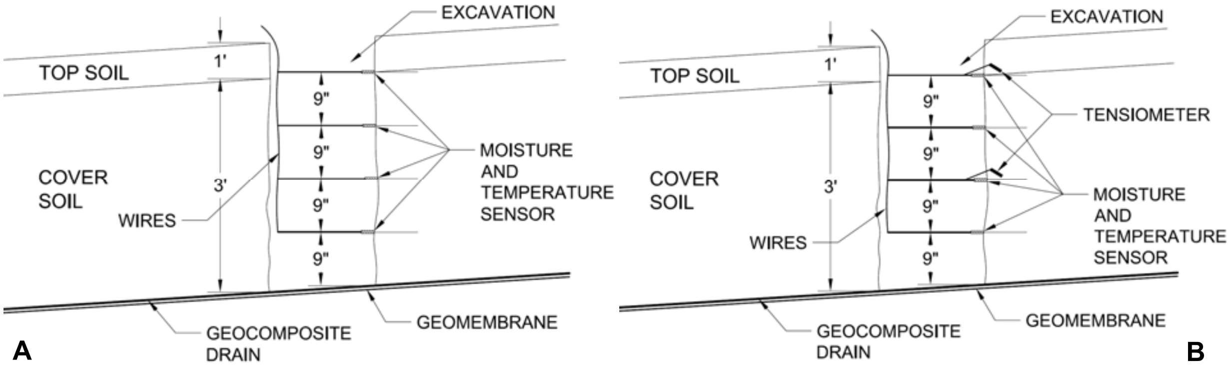


Figure 4.33: Tensiometer and moisture and temperature sensor diagram a) sensor set-up 1, and b) sensor set-up 2.

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[10] The two (2) ETgage™ were installed in July 2016.

Figure 4.34: Moisture and tensiometers installation a) excavation by hand-held auger, b) digging of trenches for sensor wiring, and c) ensuring correct depth prior to sensor placement.

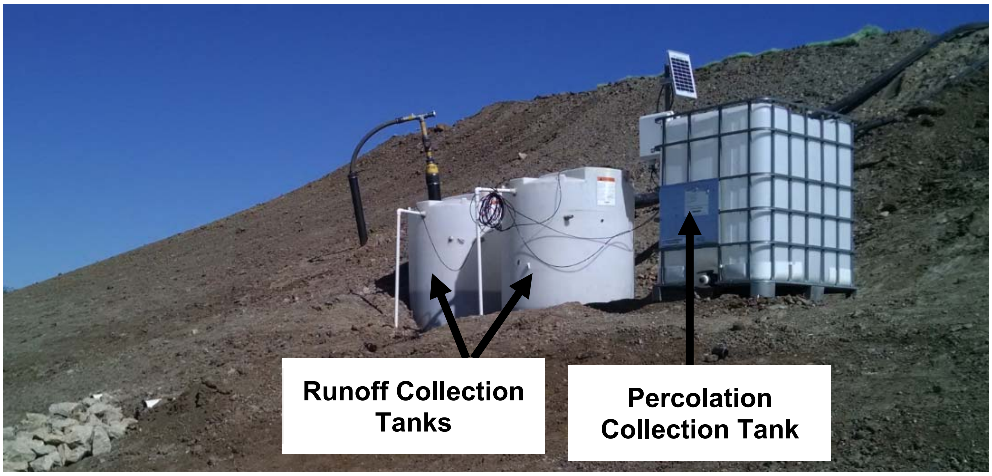

Figure 4.35: In-place runoff and percolation collection tanks.

Figure 4.36: ETgage™ installed between Lysimeters 4 and 5 (inclined sections).

Figure 4.37: ETgage™ installed between Lysimeters 1 and 2 (top sections).

Chapter 5

Results and Analysis

5.1 Introduction

This chapter includes the results, trends, summary, and conclusions from the evapotranspiration (ET) cover systems tested within six (6) 40-ft by 40-ft lysimeters (as described in Chapter 4). As discussed previously (Chapter 2), many factors can have an effect on the performance of ET cover system (percolation, runoff, soil water storage, and ET) including: climatological (quantity and intensity of precipitation, air temperature, relative humidity, and wind speed), cover slope, vegetation, preferential pathways, etc. Therefore, these factors are discussed in this chapter and how they correlated to measured results. Comparison between the ET Cover System measured results, and vegetation and cover observations are also provided.

The monitoring period can be divided into five (5) time periods based upon meteorological and general water balance performance results (Table 5.1). Although monitoring began at the end of October, 2014, the site was irrigated until the end of 2014 for vegetation establishment purposes. Therefore, it was decided to begin the monitoring period at the beginning of 2015. As previously discussed in Chapter 4, the soil water storage was measured by the use of moisture sensors placed in two (2) nests and throughout the storage layer in each of the lysimeters. Soil water potential was monitoring through two (2) tensiometers located within each lysimeter. With a tensiometer located at the topsoil and storage layer boundary (W-0”), and the other was placed in the middle of the storage layer (W-18”). Runoff and percolation were monitored by incorporating a collection system (perforated HDPE pipe surrounded by granular material and geocomposite drain) within each lysimeter that transferred collected water to separate runoff and percolation collection tanks for measurement (each lysimeter had its own runoff collection tank and percolation tank). Unless otherwise specified, the precipitation provided in the graphs is from a NOAA weather station located within 1.5 miles of the site. These graphs provide monitoring data from January 1, 2015 to May 2, 2016; a total of 486 days (approximately 1.3 years).

Table 5.1: Description of time periods of distinct meteorological and water balance results.

Time Period	Start Date	End Date	Amount of Time (Days)	Description (See Section 5.5)
1	1/1/15	7/10/15	191	Frequent precipitation events (winter, spring, and summer)
2	7/11/15	10/24/15	106	Infrequent precipitation events (summer and fall).
3	10/25/15	12/27/15	64	Relatively frequent precipitation events (fall and winter)
4	12/28/15	2/22/15	57	Infrequent precipitation events (winter)
5	2/23/16	5/2/16	68	Frequent precipitation events (spring)

5.2 Monitoring of Evapotranspiration Cover Systems

5.2.1 *Introduction*

Results and comparisons for water storage, runoff, precipitation, soil water potential, and percolation during the monitoring period for each of the lysimeters are provided in Figure 5.1 through Figure 5.23. For convenience and ease of understanding purposes, the seasons have also been incorporated into the graphs.

5.2.2 *ET Cover System (Lysimeter 1) Results, Discussion, and Conclusions*

Monitoring results for Lysimeter 1 (top slope) are provided in Figure 5.1, Figure 5.2, Figure 5.3, and Figure 5.4. The results, discussion, and conclusions are provided subsequently.

The water storage for Lysimeter 1 and daily precipitation is provided in Figure 5.1. During the first period (January to July 2015) of monitoring, frequent precipitation events occurred and a gradual increase in water storage was observed until a sharp spike in water storage was measured in April. Sharp spikes in the water storage were seen throughout the monitoring period. Additional precipitation events at the end of spring and beginning of summer (Period 1) correspond to an increase in water storage. During the summer of 2015 (Period 2), relatively small and infrequent precipitation events were measured and the measured water storage gradually decreases until the middle of fall (2015) when a large precipitation event occurred. A dramatic decrease in soil water storage at the start of Period 4 was observed, with a gradual (slight) decease measured until the beginning of Period 5 (when precipitation occurred).

The gradual increase in water storage during Period 1 could be attributed to precipitation events occurring relatively frequently during this time period, with higher increases in measured water storage when the frequency of precipitation increased. The sharp spike in water storage (April 2015) may have been a result of the high frequency of relatively large precipitation events that occurred and the resulting water infiltrating in the ET cover system. Additionally, the sharp spikes observed in the water storage could be a result, in at least a small part, to the moisture sensors placed at the topsoil/storage layer boundary. These result coorespond to results provided by Barnswell and Dwyer (2011), which noted that large precipitation events can result in a significant increase in the soil water storage in cover systems. The relative ease that the precipitated water can infiltrate through the topsoil (high hydraulic conductivity) and reach the top of the storage layer (where it was measured by the moisture sensor) could cause spikes in the measured water storage shortly after precipitation events. This conclusion cooresponds with results from individual moisture sensors, where sensors located at the topsoil/storage layer boundary measured an increase in volumetric moisture content shortly after precipitation events. Additionally, the sensors at a depth of 9-inches into the storage layer tended to measure an increase in volumetric moisture content following the increase in the moisture content observed in the sensor at the topsoil/storage layer boundary. Sensors located at deeper depths into the storage layer (at a depth of 18-inches and 27-inches) tended to measure general increases and decreases in moisture content likely as a result of general climological and ET conditions (e.g., frequent rainfall events). The volumetric moisture content changes measured in the sensors located throughout the storage layer were observed to be consistent in all of the ET cover systems. The gradual decrease observed in water storage over Period 2, is likely evidence that ET (as vegetation was established during this period) was removing the water stored in the cover system during the summer and early fall of 2016. As indicated by Abichou et al. (2005), a sharp decrease in soil water storage can be a result of severe desiccation and ET removing water from the cover system. These phenomana are likely the cause of the sharp decrease in soil water storage that was observed at the start of Period 4.

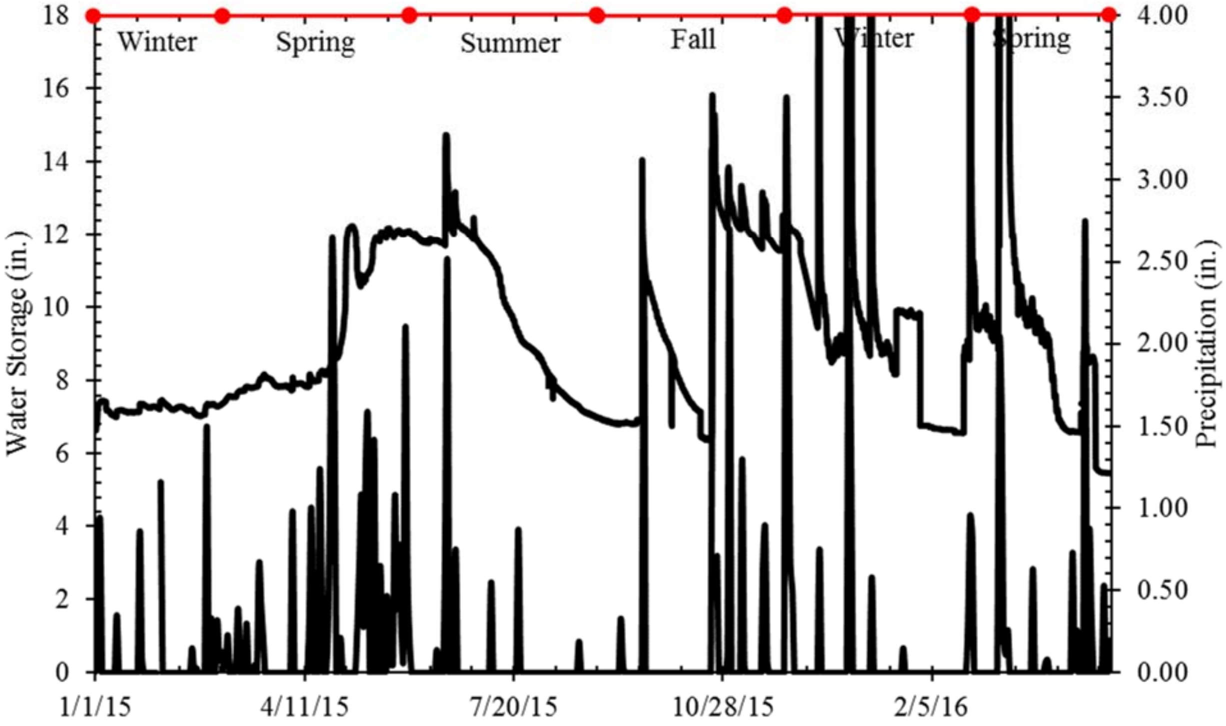

Figure 5.1: Lysimeter 1 – soil water storage and daily precipitation.

Figure 5.2 provides the cumulative precipitation, soil water storage, cumulative runoff, cumulative percolation, and cumulative ET for Lysimeter 1. As shown in Table 5.2, the cumulative precipitation, runoff, percolation, change in water storage and estimated ET were 76.72-inches, 55.12-inches (71.8% of precipitation), 3.87-inches (5.1% of precipitation), a decrease of 1.2-inches (1.6% of precipitation), and 19.40-inches (22.5% of PET), respectively. The soil water storage capacity of the system was estimated by determining the soil water storage measured from the soil moisture sensors at times when percolation was or was not measured. From this analysis, the soil water storage capacity within Lysimeter 1 is estimated at 7-inches. As shown in Figure 5.2, the soil water storage has been measured to be greater than the capacity for the majority of the monitoring period, with the exception of the summer/fall of 2015 (Period 2), a brief period during the winter of 2016 (Period 4) and spring of 2016 (Period 5). It was observed that the water storage measured during the summer/fall of 2015 is greater than the estimated storage capacity of the soil; however, little percolation was measured. The relatively high amount of potential ET at the site during the summer/fall could have removed the water that has been stored or infiltrated into the soil prior to water reaching the bottom of the cover system and becoming percolation (see Section 5.3.3).

Percolation was measured during times of precipitation (Periods 1, 3, and 5). Consistent measurements of percolation were measured during these periods, and percolation was observed shortly following precipitation events during Periods 3 and 5. Additionally, relatively large quantities of runoff have been observed during frequent and/or intense precipitation events. Large amounts of runoff were measured during Period 1, corresponding to a time when vegetation was not established. The cumulative estimated ET was less than the cumulative runoff.

The relatively large amount of runoff and percolation measured in Lysimeter 1 may be attributed to several factors. As indicated in Chapter 2, high intensity precipitation events tend to result in greater amounts of runoff. Therefore, the relatively high precipitation intensities measured at the site throughout the monitoring period is likely a major cause of the large amount of runoff measured. Another major cause of the relatively high measured runoff may be attributed to the runoff collection system design. As described in Chapter 4, a perforated HDPE pipe surrounded by granular material (gravel) and geocomposite drain was placed along the entire width of each lysimeter at the lowest point. The runoff collection system incorporates a geomembrane liner below the burrito wrap which prevents runoff from infiltrating into cover system in the vicinity of the collection system. The relatively high rate of percolation may be a result of high amount and frequency of precipitation, minimal root penetration into the storage layer, rodent burrows, shrink/swell of the clay, preferential channels, and inadequate soil water storage capacity (discussed in greater detail in subsequent sections). Percolation events tend to occur during times when the measured water storage is greater than the storage capacity of the soil; therefore, it follows that a relatively large quantity of percolation was measured (water storage was greater than the capacity for the majority of the monitoring period). As noted by Abichou et al. (2005), continuous percolation immediately following construction and being independent of rainfall and irrigation likely caused by the cover system being at a near-saturated condition during construction and compaction causing consolidation of the clayey cover soil. This is likely the cause of the percolation that was measured during the beginning of the monitoring period. Additionally, Abichou et al. (2005) noted that percolation following shortly after precipitation events could be caused by root channels and/or desiccation cracking penetrating the cover system. It is likely that desiccation cracking occurred during the drying of the cover system (Periods 2 and 4) and resulted in the percolation that was measured shortly after precipitation during Periods 3 and 5. Albrecht and Benson

(2001) noted that the hydraulic conductivity of the soil can increase by as much as 500 times due to desiccation cracking, and the cracks are unlikely to heal during times of elevated soil water storage (hydration). The presence of desiccation cracks is likely a cause of the relatively high amount of percolation measured in Lysimeter 1 (discussed in greater detail a subsequent section).

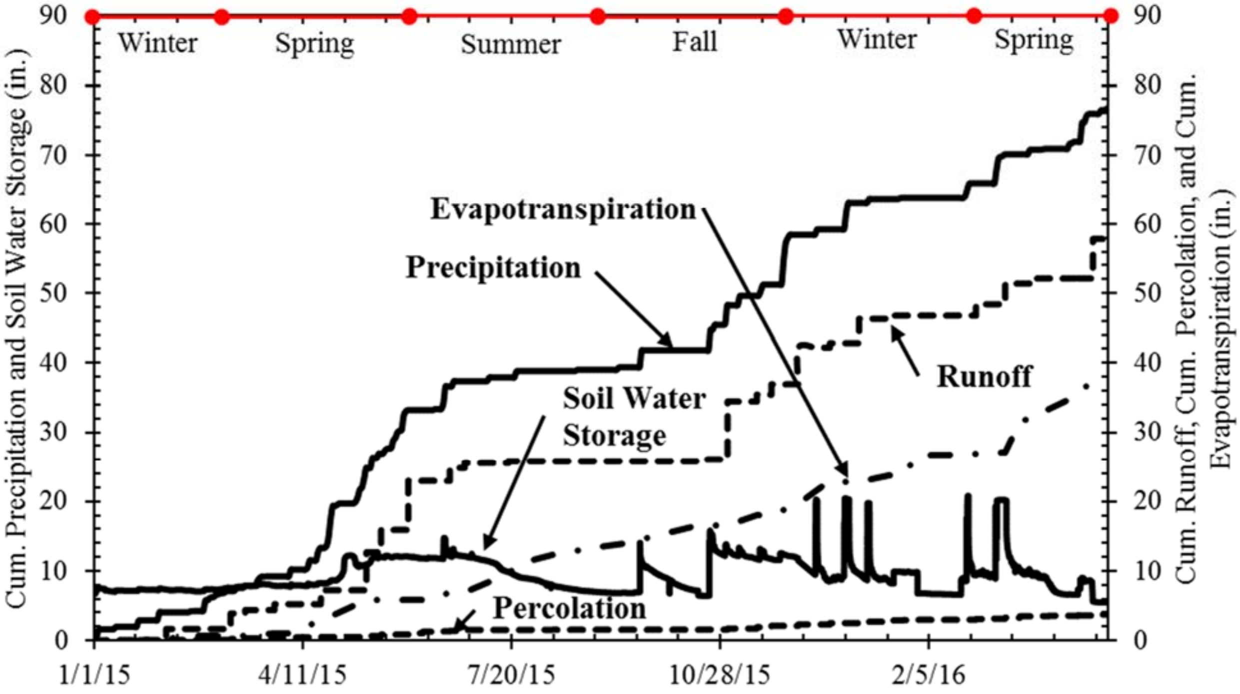

Figure 5.2: Lysimeter 1 – cumulative precipitation runoff, percolation, and evapotranspriation; and soil water storage.

The soil water potential and precipitation measured in Lysimeter 1 are provided in Figure 5.3 . When the soil is dry, soil water potential tends to be high (greater negative soil water potential), while a soil water potential at 0 kPa is indicative of saturated soil. Note that greater soil water potentials correspond to larger negative values and this notation shall be incorporated for the remainder of the document. During Period 1, a gradual decrease was measured in soil water potential at a depth of 18-inches (W-18) in the storage layer with the tensiometers placed at the topsoil/storage layer (W-0) boundary measuring near saturated conditions during this time period. An increase in soil water potential was measured during the summer and fall of 2015 (Period 2). Another increase in soil water potential was measured during the spring of 2016 (Period 4). The remainder of the time (Periods 3 and 5) shows a soil water potential of approximately 0 kPa (near or at saturated conditions).

The gradual decrease in soil water potential during Period 1 was likely due to the high frequency of precipitation events during the winter, spring, and beginning of summer in 2015. As the precipitated water infiltrates into the soil and the soil becomes more saturated, the soil water potential will tend to decrease. This result corresponds well with the general increase in water stored in the soil and the measured percolation events during this same time frame. The increase in soil water potential during Periods 2 and 4 correspond with the minimal of percolation measured and the decrease in soil water storage. Suction measurements near or at saturated conditions during Periods 3 and 5 correspond well with the high frequency and quantity of percolation events that have been measured throughout the monitoring period. In general, the tensiometers tend to provide an accurate representation of times when percolation was measured (when soil water potential is measured to be approximately 0 kPa) and times when little/no percolation was measured (when soil water potential is greater than 0 kPa).

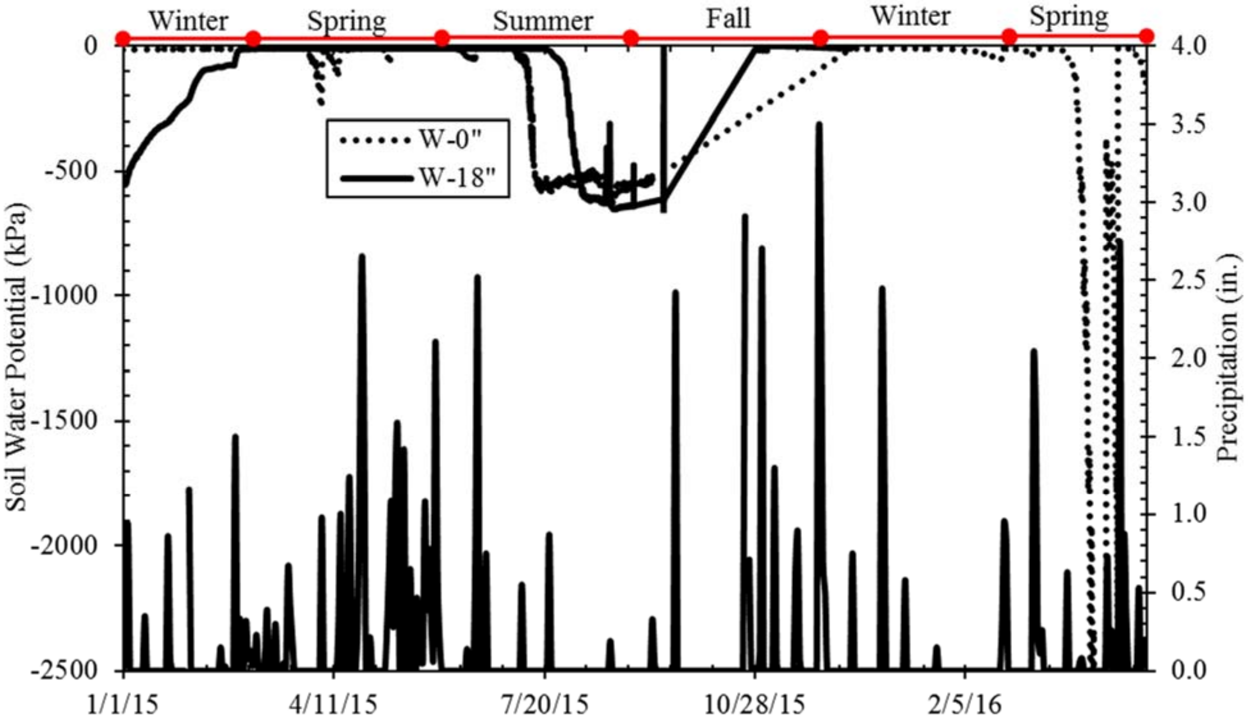

Figure 5.3: Lysimeter 1 – soil water potential and daily precipitation.

A comparison between water storage and soil water potential is provided in Figure 5.4 for Lysimeter 1. As would be expected for sensors installed in close proximiety, there is a strong coorelations between the results. As observed, as the measured water storage increases, so does the soil water potential. Additionally, periods during which the water storage is high correspond to periods when the soil water potential is at or near saturated conditions. As discussed previously, these results indicate that there is a substantial quantity of water within the ET cover system. Additionally, these times of high water storage and soil water potential at or near saturated conditions coorespond to periods where percolation was measured.

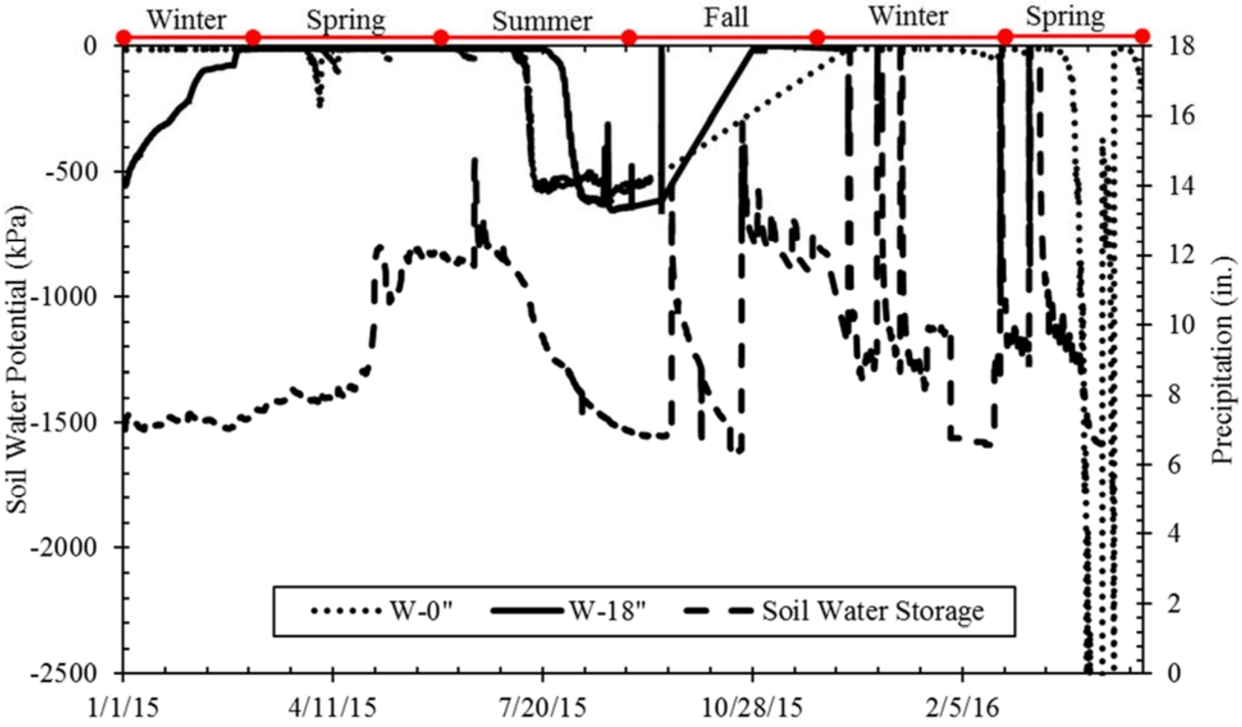

Figure 5.4: Lysimeter 1 – comparison between water storage and soil water potential.

5.2.3 *ET Cover System (Lysimeter 2) Results, Discussion, and Conclusions*

Monitoring results for Lysimeter 2 (top slope) are provided in Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8. Results, discussion, and conclusions are provided subsequently.

Figure 5.5 provides measurements of soil water storage and precipitation for Lysimeter 2. Period 1 was characterized by a high frequency of precipitation events during the winter, spring, and beginning of summer 2015. During this time period a gradual increase in water storage with a sharp spike in water storage at the end of winter was observed. Immediately after the spike, a decrease in water storage was measured during Period 1. During the summer of 2015 (Period 2), relatively small and infrequent precipitation events occurred and the measured water storage gradually decreases until a small spike as a result of a single large precipitation event in fall of 2015. This precipitation event was followed by a gradual decrease in water storage. Another spike in water storage was measured in the middle of fall at the start of Period 3 and a gradual decrease in water storage followed until spring of 2016 (during Periods 3, 4, and 5). The water stored in the cover did not return to a quantity equal to the summer/fall of 2015 (Period 2), with percolation events occurring from the peak in the middle of the fall (2015) and continuing until the end of the monitoring period (discussed in greater detail subsequently).

[11]The sharp increase in measured water storage observed during Period 1 was most likely a result of the relatively large percolation event followed by multiple smaller percolation events. Additionally, the gradual increase in measured water storage was likely due to frequent precipitation events. This corresponds to a time period when potential ET is relatively low compared to other times of the year. The precipitated water likely infiltrated the cover system and was not able to be immediately removed by ET. The decrease in water storage immediately after the spike in Period 1 is likely due to less frequent precipitation events and the water being removed from the system by either ET or percolation (percolation was measured during this time). Period 2 was characterized by a gradual drying of the cover system with a spike immediately following a precipitation event, and the gradual drying is likely due to ET removing water from the cover systems (potential ET is typically at its highest during the summer). The gradual decrease in soil water storage measured during Periods 3, 4, and 5 is likely a result of ET and percolation removing water from the cover soil, with peaks occurring as a result of percolation events.

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[11] For brevity, references to previous studies in this section which have been previously stated are not included.

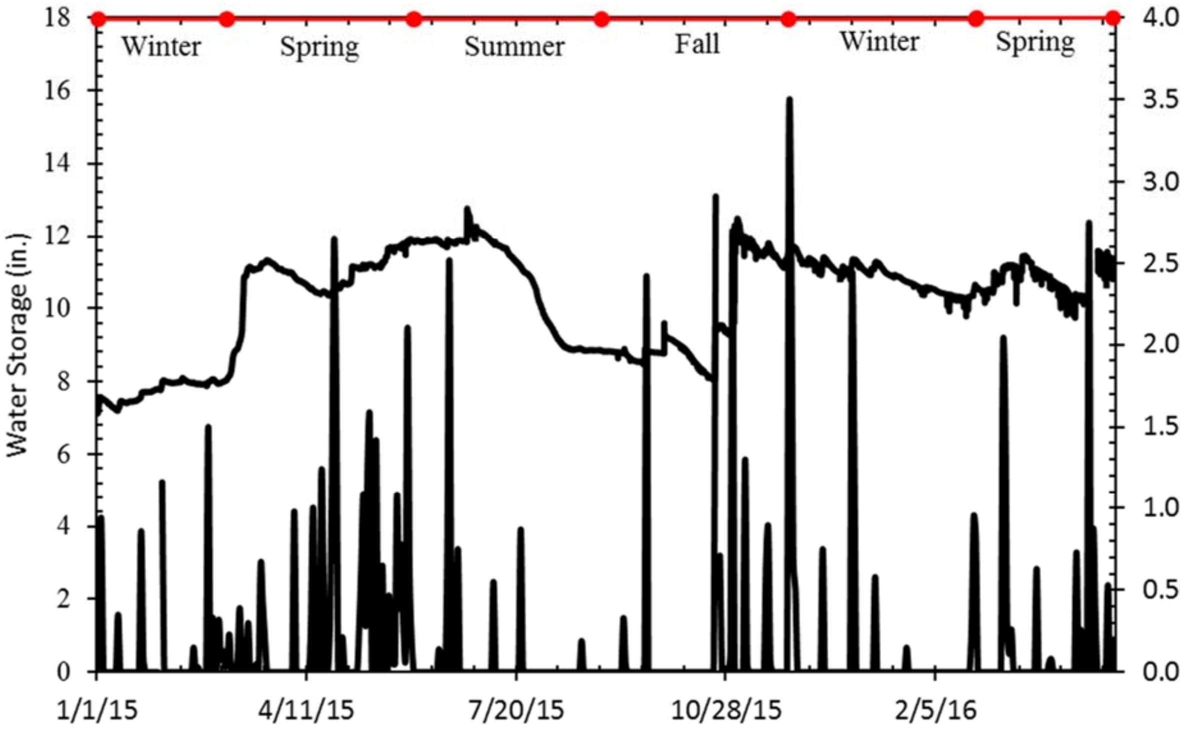

Figure 5.5: Lysimeter 2 – soil water storage and daily precipitation.

Figure 5.6 provides the cumulative precipitation, soil water storage, cumulative runoff, cumulative percolation, and cumulative ET for Lysimeter 2. As provided in Table 5.2, the cumulative precipitation, runoff, percolation, change in water storage, and estimated ET were 76.72-inches, 52.01-inches (67.8% of precipitation), 3.02-inches (3.9% of precipitation), an increase of 4.13-inches (5.4% of precipitation), and 18.71-inches (21.7% of PET), respectively. The measured results for the runoff and percolation are relatively high during the monitoring period. Based upon the soil water storage measured and percolation events, the soil water storage capacity can be estimated at 7.5-inches (190-mm). This estimate was based upon measured results at the start of the monitoring period (winter of 2015), which was the first time period that percolation was not measured. It was observed that during the summer and fall of 2015 (Period 2), the soil water storage measured is greater than 7.5-inches (approximately 8.5-inches); however, little to no percolation was measured. Runoff and percolation was measured during times of precipitation (notably during Periods 1, 3, and 5). Relatively uniform percolation was measured during these periods (Periods 1, 3, and 5) and Period 4, and percolation was observed shortly following precipitation events during Periods 3 and 5.

As with Lysimeter 1, the relatively large amount of runoff may be attributed to high rainfall rates measured throughout the monitoring period and the runoff collection system design. The relatively high rate of percolation may be attributed to several factors. It was suggested by Albright et al. (2005) that a relatively uniform rate of percolation is indicative of flow through the soil matrix; however, percolation measured shortly after precipitation events would suggest the presence of preferential flow. As the percolation measured in Lysimeter 2 is both relatively uniform and follows shortly after precipitation events, it is suggested that water is flowing through the soil matrix and preferential flow pathways. If the entire cover soil is saturated, then any additional water applied theoretically would result in percolation. Along with preferential flow, the saturated cover soil (further discussed subsequently) may also explain the percolation events which were measured shortly after precipitation events. A change in the hydraulic properties and storage capacity of cover systems over the service life of the cover has been indicated by a number of researchers (Chamberlain and Gow 1979; Beven and Germann 1982, Suter et al. 1993, and Albrecht and Benson 2001). The researchers indicated that the change may be due to natural pedogensis processes such as insect and animal burrowing, freeze-thaw cycling, wet-dry cycling, and/or plant root growth. These types of phenomena and the apparent change in soil density observed in the cover systems were likely the cause of the apparent change in soil water storage capacity.

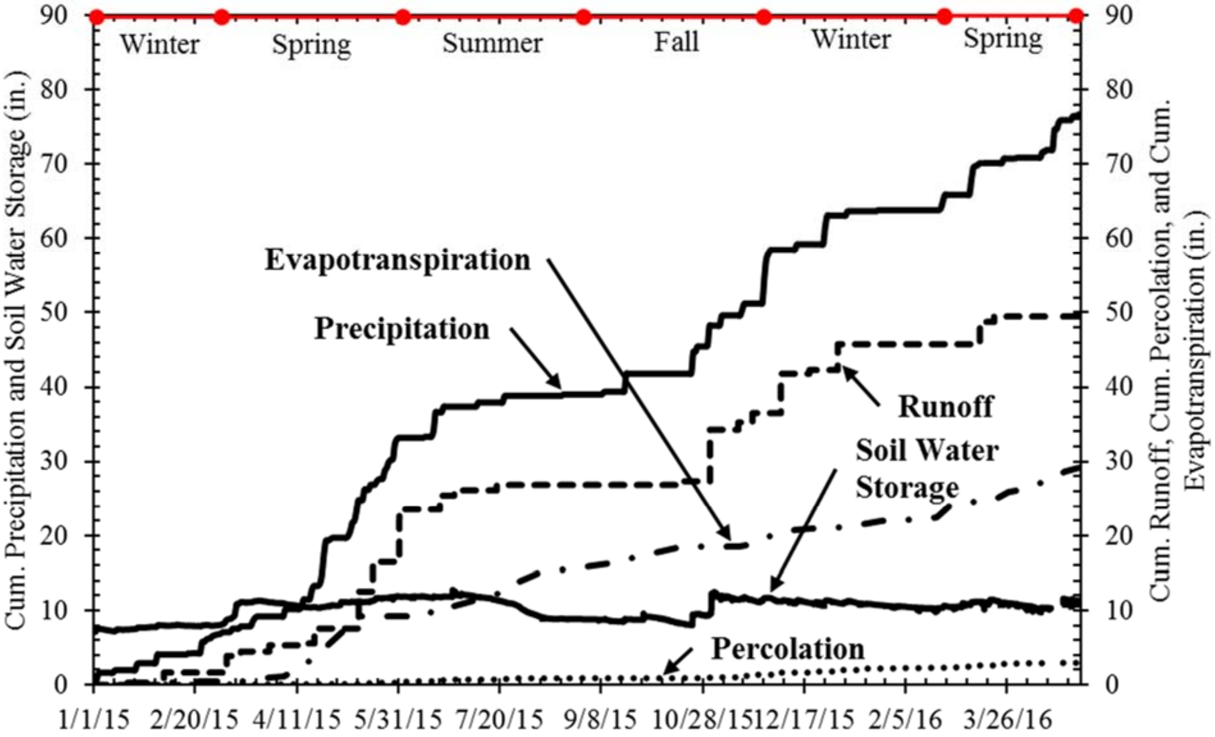

Figure 5.6: Lysimeter 2 – cumulative precipitation runoff, percolation, and evapotranspriation; and soil water storage.

Figure 5.7 provides the soil water potential and precipitation during the monitoring period for Lysimeter 2. Measured soil water potential values for Lysimeter 2 are very similar to Lysimeter 1. The tensiometer at the topsoil/storage layer boundary (W-0) measured almost saturated condition for nearly the entire length of the monitoring period, except during the summer/fall of 2015 (Period 2) and spring of 2016 (Period 4). The tensiometer placed in the middle of the storage layer (W-18) measured a high soil water potential (indicative of a dry soil) at the start of the monitoring period; and then a gradual decrease in soil water potential (indicative of the soil becoming wetter). With the exception of the start of the monitoring period (Period 1) and summer/fall of 2015 (Period 2), W-18 measured near/at saturated conditions for the entire monitoring period. It was also observed that during the summer of 2015 (Period 2), the tensiometer at the topsoil/storage layer boundary measured a sharp increase in soil water potential prior to the same increase being measured in the tensiometer located in the middle of the storage layer.

Similar to Lysimeter 1, during periods when the tensiometers measured saturated conditions, percolation events were measured; and during times when greater soil water potentials were measured, little to no percolation was observed. As it appears that the soil near the atmosphere/soil surface dried prior to greater depths, it may indicate that the water stored in the soil is being removed from the top of the cover system by ET rather than through percolation. This drying time period corresponds with the highest potential ET at the site and relatively infrequent precipitation events. As indicated by Benson et al. (2002), having water still stored in the cover system after the dry season results in a smaller reservoir for soil water storage during the wetter season and may lead to percolation events. It should also be noted that the soil water potentials measured by the tensiometers during the summer and fall of 2015 (Period 2) never measured very dry soil conditions (soil water potentials near -2500 kPa). This would suggest that ET (or percolation) did not remove all or a majority of moisture from the soil prior to the frequent precipitation events occurring at the beginning of fall (2015) (Period 3). A smaller soil water reservoir is available at the end of a drying period if all of the moisture in the soil is not removed, resulting in an increased possibility for percolation if the following time period has frequent precipitation events. Therefore, the apparent lack of completely dry soil at the end of Period 2 may be a major cause for the percolation measured during Period 3 when frequent precipitation occurred.

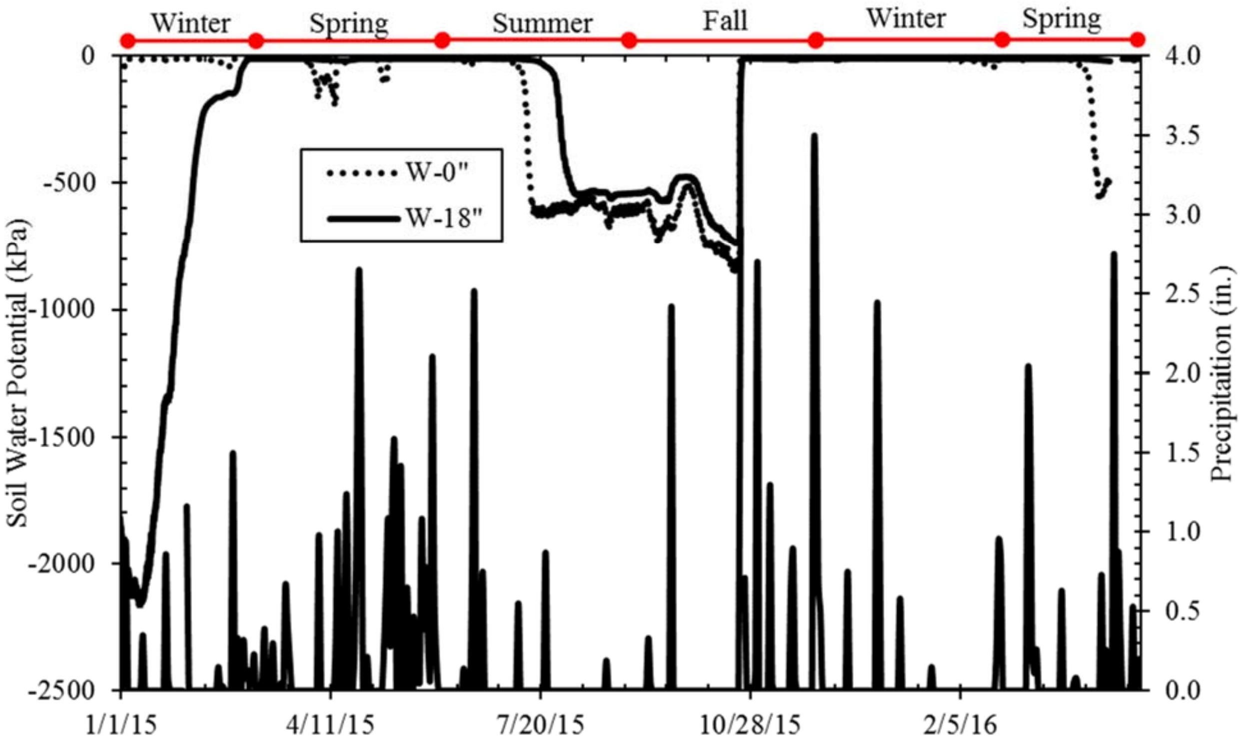

Figure 5.7: Lysimeter 2 – soil water potential and daily precipitation.

A comparison between water storage and soil water potential is provided in Figure 5.8 for Lysimeter 2. Similar to Lysimter 1, there was a strong coorelation between the soil water storage and water potential results. As observed, as the measured water storage decrease, so does the soil water potential. Additionally, periods during which the water storage is low generally correspond to periods when the soil water potential is not at or near saturated conditions. During drying and wetting periods, results for the soil water storage and water potential show a very strong coorelation (i.e., increases measured in the soil water potential were observed at the same time decreases in the soil water storage was observed). Additional conclusions have been previously discussed in the Lysimter 1 section, and shall not be repeated.

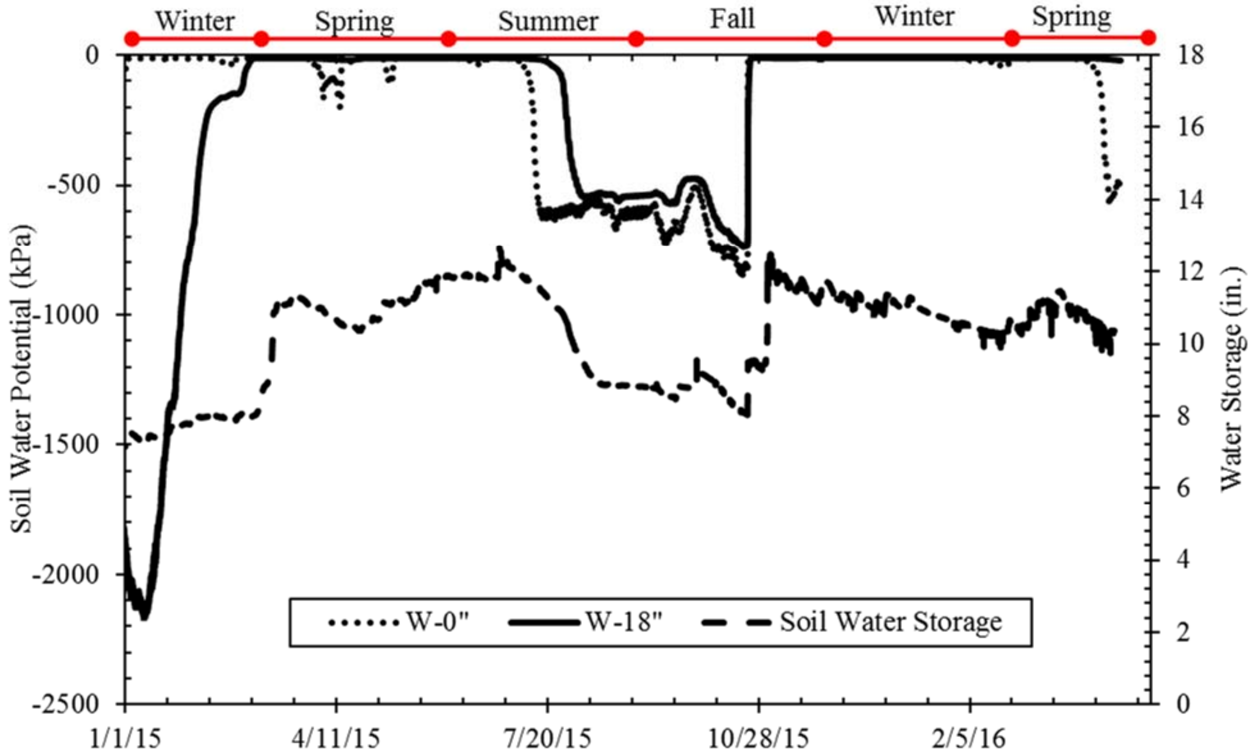

Figure 5.8: Lysimter 2 - comparison between soil water potential and soil water storage.

5.2.4 *ET Cover System (Lysimeter 3) Results, Discussion, and Conclusions*

Monitoring results for Lysimeter 3 (top slope) are provided in Figure 5.9, Figure 5.10, Figure 5.11, and Figure 5.11. Results, discussion, and conclusions are provided subsequently.

Measured water storage and daily precipitation for Lysimeter 3 is provided in Figure 5.9. During Period 1, a gradual increase in water storage was measured when there was a high frequency of precipitation. It should be noted that the increase measured in the stored water was not as dramatic in

Lysimeter 3 when compared to Lysimeters 1 and 2. Similar results to Lysimeters 1 and 2 were measured for the remainder of the monitoring period. Where the water stored in the storage layer decreased during the summer and fall of 2015 (Period 2) and increases dramatically during periods of frequent and substantial precipitation events in the fall and winter (2015) (Period 3). Small increases in the water storage were measured throughout the monitoring period following precipitation events.

Similar to Lysimeters 1 and 2, the gradual increase in water storage during Period 1 was likely a result of the high frequency of precipitation events and the resulting infiltration. The relatively small spike during Period 1 was likely a result of a relatively substantial amount of water stored in the cover system at the beginning of the monitoring period. The relatively substantial water storage present could be attributed to greater amounts of water being utilized during the construction of Lysimeter 3 and/or the irrigation that was applied to the cover in an effort to help establish vegetation. Again, the decrease in stored water during summer of 2015 (Period 2) was likely a result of ET removing water from the cover system; and the increase in the fall and winter (Period 3) was likely a result of precipitation infiltrating into the soil. As was discussed in Chapter 2, a high hydraulic conductivity of the top soil layer (e.g., un-compacted topsoil) will cause greater amounts of infiltration when compared soil with a lower hydraulic conductivity (e.g., compacted clay). This suggests that the small changes in the water storage measured after precipitation was likely a result of the infiltration flowing through the topsoil and being measured by the moisture sensors at the topsoil/storage layer and at a shallow depth within the storage layer. This conclusion is supported by an increase in moisture content measured in said sensors.

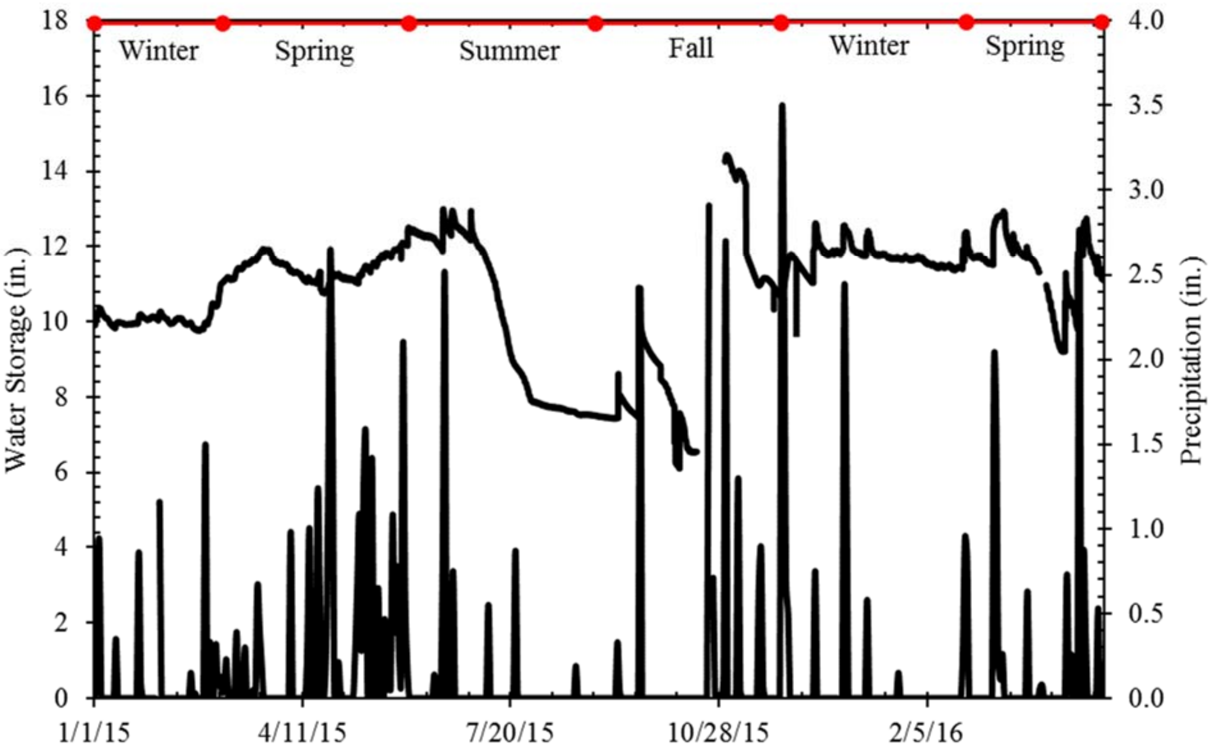

Figure 5.9: Lysimeter 3 – soil water storage and precipitation.

[12]The cumulative precipitation, soil water storage, cumulative runoff, cumulative percolation, and cumulative ET is provided in Figure 5.2 for Lysimeter 3. Cumulative precipitation, runoff, percolation, change in water storage, estimated ET, were 76.72-inches, 46.53-inches (60.7% of precipitation), 3.39-inches (4.4% of precipitation), an increase of 0.78-inches (1.0% of precipitation), and 25.59-inches (29.7% of PET), respectively (Table 5.2). Based upon the soil water storage measured and percolation events, the soil water storage capacity can be estimated at 8-inches (203-mm). This estimate is based on measured results during the summer and fall of 2015 (Period 2), which was the only time period that percolation was not measured from Lysimeter 3. Runoff and percolation was measured during times of precipitation (notably during Periods 1, 3, and 5). Relatively uniform percolation was measured during these periods (Periods 1, 3, and 5) and Period 4, and percolation was observed shortly following precipitation events during Periods 3 and 5 and during the beginning of the monitoring period. Large quantities of runoff were measured when high intensity and frequent precipitation events occurred.

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[12] For brevity, references to previous studies in this section which have been previously stated are not included.

As the measured soil water storage is greater than the estimated soil water storage capacity (with the majority of measured results 2-inches greater than the estimate soil water storage capacity), it follows that relatively large amounts of percolation have been measured. As with Lysimeter 1 and 2, the relatively large amount of runoff may be attributed to high precipitation intensities measured throughout the monitoring period and the runoff collection system design. The relatively high rate of percolation may be attributed to several factors as discussed in the Lysimeter 1 section. As the percolation measured in Lysimeter 3 follows shortly after precipitation events and is relatively uniform, it suggests that water was flowing through preferential flow pathways and the soil matrix (from conclusions suggested by Albright et al., 2005). As discussed previously, the percolation measured during the beginning of the monitoring period was likely a result of the cover system being at or near-saturated condition during construction and compaction causing consolidation of the storage layer (Figure 5.11) (Abichou et al., 2005).

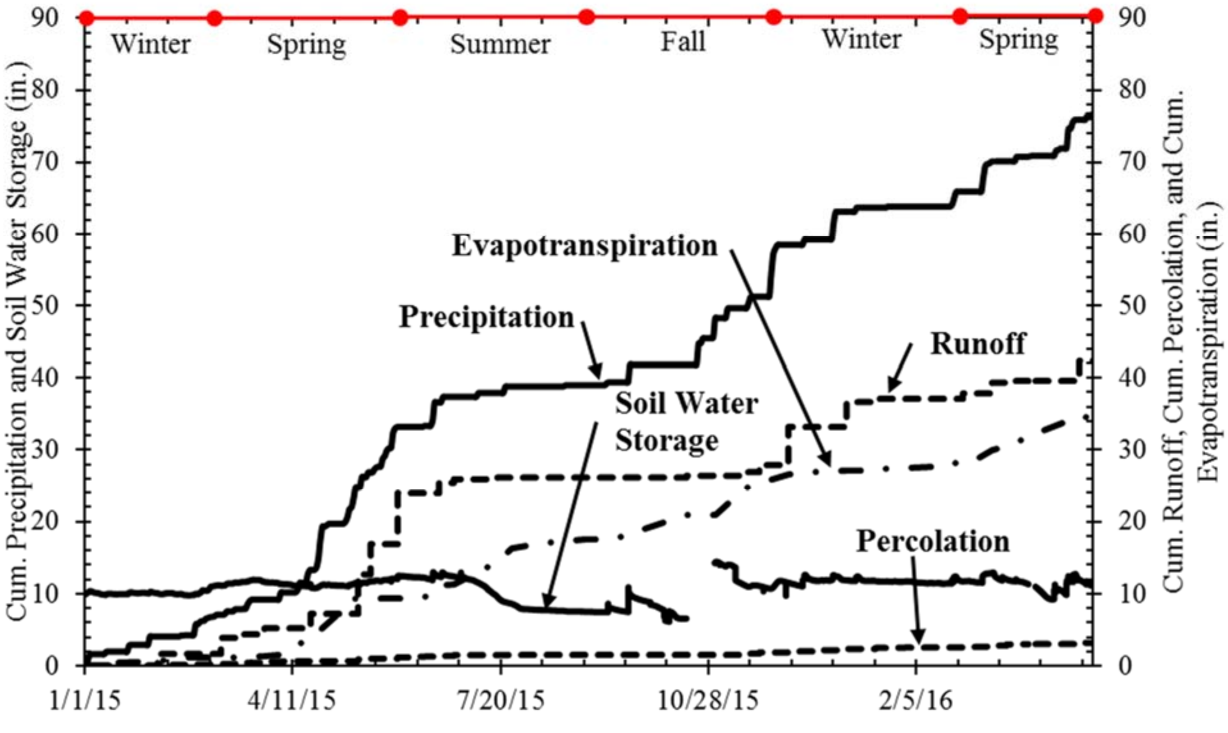

Figure 5.10: Lysimeter 3 – cumulative precipitation runoff, percolation, and evapotranspriation; and soil water storage.

The measured soil water potential for Lysimeter 3 and daily precipitation is provided in Figure 5.11. Measured soil water potential values for Lysimeter 3 are fairly similar to Lysimeters 1 and 2, where near or at saturation conditions were measured throughout the majority of the monitoring period. Both tensiometers measuring soil water potential near or at saturated conditions (soil water potential of 0 kPa) at the start of the monitoring period corresponded well with the relatively high amount of stored water measured (Figure 5.10) within the cover system. A dramatic increase in soil water potential was measured by the tensiometer placed at the topsoil and storage layer boundary (W-0”) at the end of the monitoring period (spring of 2016). Dramatic decreases in soil water potential resulting in the soil water potential to measure at or near saturated conditions were observed to follow shortly after precipitation events.

The measured suction at or near-saturated conditions and the high water storage measured in the cover observed during Periods 1, 4, and 5 suggest that large quantity of water were present throughout the storage layer, and that percolation events would follow [percolation was observed throughout these periods (Figure 5.10)]. It should be noted that the increase in soil water potential during the large amount of precipitation events (fall and winter of 2015 – Period 4) may be indicative of false readings and/or an issue(s) with the tensiometers. Similar to the other lysimeters, the decrease in soil water potential measured at the top soil and storage layer boundary suggests that the precipitation was easily infiltrating and flowing through the topsoil, and being measured by tensiometers placed directly below.

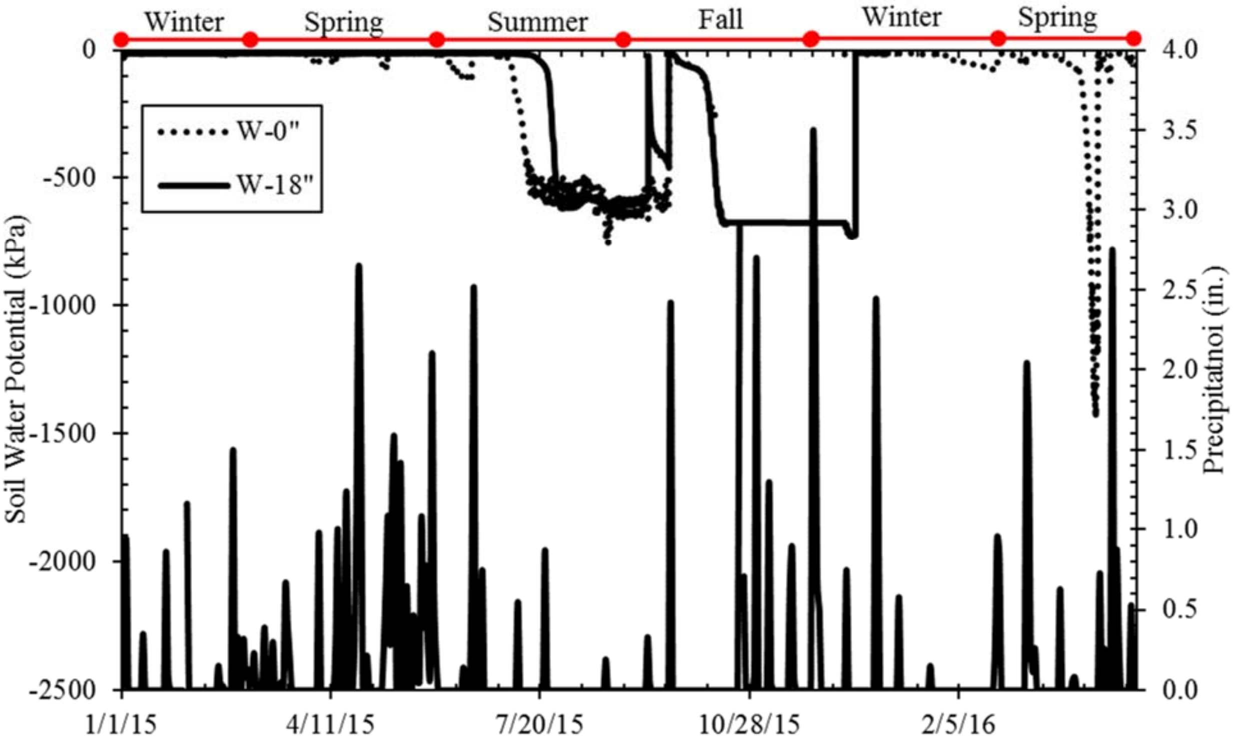

Figure 5.11: Lysimeter 3 – soil water potential and daily precipitation.

A comparison between water storage and soil water potential is provided in Figure 5.11 for Lysimeter 3. There was a strong correlation between the soil water potential and water storage, similar to Lysimeters 1 and 2. In contrast to Lysimeter 1 and 2, soil water potential is at or near saturated conditions at the beginning of the monitoring period. Water storage measured in the ET cover system was greater in this period than Lysimeters 1 and 2, suggesting that Lysimeter 3 had more water stored in the cover system and as a result measured soil water potential near or at saturated conditions. Additional conclusions have been previously discussed in the Lysimeters 1 and 2 sections, and shall not be repeated.

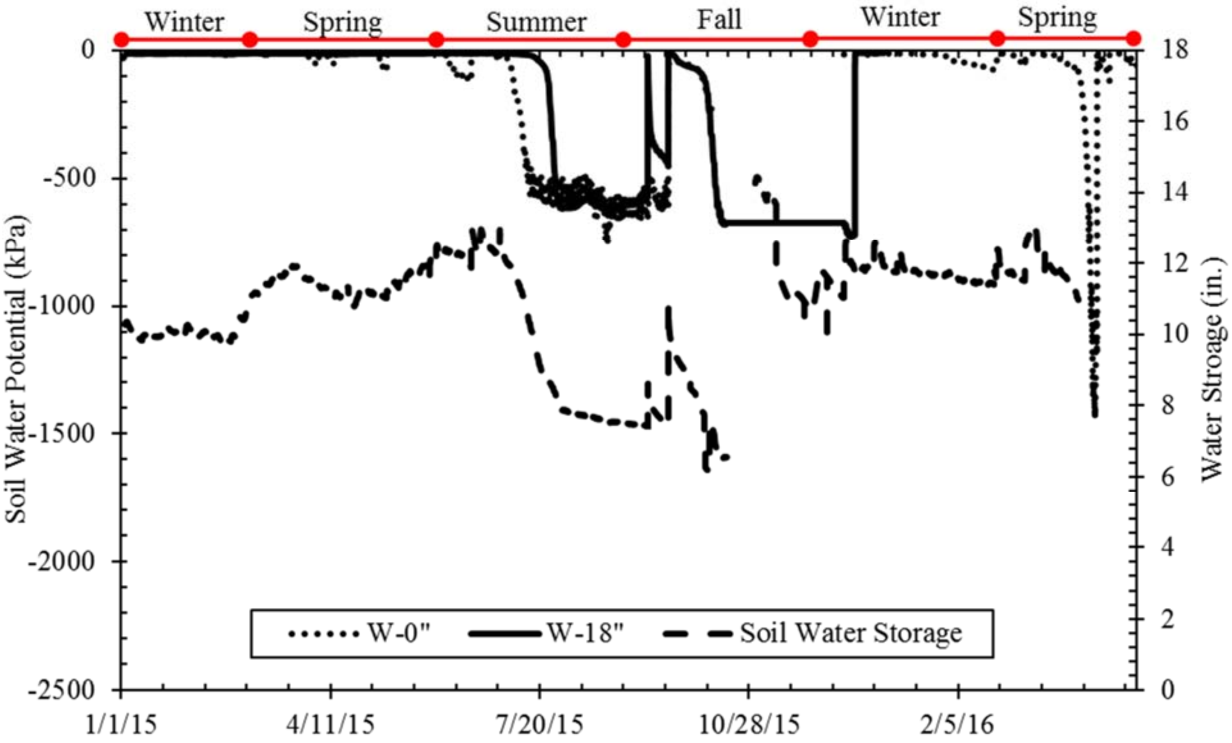

Figure 5.12: Lysimeter 3 - comparison between soil water potential and soil water storage.

5.2.5 *ET Cover System (Lysimeter 4) Results, Discussion, and Conclusions*

Monitoring results for Lysimeter 4 (inclined section) are provided in Figure 5.13, Figure 5.14, Figure 5.15, and Figure 5.16. These results, discussion, and conclusions are provided subsequently.

Figure 5.13 provides the water storage and daily precipitation for Lysimeter 4. Similar to the other lysimeters, the large quantity and frequency of precipitation events during Period 1 corresponded to a gradual increase in water storage during the time period, with a sharp increase in water storage at the end of spring (2015) shortly after multiple precipitation events. Similar water storage trends were observed when compared to the other lysimeters during the summer and fall of 2015 (Period 2), with the soil water content gradually decreasing to a quantity observed at the beginning of the monitoring period. A large quantity and frequency of precipitation events were measured during the fall and winter of 2016, and again corresponded to increases in the observed soil water storage. Data collection issues occurred during the winter and start of spring of 2015/2016; however, it was observed that the water storage was approximately equal at the start and end of the issues. Similar to the other lysimeters, it is likely that the water storage measured during this time period remained relatively high.

During Period 2 (gradual decrease in water storage was observed), it is likely that ET was removing the moisture stored in the cover system and returning the water storage to a quantity approximately equal to a quantity measured at the beginning of the monitoring period (small quantities of percolation were measured during this period). Barnswell and Dwyer (2011) observed that 100-year rainfall events (i.e., substantial precipitation events) caused a significant increase in the soil water storage of the ET covers and resulted in considerable amounts of percolation. This observation by Barnswell and Dwyer (2011) matches the observed soil water storage for all of the lysimeters, where large precipitation events during the monitoring period correspond to large increases in the soil water storage in the cover systems.

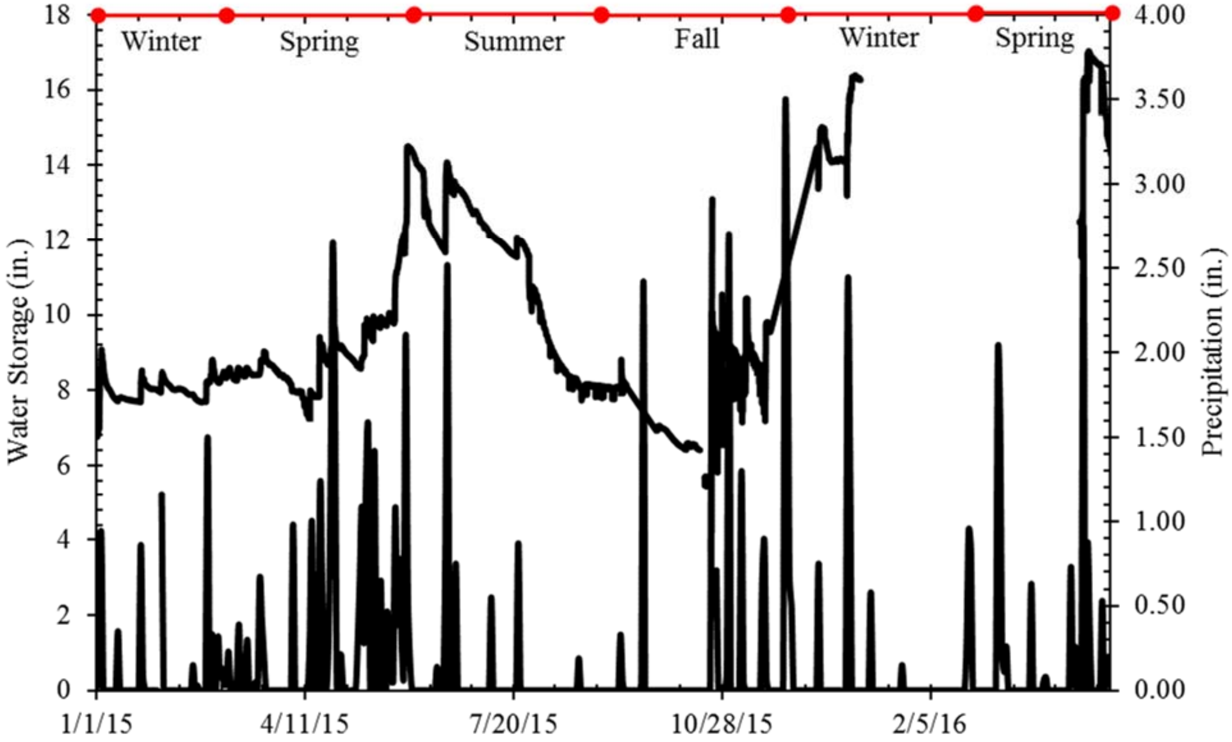

Figure 5.13: Lysimeter 4 – soil water storage and daily precipitation.

Lysimeter 4 observations for cumulative precipitation, soil water storage, cumulative runoff, cumulative percolation, and cumulative ET are provided in Figure 5.14. As indicated in Table 5.2, the cumulative precipitation, runoff, percolation, change in water storage, and estimated ET were 76.72-inches, 31.90-inches (41.6% of precipitation), 4.32-inches (5.6% of precipitation), an increase of 7.41-inches (9.6% of precipitation), and 33.62-inches (39.0% of PET), respectively. Runoff and percolation were measured during times of frequent precipitation (Periods 1, 3, and 5). Percolation was observed to be relatively uniform during these periods (Periods 1, 3, and 5) and Period 4. Percolation was observed shortly following precipitation events during Periods 3 and 5, and during the beginning of the monitoring period (Period 1). Throughout the monitoring period, relatively large quantities of runoff were measured when high intensity and frequent precipitation events occurred. Based upon the soil water storage measured and percolation events at the beginning of monitoring period (start of Period 1) and during the summer and fall of 2015 (Period 2), the soil water storage capacity can be estimated at 8-inches (203-mm). Large quantities of precipitation and high intensity events have occurred throughout the monitoring period, as indicated by the large quantity and the dramatic increase shown in Figure 5.14 (similar to the other lysimeters).

As with the other lysimeters, the relatively high quantity of percolation could be attributed to several factors as discussed in the Lysimeter 1 discussion section. Relatively large quantities of runoff were measured, and may be attributed to high precipitation intensities measured throughout the monitoring period and the runoff collection system design. The measured water storage in the cover system was observed to be greater than the estimate storage capacity and corresponded to times of percolation, As with the other lysimeters. As suggested by Albright et al. (2005), relatively uniform percolation rate would be indicative of flow occurring through the soil matrix. Additionally, the percolation measured soon after precipitation events would be indicative of preferential flow. High intensity precipitation events tend to result in greater amounts of runoff (see discussion in Chapter 2), which appears to correspond to the measured results during the monitoring period.

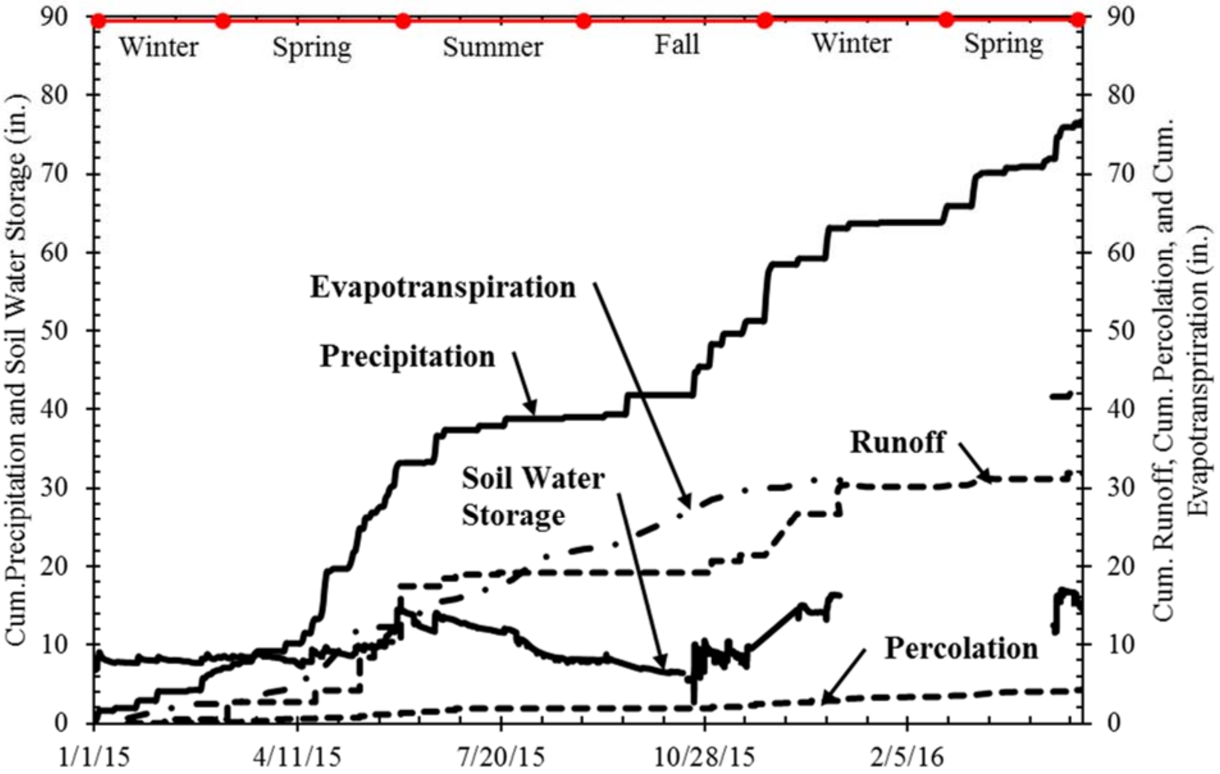

Figure 5.14: Lysimeter 4 – cumulative precipitation runoff, percolation, and evapotranspriation; and soil water storage.

The soil water potential observed in Lysimeter 4 and daily precipitation is provided in Figure 5.15. Measured soil water potential values for Lysimeter 4 were quite similar to Lysimeters 3 (and fairly similar to Lysimeters 1 and 2), where near or at saturation conditions were measured throughout the monitoring period. The exception of saturated conditions measured was during Period 2. Both tensiometers measured soil water potential near or at saturated conditions (soil water potential of 0 kPa) at the start of the monitoring period and fluctuations in measured soil water potential was observed more in the tensiometer placed at the topsoil and storage layer boundary (W-0”) when compared to the tensiometer located in the middle of the storage layer (W-18”). Increases in the soil water potential were measured during the spring of 2015 (Period 1) between precipitation events. Additionally, it was also observed during Period 1 that the soil water potential was greater at the topsoil and storage layer boundary when compared to greater depths.

The increase in soil water potential observed in W-0” (near the soil surface) during Period 1 suggest that ET was removing moisture from the topsoil and upper portion of the storage layer. Additionally, during this time period, a small increase in soil water potential was measured by the tensiometer in the middle of the storage layer (W-18”). This would suggest that ET was starting to remove moisture from the middle of the storage layer; however, frequent precipitation events following the change in soil water potential likely caused water to infiltrate into the storage layer and the tensiometers to measure saturated conditions again. It was observed that the soil near the atmosphere appeared to dry sooner than the soil deeper in the cover system, which corresponds to literature (see Chapter 2). This is indicatative of water stored in the cover system being removed by ET.

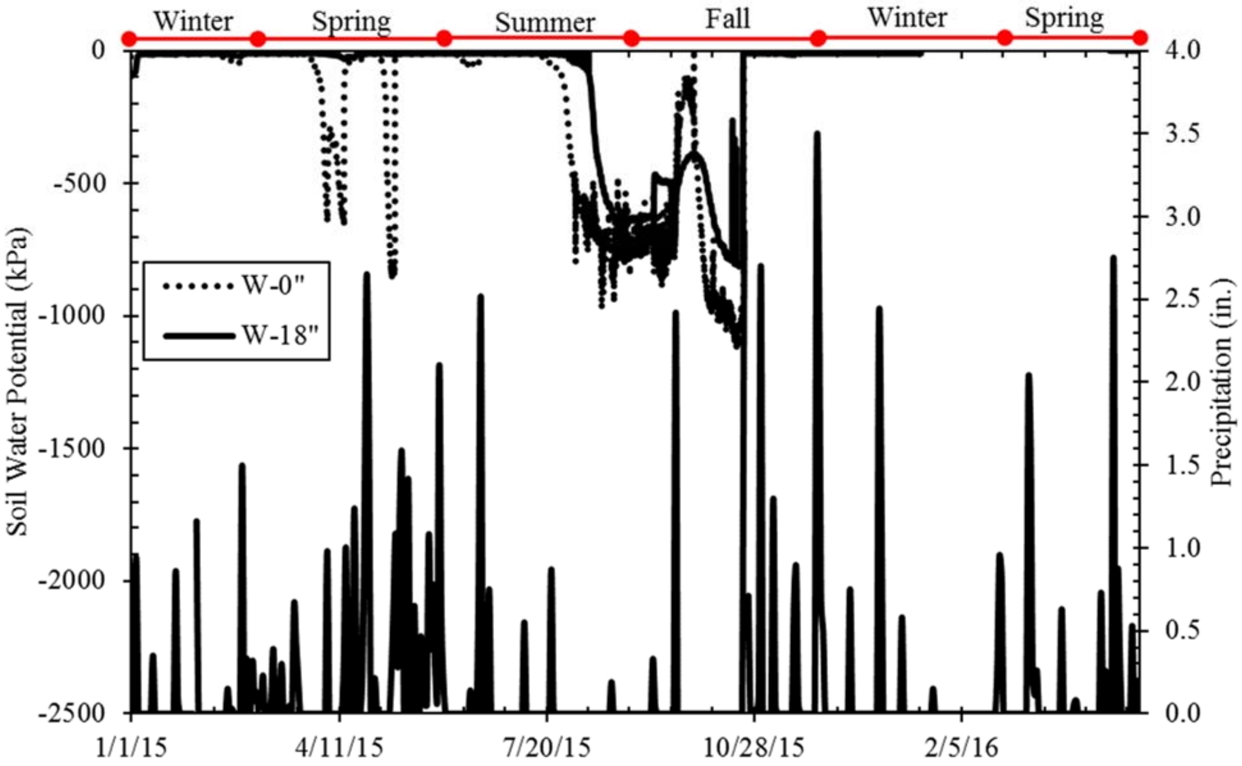

Figure 5.15: Lysimeter 4 – soil water potential and daily precipitation.

A comparison between water storage and soil water potential is provided in Figure 5.16 for Lysimeter 4. Similar to the other ET cover Sections, there was a strong correlation between the soil water potential and water storage. Additionally, increases in water potential from the tensiometer placed at the topsoil and storage layer boundary correspond with minor decreases in the soil water storage. Additional conclusions have been previously discussed in the other comparison sections, and shall not be repeated.

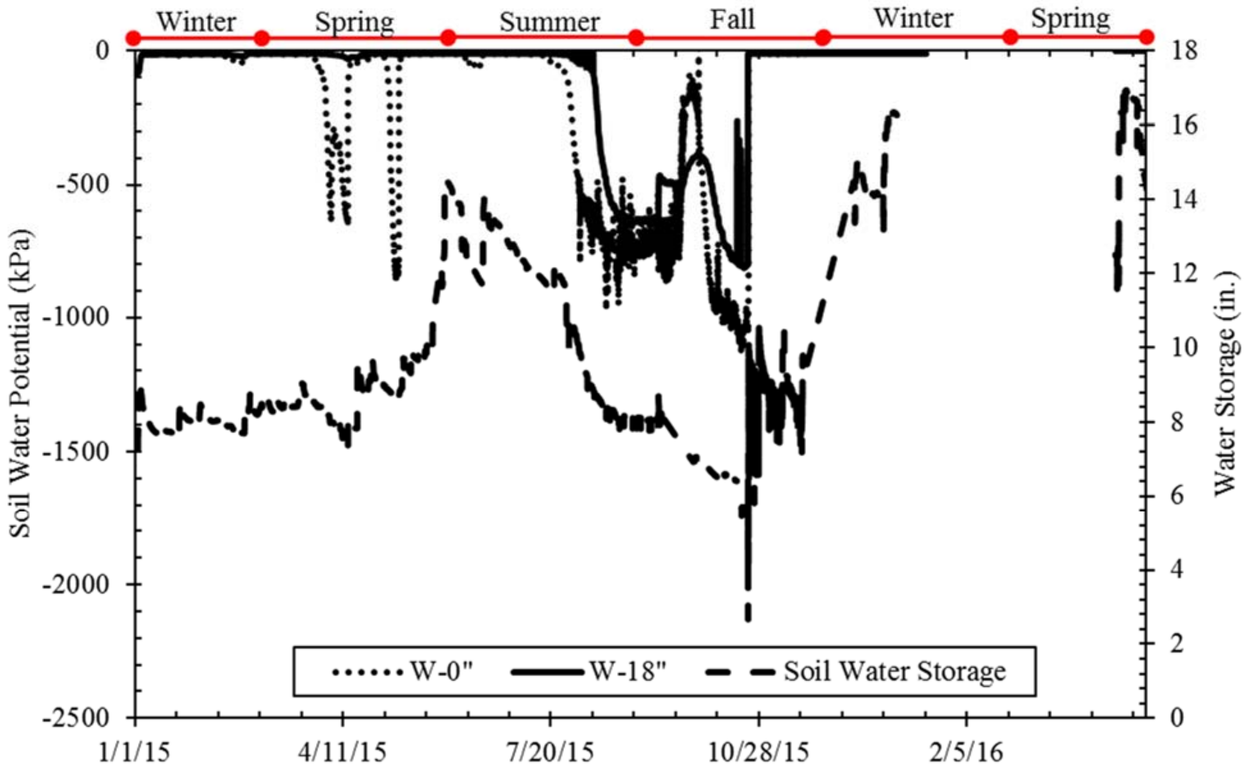

Figure 5.16: Lysimeter 4 - comparison between soil water potential and soil water storage.

5.2.6 *ET Cover System (Lysimeter 5) Results, Discussion, and Conclusions*

Monitoring results for Lysimeter 5 (inclined section) are provided in Figure 5.17, Figure 5.18, Figure 5.19, and Figure 5.20. These results, discussion, and conclusions are provided subsequently.

The water storage for Lysimeter 5 and precipitation during the monitoring period is provided in Figure 5.17. As with many of the other ET cover systems, the high frequency of precipitation events during the end of winter and spring 2015 (Period 1) corresponded to a gradual increase in water storage, with a peak at the beginning of summer when precipitation events become less frequent (Period 2). In the middle of summer of 2015 (Period 2), there was a relatively large precipitation event and corresponded to a delayed increase in water storage. Similar to the other lysimeters, frequent precipitation events occurred in the middle of fall (2015) (start of Period 3), corresponding to a dramatic increase in the water stored in the cover system. A gradual decrease in measured water storage was observed from the peak in the fall to the end of winter of 2015/2016 (during times of frequent precipitation and percolation events) (Periods 3 and 4). Data collection issues occurred during the winter and start of spring of 2015/2016; however, it was observed that the water storage was approximately equal at the start and end of the issues. Similar to the other lysimeters, it is likely that the water storage measured during this time period remained relatively high.

As provided in previous discussion on the ET cover system results, the increase in stored water during Period 1 was likely due to frequent precipitation events and the resulting infiltration into the cover system. Likely as a result of ET removing water from the storage layer and the relatively infrequent precipitation during the summer of 2015 (Period 2), the water storage decreased to a quantity approximately 0.5-inches below the beginning of the monitoring period. The low hydraulic conductivity of the storage layer (compacted clay layer) should have required relatively large amounts of time for infiltrated water to flow through. Therefore, it is suggested that the delay in response (increase) in the measured water storage was likely a result of the infiltration slowly flowing through the cover system. During Periods 3 and 4, a general decrease in water storage was observed, the water in the soil cover was likely removed from the cover system by both percolation (as discussed subsequently) and by ET.

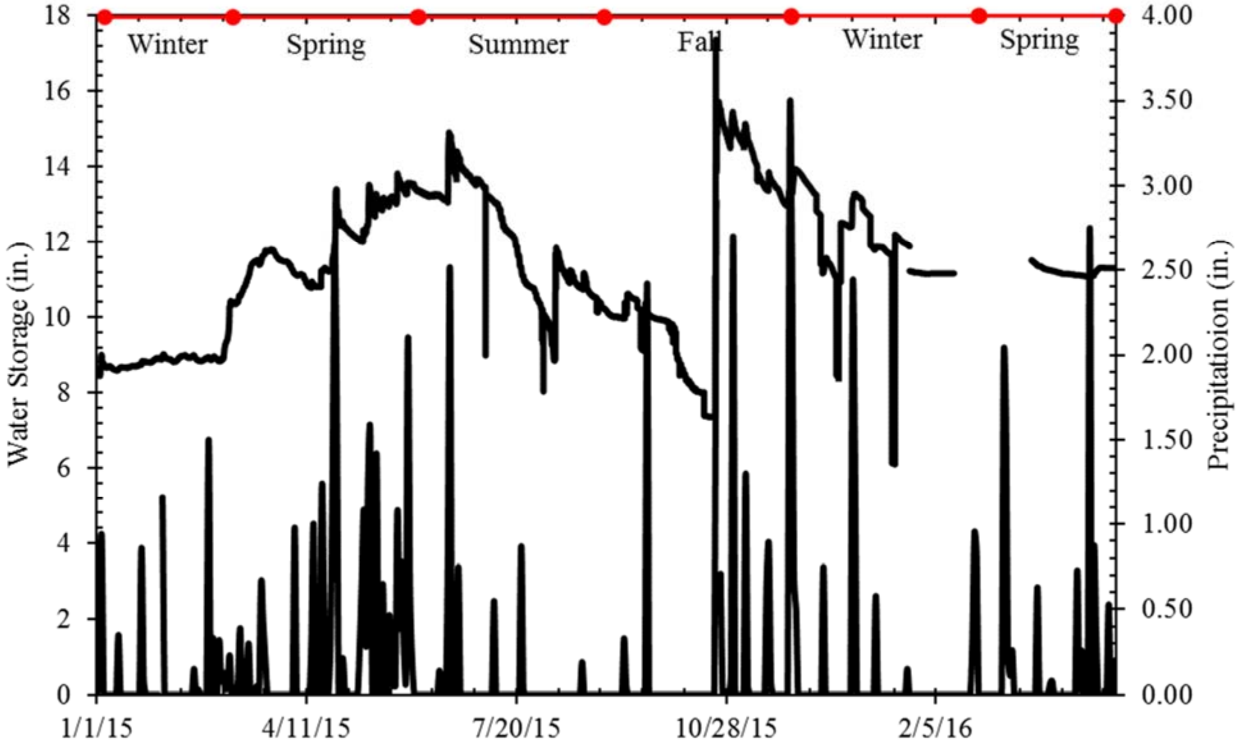

Figure 5.17: Lysimeter 5 – soil water storage and daily precipitation.

Figure 5.18 provides the cumulative precipitation, soil water storage, cumulative runoff, cumulative percolation, and cumulative ET for Lysimeter 5. The cumulative precipitation, runoff, percolation, change in water storage, and estimated ET were 76.72-inches, 26.72-inches (34.8% of precipitation), 4.50-inches (5.9% of precipitation), and an increase of 2.81-inches (3.7% of precipitation), and 42.90-inches (49.8% of PET), respectively (Table 5.2). Relatively high amounts of precipitation and runoff have been measured throughout the monitoring period. The precipitation generally occurred during Periods 1, 3, and 5; corresponding to times of frequent precipitation events. Runoff was observed during times of intense and frequent precipitation events during Periods 1, 3, and 5. From the soil water storage measured and percolation events, the soil water storage capacity can be estimated at 8.25-inches (209-mm). This estimate is based on measured results at the start of the monitoring period (winter of 2015), which was the first time period that percolation was not measured. It was observed that during the summer and fall of 2015, the soil water storage measured was greater than 8.25-inches (approximately 10-inches) when little to no percolation was measured. As discussed previously, a relatively large quantity of percolation was measured during the fall and winter of 2015/2016 during a time that the soil water storage decreased.

As with the other lysimeters, the relatively high quantity of percolation may be attributed to several factors as provided in the Lysimeter 1 discussion. Relatively large quantities of runoff measured may be attributed to high rainfall rates measured throughout the monitoring period, and the runoff collection system design. The apparent change in soil water storage capacity was likely a result of the changes in soil density and shrink and swelling cycles during the monitoring. Additionally, precipitation events occurring relatively soon after a precipitation event could suggest that shrink and swelling cycles could have caused cracks to develop in the storage layer (dessication cracks), which act as preferential flow paths that allowed the precipitation reaching lysimeter surface to move relatively quickly (greater than if the compacted clay was intact) through the cover system. The decrease in soil water storage during the fall and winter of 2015/2016 (relatively low potential ET) was likely a result of mainly percolation, with the aid of ET.

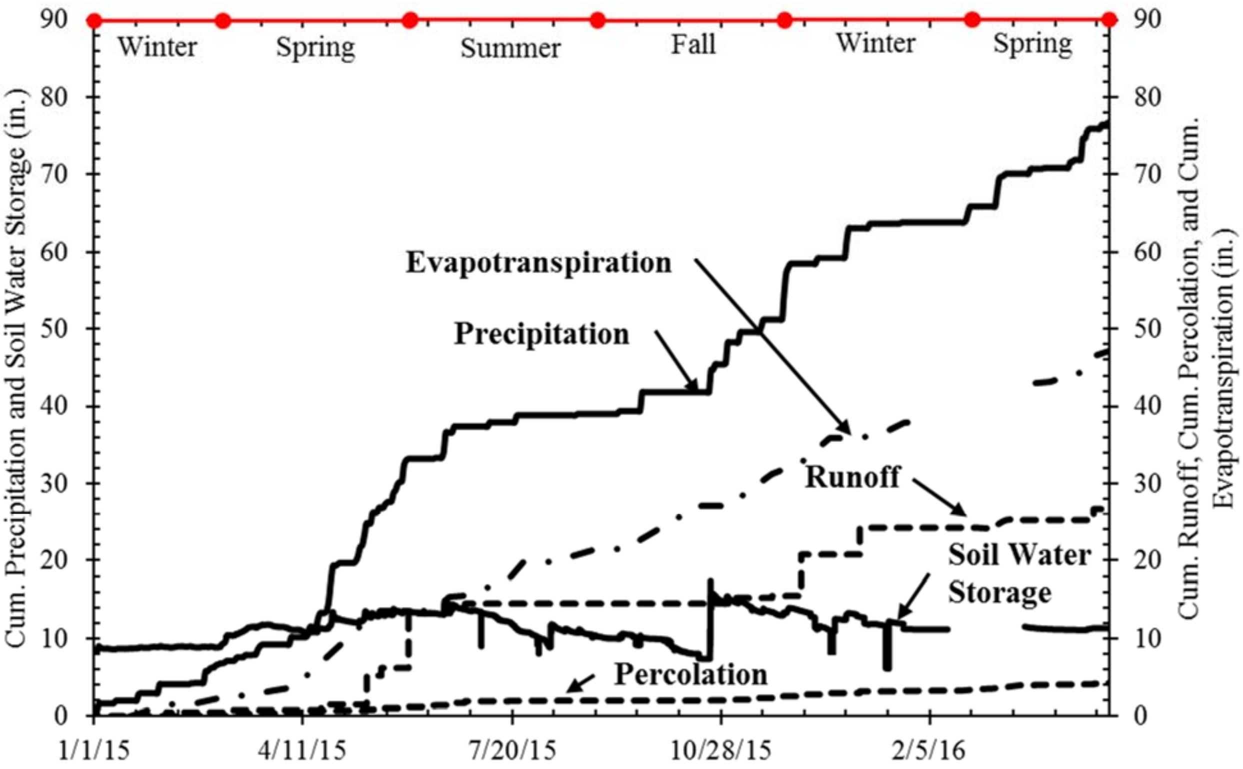

Figure 5.18: Lysimeter 5 – cumulative precipitation runoff, percolation, and evapotranspriation; and soil water storage.

soil water potential for Lysimeter 5 and precipitation results are provided in Figure 5.19. The tensiometer placed in the middle of the storage layer (W-18") measured a high soil water potential (indicative of a dry soil) at the start of the monitoring period (Period 1), and measured a gradual decrease in soil water potential (indicative of the soil becoming wetter). The tensiometer at the topsoil/storage layer boundary (W-0") measured saturated condition for nearly the entire length of the monitoring period, expect during the end of summer and middle of fall in 2015 (Period 2) and spring of 2016 (Period 5). Issues with the tensiometers occurred during the summer and fall in 2015 and was corrected in the middle of fall of 2015. Measured results during the start and end of these issues were similar to those measured in other lysimeters; therefore, it is likely that the storage layer soil was unsaturated during this time period. An increase in soil water potential was measured in both the tensiometer at the topsoil and storage layer boundary and the tensiometer in the middle of the storage layer, during the spring of 2016 (Period 5), during a time when there was a short gap in relatively large precipitation events. Relatively large gaps in precipitation were observed during the winter of 2015/2016 (Period 3); however, a decrease in soil water potential was not measured.

During Period 1, the decrease in soil water potential observed in W-18" was likely due to the frequent precipitation events and the resulting infiltrated water flowing into the middle of the cover storage layer. An increase in soil water potential as observed during the spring (when relatively frequent precipitation events occurred) (Period 5) and no increase in soil water potential was observed during the winter (when larger gaps in precipitation occurred) suggests that the increase in potential ET from the winter to spring resulted in a larger rate of stored water removal throughout the cover system.

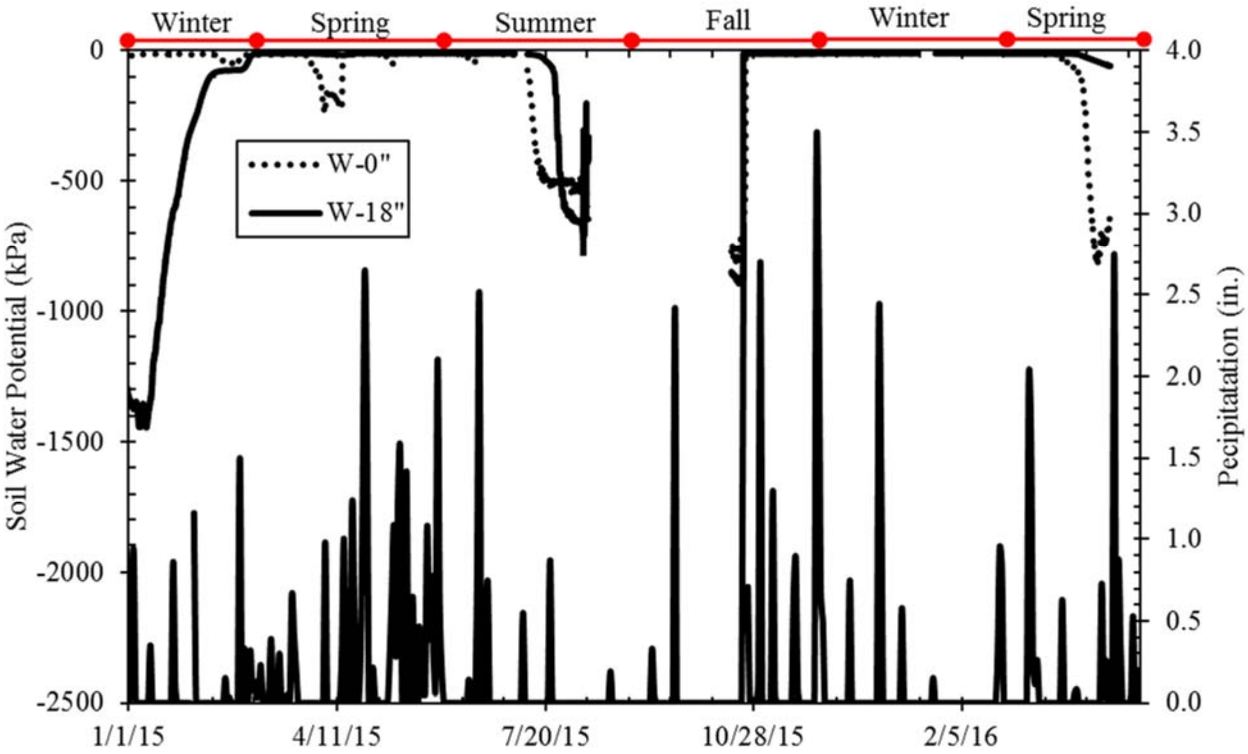

Figure 5.19: Lysimeter 5 – soil water potential and daily precipitation.

A comparison between water storage and soil water potential is provided in Figure 5.20 for Lysimeter 5. There was a strong correlation between the soil water potential and water storage, similar to the other ET cover systems. Increases in water potential measured by the tensiometer at the topsoil and storage layer boundary coorespond to small decreases in soil water storage, similliar to Lysimeter 4. For brevity, the conclusions previously discussed for the other ET cover sections shall not be repeated.

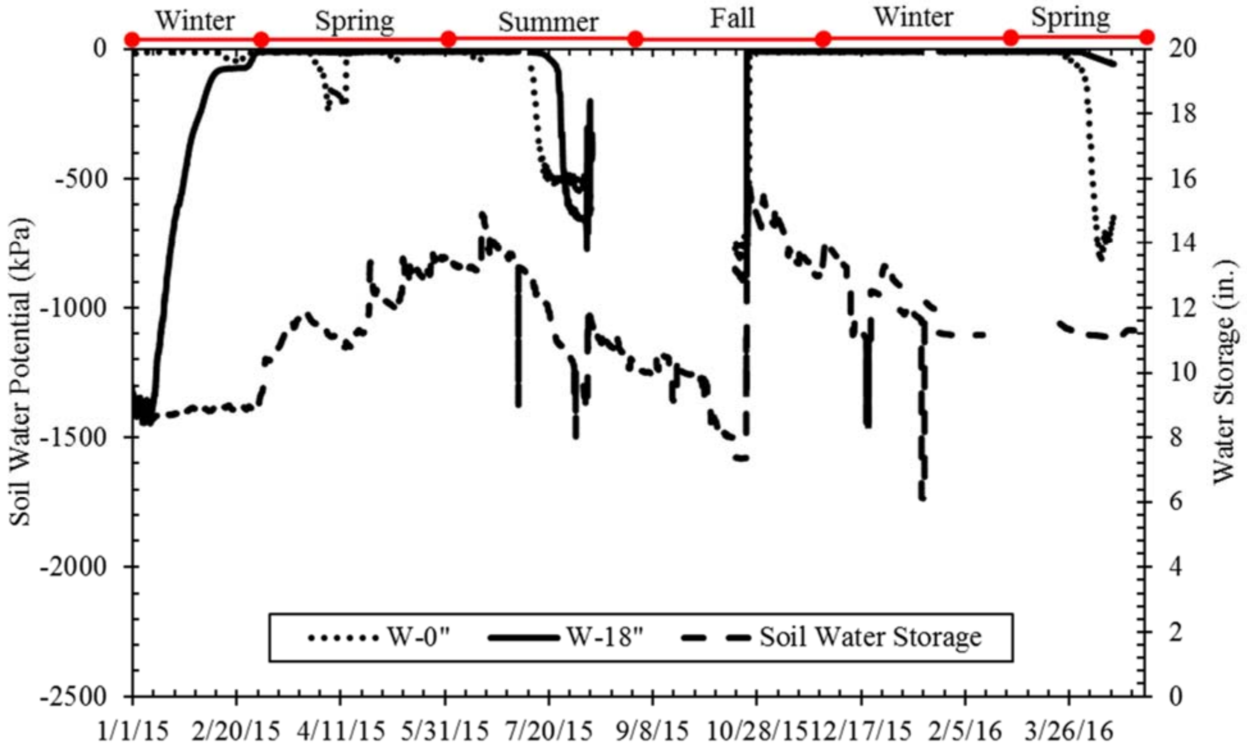

Figure 5.20: Lysimeter 5 - comparison between soil water potential and soil water storage.

5.2.7 *ET Cover System (Lysimeter 6) Results, Discussion, and Conclusions*

Monitoring results for Lysimeter 6 (inclined section) are provided in Figure 5.21, Figure 5.22, Figure 5.23, and Figure 5.24. The results, discussion, and conclusions are provided subsequently.

Figure 5.21 provides the water storage for Lysimeter 6 and precipitation throughout the monitoring period. The gradual increase in the water storage with a sharp increase in water storage at the end of winter (Period 1) was observed during a period of high frequency precipitation events. A relatively constant quantity of stored water was observed in the cover system during a time period with frequent precipitation (spring and beginning of summer of 2015). During this time period, a relatively large quantity of water was being removed from the cover system by percolation (as discussed subsequently). A large decrease in measured water storage in the cover system was observed during the summer of 2015 (Period 2), corresponding to a season of high potential ET and infrequent precipitation events. Issues with the sensors occurred during the fall of 2015; however, it was observed that there was a general increase in water stored in the cover from the beginning to the end of the monitoring issues.

The gradual increase in the water storage with a sharp increase in water storage was measured at the end of winter (Period 1) was likely a result of infiltrated water from the high frequency of precipitation events during the winter when the rate of potential ET was relatively low. The relatively constant quantity of water stored in the cover system during a time period with frequent precipitation (spring and beginning of summer of 2015) was likely due to the relatively high potential ET being able to remove some of the infiltrated water. In addition to water being removed by ET during this time period, a relatively large quantity of water was being removed from the cover system by percolation (as discussed subsequently). A large decrease in measured water stored in the cover system was observed during the summer of 2015 (Period 2), which was likely due to the high potential ET removing water from the soil (relatively little percolation was measured during this time period).

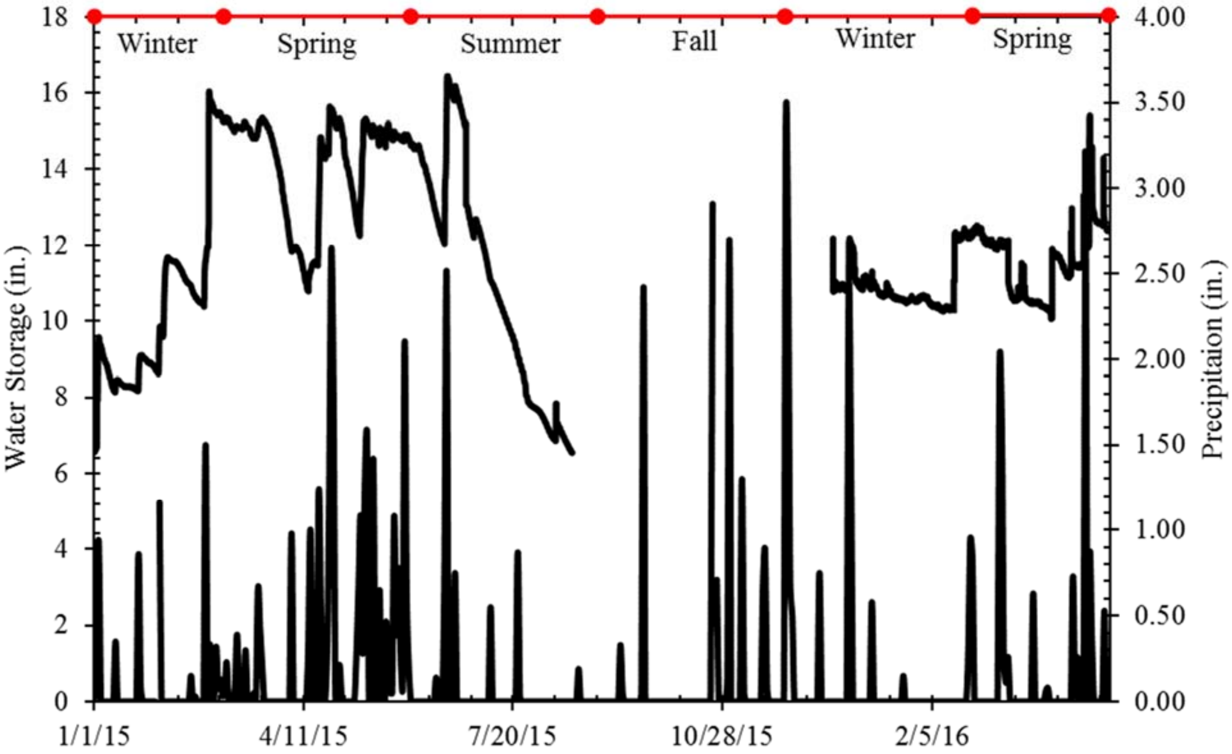

Figure 5.21: Lysimeter 6 – soil water storage and daily precipitation.

Cumulative precipitation, soil water storage, cumulative runoff, cumulative percolation, and cumulative ET during the monitoring period is provided in Figure 5.21 for Lysimeter 6. The cumulative precipitation, runoff, percolation, change in water storage, and estimated ET were 76.72-inches, 52.33-inches (68.2% of precipitation), 3.60-inches (4.7% of precipitation), an increase of 5.6-inches (7.3% of precipitation), and 16.72-inches (19.4% of PET), respectively (Table 5.2). Percolation was measured during times of precipitation (Periods 1, 3, and 5). Consistent measurements of percolation were observed during these periods, and percolation was observed shortly following precipitation events during Periods 3 and 5. During frequent and/or intense precipitation events, relatively large quantities of runoff were observed. During the start of Period 1, when vegetation was not established, large quantities of runoff were measured. Based upon the soil water storage measured and percolation events, the soil water storage capacity can be estimated at 7.0-inches (178-mm). As shown in Figure 5.21, the soil water storage was measured to be greater than the capacity for the majority of the monitoring period, with the exception of a short period at the start of monitoring and during the middle and end of summer 2015 (Period 2). It is presumed that the water that was stored in the cover was lower than the capacity throughout the summer and most of the fall of 2015 (Period 2), as little percolation was measured during this time period.

As with the other lysimeters, the relatively high quantity of percolation may be attributed to several factors as discussed in the Lysimeter 1 section, and at the end of this section. Relatively large amounts of measured runoff may be attributed to high precipitation rates measured throughout the monitoring period and the runoff collection system design. Large quantities of precipitation measured throughout much of the monitoring period (with the exception of summer and fall of 2016) was likely the cause of the large quantities of runoff, percolation, and stored water within the cover system. Abichou et al. (2005) suggested that percolation following shortly after precipitation events could be caused by root channels and/or desiccation cracking penetrating the cover system. It is likely that desiccation cracking occurred during the drying of the cover system (Periods 2 and 4), and may have been a cause of the percolation that was measured shortly following precipitation events during Periods 3 and 5.

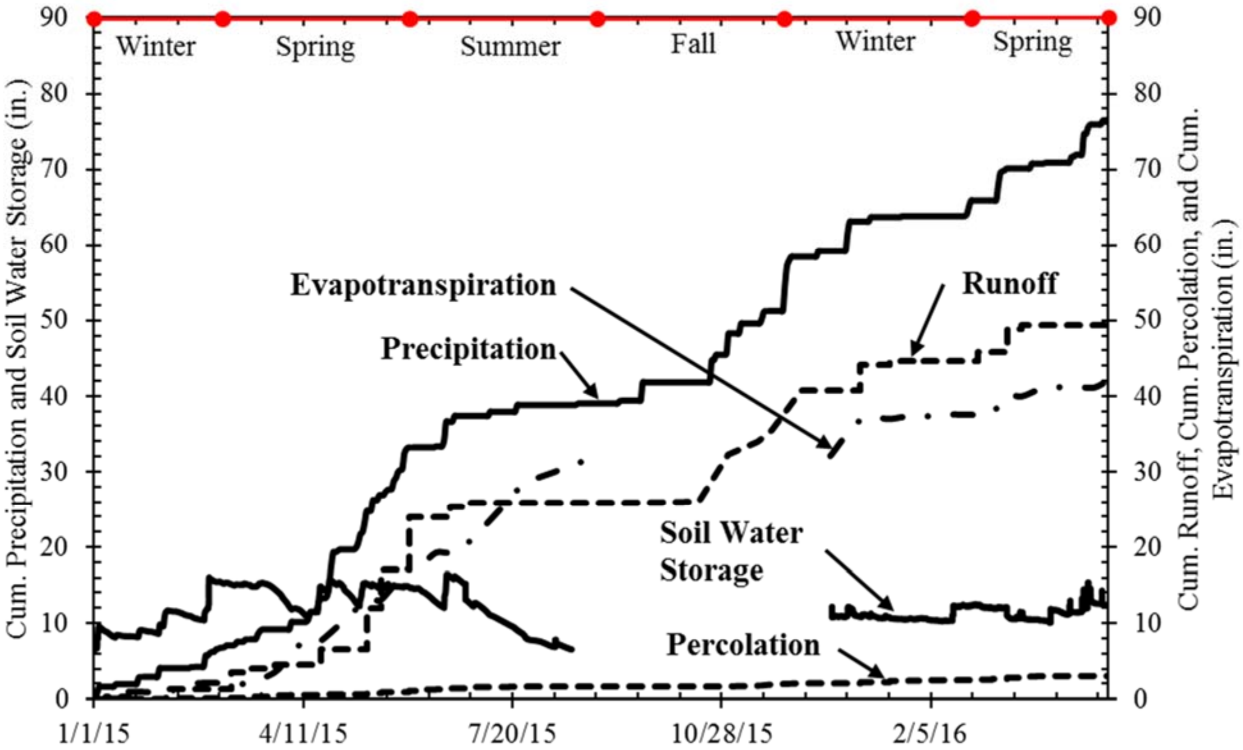

Figure 5.22: Lysimeter 6 – cumulative precipitation runoff, percolation, and evapotranspriation; and soil water storage.

Figure 5.23 provided the soil water potential in Lysimeter 6 and precipitation during the monitoring period. The tensiometers placed in the middle of the storage layer (W-18”) measured higher soil water potentials than 0 kPa at the start of the monitoring period (Period 1) and decreased shortly after the start of monitoring. A small rise in soil water potential was observed in the middle of spring (Period 1) during times of frequent and relatively large percolation events. Issues with the sensors occurred during the summer/fall of 2015 (Periods 2 and 3); however, it was observed that the soil was saturated when the sensors were brought online again. A relatively large increase in soil water potential was observed in the tensiometer placed at the storage layer and topsoil boundary, and a small increase in soil water potential was observed in the middle of the storage layer at the beginning of Period 5.

It is suggested that the frequent precipitation events and resulting infiltration resulted in a gradual decrease in soil water potential (indicative of the soil becoming wetter) at the start of the monitoring period. The small increase in soil water potential in the tensiometer at the topsoil and storage layer boundary (W-0”) during Period 1 was likely a result of relatively high potential ET during that time of year removing water relatively quickly from the topsoil layer. The saturated conditions measured during Periods 1, 3, and 5 was likely due to the high frequency of precipitation events throughout these periods. As it appears that the soil near the atmosphere/soil surface was drying prior to greater depths, it may indicate that the water stored in the soil was being removed by the ET rather than through percolation events. Period 2 corresponds with the highest potential ET at the site and relatively infrequent precipitation events, likely resulting in the increase in soil water potential observed as water was removed from the cover system.

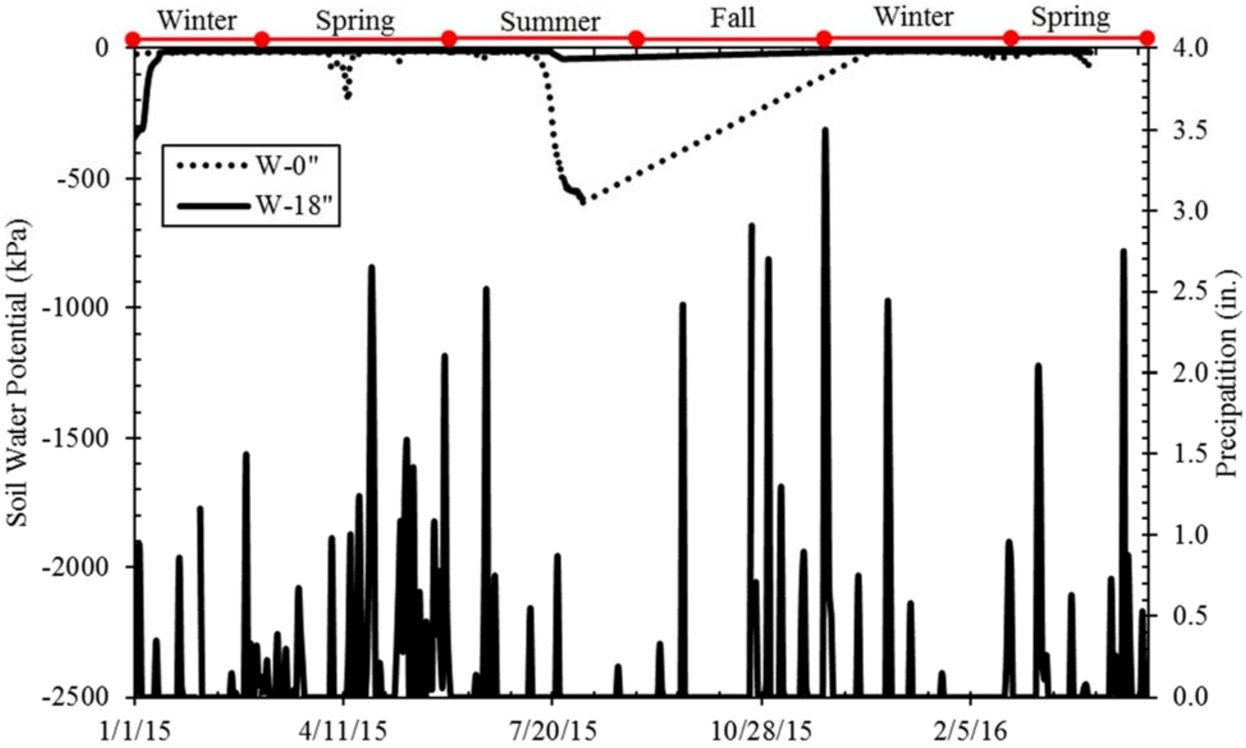

Figure 5.23: Lysimeter 6 – soil water potential and daily precipitation.

A comparison between water storage and soil water potential is provided in Figure 5.24 for Lysimeter 6. A strong correlation between periods of soil water potential at or near saturated conditions and relatively high quantities of water stored in the cover system, similar to the other ET cover sections. Similar to Lysimeters 4 and 5, increases in the soil water potential at the topsoil and storage layer boundary correspond to decreases in soil water storage. The additional conclusions stated in the other Lysimeter sections shall not be repeated.

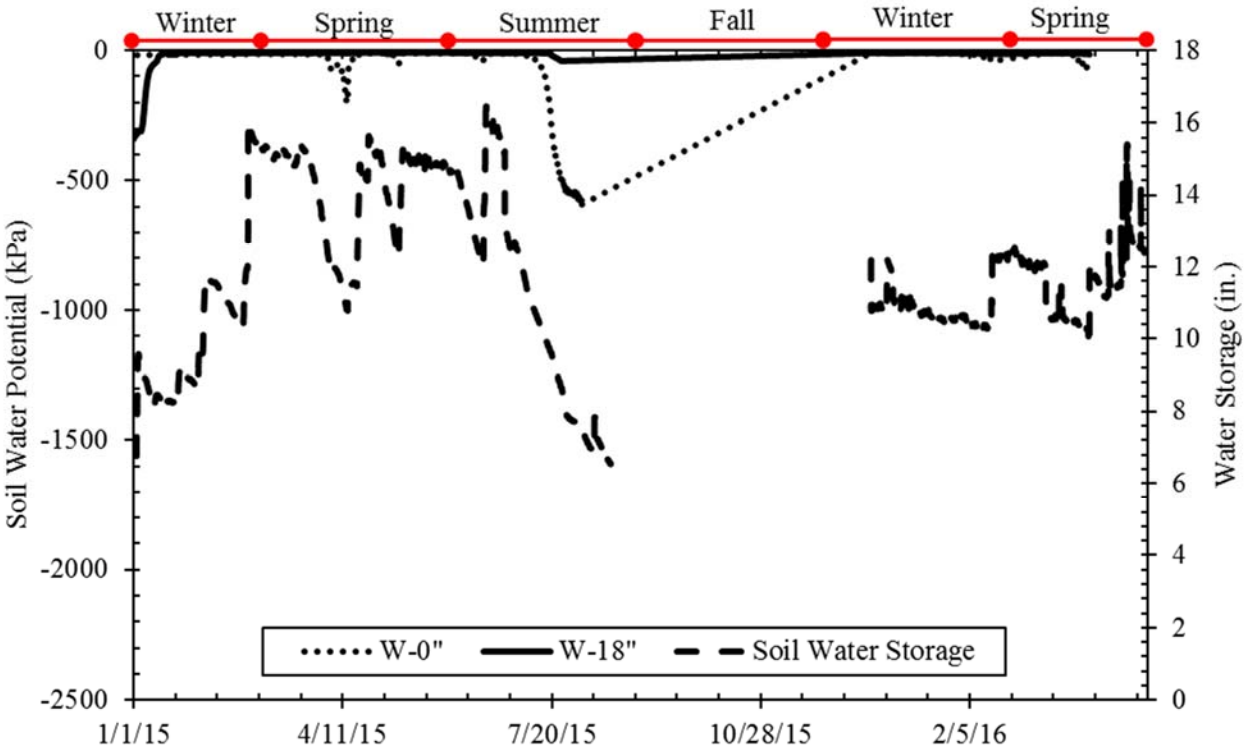

Figure 5.24: Lysimeter 6 - comparison between soil water potential and soil water storage.

5.3 Comparison of Evapotranspiration Cover Systems

A summary of the measured results for runoff, percolation, and change in soil water storage during the monitoring period is provided in Table 5.2. For ease of understanding, colors have been added to the tables to indicate ET cover systems with the same planted vegetation (i.e., Lysimeters 1 and 4, Lysimeters 2 and 5, and Lysimeters 3 and 6) as discussed in Chapter 4. These same colors have been incorporated into all tables within this section. As discussed in Chapter 4, Lysimeters 1, 2, and 3 were constructed to represent the top deck of a typical landfill (approximate slope of 2%); and Lysimeters 4, 5, and 6 were constructed to represent the sideslope (approximate slope of 25%). As discussed previously and additional discussion provided subsequently, runoff and percolation measurements are relatively high over the monitoring period.

Table 5.2: Summary of measured runoff, percolation, and soil water storage; and estimated ET.

ET Cover Section (Approximate Slope)	Runoff (Inch) [Percentage of Precipitation]	Percolation (Inch) [Percentage of Precipitation]	Change in Soil Water Storage (Inch) [Percentage of Precipitation]	Estimated Evapotranspiration (Inch) [Percentage of PET]
1 (2%)	55.12 [71.8]	3.87 [5.1]	-1.21 [-1.6]	19.40 [22.5]
2 (2%)	52.01 [67.8]	3.02 [3.9]	4.13 [5.4]	18.71 [21.7]
3 (2%)	46.53 [60.7]	3.39 [4.4]	0.78 [1.0]	25.59 [29.7]
4 (25%)	31.90 [41.6]	4.32 [5.6]	7.41 [9.6]	33.62 [39.0]
5 (25%)	26.72 [34.8]	4.50 [5.9]	2.81 [3.7]	42.90 [49.8]
6 (25%)	52.33 [68.2]	3.60 [4.7]	5.6 [7.3]	16.72 [19.4]

5.3.1 *Percolation*

Cumulative percolation for each ET cover system and cumulative precipitation is provided in Figure 5.25; and percolation, percolation as a percentage of precipitation, and effective hydraulic conductivity for each time period provided in Table 5.3, Table 5.4, and Figure 5.26. Each of the tables have been divided into the periods outlined in Table 5.1, and the total quantity of percolation measured for each lysimeter over the entire monitoring period is provided in Table 5.2. Percolation as a percentage of precipitation was calculated by dividing the quantity of percolation measured during a period by the quantity of precipitation measured during that same period, then equating that value as a percentage. Effective hydraulic conductivities were calculated by dividing the volume of percolation measured during each time period by the surface area of the 40-ft x 40-ft lysimeter. This value was then divided by the time for each period. General trends, results, conclusions, and discussion are provided subsequently. Additionally, a comparison between the summation (total) percolation for ET cover section seeded with the same vegetation is provided in Figure 5.27, and yearly percolation results are provided in Table 5.5.

Percolation events generally tend to follow precipitation events, with little percolation measured during the summer/fall of 2015 (Period 2) and a brief period during the winter of 2015 to 2016. Relatively significant amounts of percolation were measured during other periods throughout monitoring (Periods 1, 3, 4, and 5). Dry periods are generally necessary for the ET cover system to minimize percolation into the underlying waste, as water is removed from the system during these dry periods. As discussed by Benson et al. (2002), having water stored in the cover after the dry season can result in percolation events as a smaller reservoir for soil water storage is available during wetter season(s). Therefore, it is understandable that many percolation events were observed in the ET cover systems, since there were relatively few extended dry periods during the monitoring period. Additionally, the cover systems appeared to still have stored water after Period 2, as previously discussed. Additionally, the cover systems did not appear to significantly dry during Period 2 indicated by the tensiometers not measuring a soil water potential of at or near 2,500 kPa, cooresponding to be the lowest soil moisture that can be achieved in the field (i.e., the most water that can be removed by ET). It was also observed that percolation events generally had a delayed response to precipitation events, indicative of flow through the soil matrix. During the fall and early winter of 2015 (Periods 3 and 4), varying amounts of precipitation was measured at the site (i.e., high amounts of precipitation followed by relatively low, but still significant quantities); however, relatively high amounts of percolation was measured throughout the same time. This could be explained by the ET cover systems being saturated during that time and any additional water added to the system resulting in percolation. A similar trend of varying amounts of precipitation was measured at the beginning of the monitoring period during Period 1; however, measured percolation varied to a greater extent during Period 1 when compared to the Periods 3 and 4. This could be a result of the cover system not being saturated (as measured by the tensiometers) during Period 1, and ET being able to remove infiltrated water in the cover system during times of relatively low amounts of precipitation. Additionally, the percolation results during Period 2 could have been affected by the relatively short amount of time since construction and the lack of wet and drying cycles that a ET cover system would normally experience throughout its design life. It was suggested by Abichou et al. (2005) noted that preferential flow pathways may developed after a drought. Therefore, preferential flow pathways may have developed during Period 2 (dry period) and may be a main reason for the substantial amount of percolation measured throughout the remainder of the monitoring period. It should be noted that desiccation cracks were observed in the cover system after Period 2, as discussed in Section 5.4 Large amounts of precipitation were measured during the spring of 2015 (Period 5) and likely was a main reason for the large amount of percolation measured in all of the lysimeters. This is to be expected as the tensiometers and moisture sensors showed that the soil was at or near saturated conditions during this period, and additional water infiltrated into a saturated cover system should theoretically result in a percolation event.

The same general percolation trends have been observed in all of the ET cover systems. The average, minimum, and maximum percolation as a percentage of precipitation was 5.6%, 0.7%, and 12.8%, respectively. Ranking the highest percolation to lowest percolation (generally) measured in each period for all of the ET cover systems is as follows: Period 1, Period 3, Period 5, Period 4, and Period 2 (Period 3 and 5 were observed to have similar percolation results). Periods 1, 3, and 5 correspond to times when relatively large amounts of percolation were measured at the site. Additionally, during the longest dry period (Period 2 – summer of 2015) relatively small amounts of percolation were measured in for all of the ET cover systems. Ranking the highest to lowest (generally) for measured percolation as a percentage of precipitation is as follows: Period 4, Period 5, Period 3, Period 1, and Period 2. Period 4 being a short dry period but still having the greatest percolation as a percentage of precipitation suggest relatively substantial quantities of percolation may occur during short dry periods if they follow a period of frequent precipitation and the cover system is at or near saturated conditions. Although Period 1 had the highest quantities of percolation measured, it ranked as the second lowest (general) percolation as a percentage of precipitation. This was likely a result of the lengthy amount of time included in Period 1, and that the cover did not appear to be at or near saturated conditions at the start of the monitoring period. The conclusions for Periods 1 and 4 suggest that soil water storage conditions prior to periods of high or low precipitation can significantly affect the quantity of percolation (i.e., little percolation may occur if the cover soil is completely dry followed by a period of frequent precipition, or large amounts of percolation may occur if the cover soil is saturated followed by a period of relatively infrequent precipitation). Ranking the highest to lowest (generally) effective hydraulic conductivities measured for all of the lysimeters is as follows: Period 3, Period 4, Period 1, Period 5, Period 2. It should be noted that the order of ranking for effective hydraulic conductivities, percolation as a percentage of precipitation, and quantity of percolation measured are all different. This is a result of the varying amounts of time within each period, which the quantity of percolation and percolation as a percentage of precipitation does account for; therefore, the effective hydraulic conductivity provides a better direct comparison between periods. Greater hydraulic conductivities were observed in Period 4 when compared to Period 5, even though Period 4 was observed as a relatively short dry period. The relatively uniform rate of measured percolation during Period 4 for the ET cover systems would suggest that flow occurred through the soil matrix (general conclusion modified from Albright et al., 2005). This delay in percolation from precipitation events is expected as infiltration will require relatively substantial amounts of time to flow through a cover system with low hydraulic conductivities, provided that preferential flow pathways are not present. Additionally, water stored at greater depths within the cover system may not be removed during relatively short dry periods, and may result in percolation even during these dry periods.

A comparison between ET cover percolation results measured by each lysimeter indicate that the ET cover sections with the lowest amount of runoff measured (Lysimeter 4 and 5) produced the greatest quantity of percolation. This is the expected result as precipication that is not removed from the cover section by runoff would result in more infiltration (greater amount of water stored in the cover) and likely greater amounts of percolation. It is also observed that ET cover sections 3 and 6 (sodded and seeded) produced similar quantities of percolation. This is likely a result of the similarities between the vegetation seeded and growing during the monitoring period, as discussed in Section 5.4. It was also observed that little percolation was measured in Lysimter 2 at the beginning of the monitoring period (Period 1), followed by producing similar percolation results to the other lysimeters during the remainder of the monitoring period. As subsequently discussed, the soil water storage of all of the lysimeters was approximetly equal at the end of Period 1 (when substantial precipitation occurred). This result would suggest that percolation events during the start of the monitoring period may be significantly affected by differences in the moisture content of the soil during the construction and irrigation phase (if applicable). Additionally, this may indicate the a substantial wet or dry period may be required to produce reliable and representative ET cover performance results.

A comparison between yearly percolation measured results are provided in Table 5.5, and also provides for 2015 results up to May 2 (equivalent of 2016 results). It was observed that 2016 produced greater amounts of percolation when compared to 2015, when quantities of precipication for from the start of the year to May 2 are approximetly equal (19.7-inches for 2015 and 17.5-inches for 2016). This result would indicate the development of rodent burrows, desiccation cracking, and the large quantity of water stored in the cover system at the start of 2016 which were observed. Differences between each ET cover section for the yearly results have been discussed previously.

The requirements set by the Texas Commission on Environmental Quality (TCEQ) for percolation during performance verification (e.g., lysimeter studies) is 8 mm/year (0.31 inch/year) (TCEQ, 2012), and the equivalent hydraulic conductivity given this requirement is 2.54 x 10^{-8} cm/sec. Low effective hydraulic conductivities have been observed during the monitoring period (on the order of 1 x10^{-7} cm/sec); however, the quantity of percolation measured was relatively high. Percolation has been observed to be greater than the TCEQ requirement for all of the ET cover sections (

Table 5.4 and Figure 5.26), and similar effective hydraulic conductivities to the TCEQ requirement were observed only during Period 2 (extended dry period). Therefore, this result suggest that low effective hydraulic conductivities can be incorporated into the ET cover systems and still result in relatively high quantities of percolation. It should be noted that relatively low rates of percolation (effective hydraulic conductivities), such as 8 mm/year, generally have only been observed in arid regions by previous researchers (see Chapter 2). Smesrud et al. (2012) noted that during decommissioning of test sections, the saturated hydraulic conductivity from laboratory results were lower than those during construction, indicating a more permeable soil over time. This result implies that the hydraulic conductivity of the soil can change over time. Additionally, a number of researched (Chamberlain and Gow 1979; Beven and Germann 1982, Suter et al. 1993, and Albrecht and Benson 2001) have indicated a change in the hydraulic properties and storage capacity of cover systems over the service life of the cover system due to freeze-thaw cycling, wet-dry cycling, natural pedogensis processes (such as insect and animal burrowing), and plant root growth. As indicated in

Table 5.4 and Figure 5.26, the effective hydraulic conductivity of all of the ET cover systems have been observed to change over the monitoring period. It should be noted that laboratory saturated hydraulic conductivities have not been conducted on the ET cover systems during the monitoring period; therefore, it is difficult to definitively determine if the saturated hydraulic conductivity have changed during the monitoring period.

Figure 5.27 provides a comparison between the summation (total) percolation for ET cover section seeded with the same vegetation throughout the monitoring period. As percolation is the main evaluation performance parameter of landfill cover systems, the graph provides the key performance of the vegetation that was planted for a typical landfill layout (including both top and inclinded sections). Additionally, since each of the set of lysimeters were constructed as identical as construction would allow and detrimental effects (i.e., rodent burrows and desiccation cracking) that would be present during a final landfill cover system, Figure 5.27 can provide a reliable comparison between vegetation performance. The results indicate that the measured percolation indicate that the ET cover sections vegetated with bermuda sod and seed (Lysimeters 3 and 6) reduced the total quantity of percolation by 0.53-inches and 1.2-inches for Lysimeters 2 and 5 and Lysimeter 1 and 4, respectively. Differences in the vegetation which have an affect on these results are presented in Section 5.4.

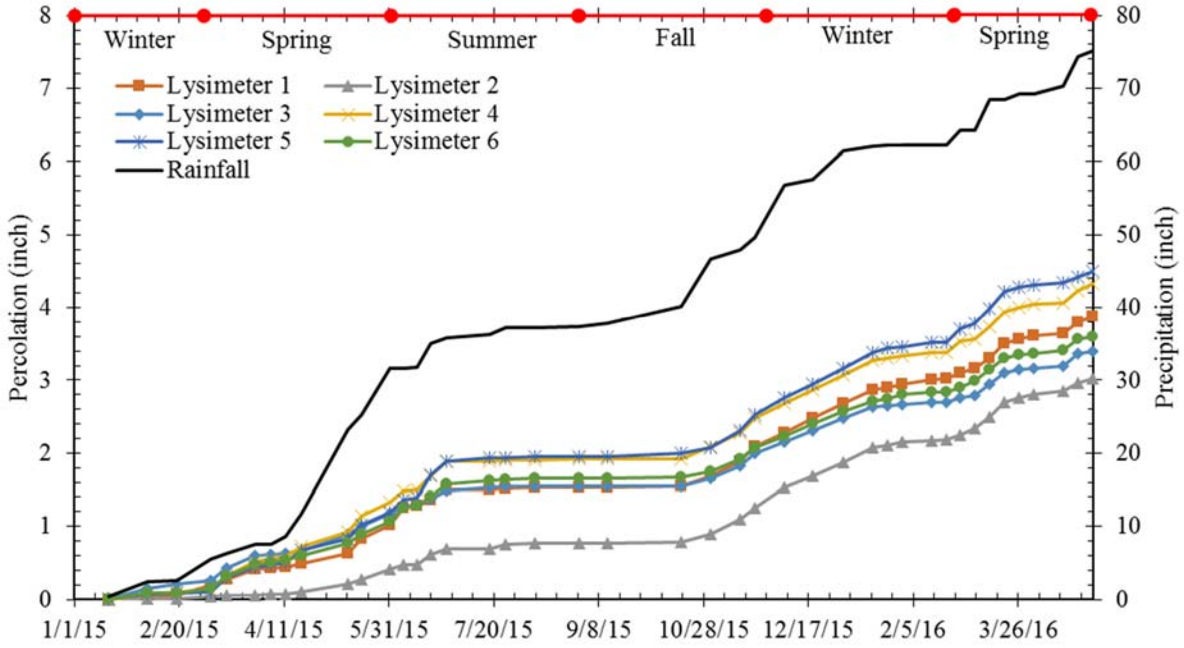

Figure 5.25: Comparison between percolation of each ET cover section and precipitation.

Table 5.3: Percolation (inch) [percentage of precipitation] results for each time period and ET cover section.

ET Cover Section (Approximate Slope)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)
1 (2%)	1.50 [4.0]	0.04 [1.0]	0.94 [5.4]	0.54 [11.7]	0.85 [6.6]
2 (2%)	0.70 [1.9]	0.09 [2.0]	0.89 [5.1]	0.50 [10.9]	0.84 [6.5]
3 (2%)	1.49 [4.0]	0.06 [1.4]	0.76 [4.4]	0.39 [8.5]	0.69 [5.4]
4 (25%)	1.89 [5.1]	0.03 [0.7]	0.95 [5.5]	0.52 [11.2]	0.93 [7.2]
5 (25%)	1.89 [5.0]	0.11 [2.4]	0.95 [5.4]	0.59 [12.8]	0.97 [7.6]
6 (25%)	1.58 [4.2]	0.09 [2.0]	0.73 [4.2]	0.44 [9.5]	0.75 [5.9]
Precipitation	35.77	4.44	17.40	4.61	12.89

Table 5.4: Effective hydraulic conductivity (cm/sec) [mm/year] results for each time period and ET cover section.

ET Cover Section (Approximate Slope)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)	Average (1/1/15 to 5/2/16)
1 (2%)	2.33 x 10^{-7} [73]	1.25 x 10^{-8} [4]	4.38 x 10^{-7} [138]	2.83 x 10^{-7} [89]	2.01 x 10^{-7} [63]	2.33 x 10^{-7} [74]
2 (2%)	1.09 x 10^{-7} [34]	2.45 x 10^{-8} [8]	4.17 x 10^{-7} [132]	2.64 x 10^{-7} [83]	1.97 x 10^{-7} [62]	2.02 x 10^{-7} [64]
3 (2%)	2.32 x 10^{-7} [73]	1.74 x 10^{-8} [5]	3.53 x 10^{-7} [111]	2.05 x 10^{-7} [65]	1.63 x 10^{-7} [51]	1.94 x 10^{-7} [61]
4 (25%)	2.94 x 10^{-7} [93]	8.34 x 10^{-9} [3]	4.44 x 10^{-7} [140]	2.71 x 10^{-7} [86]	2.20 x 10^{-7} [69]	2.47 x 10^{-7} [78]
5 (25%)	2.93 x 10^{-7} [93]	2.94 x 10^{-8} [9]	4.42 x 10^{-7} [139]	3.09 x 10^{-7} [98]	2.29 x 10^{-7} [72]	2.61 x 10^{-7} [82]
6 (25%)	2.46 x 10^{-7} [78]	2.45 x 10^{-8} [8]	3.43 x 10^{-7} [108]	2.29 x 10^{-7} [72]	1.77 x 10^{-7} [56]	2.04 x 10^{-7} [64]

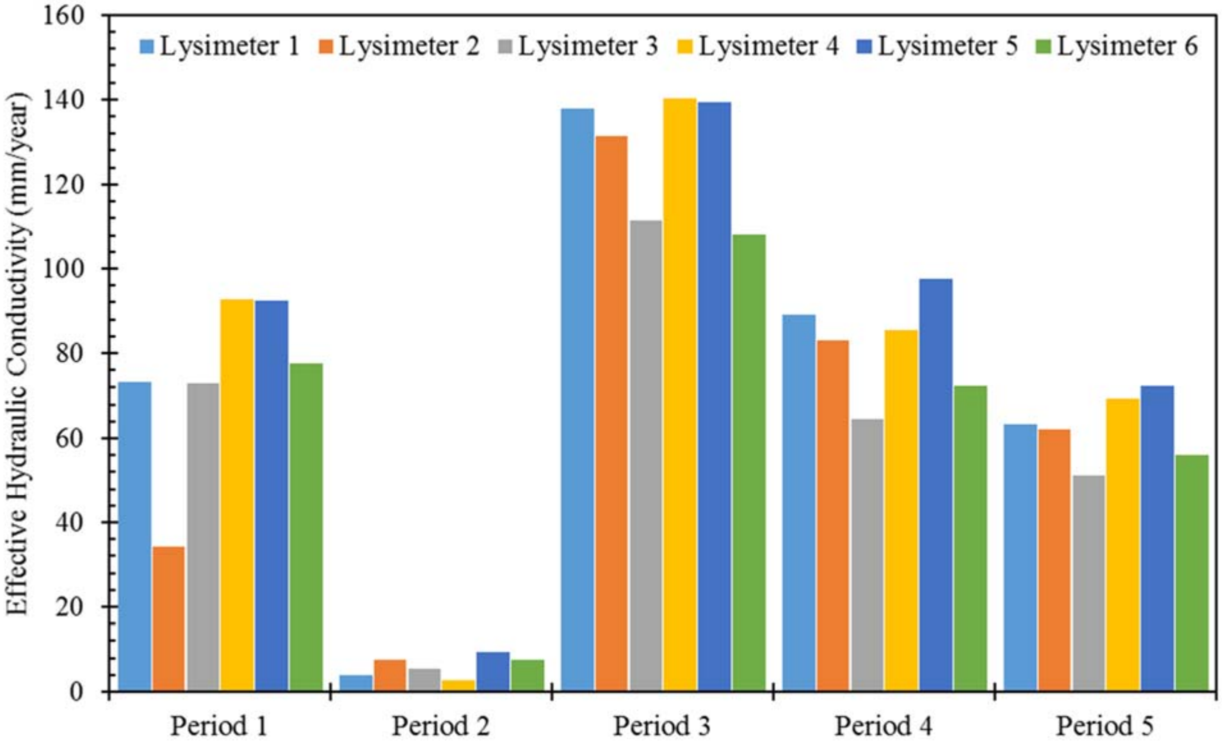

Figure 5.26: Effective hydraulic conductivity (mm/year) for each period.

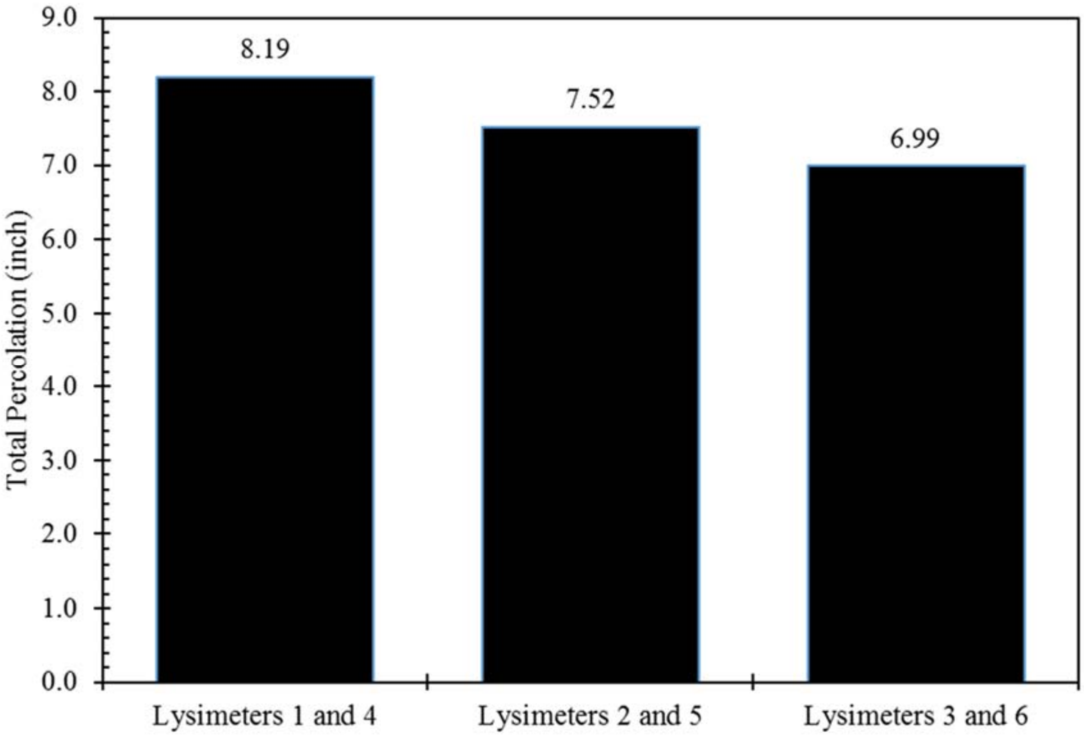

Figure 5.27: Comparison between total percolation for ET cover sections seeded with the same vegetation for the monitoring period.

Table 5.5: Comparison of yearly percolation (inch) [percentage of precipitation] for ET cover sections.

ET Cover Section (Approximate Slope)	2015 (1/1/15 to 12/31/15)	2015 (1/1/15 to 5/2/15)	2016 (1/1/16 to 5/2/16)
1 (2%)	2.48 [4.19]	0.48 [2.46]	1.39 [7.96]
2 (2%)	1.68 [2.84]	0.10 [0.50]	1.34 [7.65]
3 (2%)	2.31 [3.90]	0.69 [3.50]	1.08 [6.18]
4 (25%)	2.87 [4.85]	0.72 [3.66]	1.45 [8.29]
5 (25%)	2.94 [4.96]	0.68 [3.47]	1.56 [8.94]
6 (25%)	2.40 [4.06]	0.61 [3.08]	1.19 [6.81]
Precipitation	59.2	19.7	17.5

5.3.2 *Runoff*

Cumulative runoff for each lysimeter and cumulative precipitation is provided in Figure 5.28, runoff for each period is provided in Table 5.6, and a comparison between the summation (total) runoff for ET cover sections seeded with the same vegetation is provided in Figure 5.29. Additionally, a yearly comparison between 2015 and 2016 is provided in Table 5.7

As would be expected, during relatively dry periods (Periods 2 and 4) the measured runoff is minimal while during relatively wet periods (Periods 1, 3, and 5) measured runoff is relatively high. Additionally, quantity of runoff measured is much greater than during other monitoring periods. As discussed in Section 5.4, vegetation during the beginning of the monitoring period (Period 1) has not been established and a greater density of vegetation was visually observed on the inclined sections. Results shown in Figure 5.28 and Table 5.6 indicate that the measured runoff for the top sections tended to be greater than the inclined sections, and Lysimeters 3 and 6 (sodded cover systems) showed similar measured runoff results. The average, minimum, and maximum runoff as a percentage of precipitation was 52%, 0%, and 97%, respectively. Ranking the highest runoff to lowest runoff (generally) measured in each period for all of the ET cover systems is as follows: Period 1, Period 3, Period 5, Period 4, and Period 2 (Table 5.6). Additionally, ranking the highest runoff as a percentage of precipitation to lowest runoff (generally) measured in each period for all of the ET cover systems is as follows: Period 4, Period 3, Period 1, Period 5, and Period 2 (Table 5.6). It should be noted that the order of ranking between the two is different, and Period 1 had the greatest amount of runoff but not the greatest runoff as a percentage of precipitation (although vegetation was not established at the start of the period). Additionally, the greatest runoff as a percentage of precipitation was observed in a relatively short dry period (Period 4). Results in Figure 5.29 show that Lysimeters 3 and 6 (bermuda sod and seeded) had the highest total summation of runoff when compared to the other lysimeters. Greater differences between measured runoff quantities for each ET cover system were observed during periods of greater quantities of precipitation (Periods 1, 3, and 5) when compared to periods of less precipitation (Periods 2 and 4). Yearly runoff measured results shown in Table 5.7 and the 2015 results up to May 2 (equivalent timespan of 2016) generally showed that 2015 runoff quantities were greater than 2016.

It is intuitive that less runoff would result in more infiltration and possibly lead to greater amounts of percolation for ET cover systems. As greater densities of vegetation have been observed on the inclined sections (discussed in Section 5.4), this could result in the greater amounts of percolation observed in the inclined section, as the amount of infiltration would increase with a decrease in runoff. Additionally, this result suggests that the slope of the cover system may not play as critical role in the quantity of runoff as previously indicated in Chapter 2. It has been suggested by Abichou et al. (2005) that denser vegetation would result in more resistance to surface flow; therefore, less measured runoff. Benson et al. (2002) indicated that having mature vegetation in humid climates is critical for the performance of alternative cover systems as large volumes of water require management. Additionally, Benson et al. (2002) measured a decline in percolation rate by more than a factor of 25 as vegetation (trees) became established. Therefore, higher quantities of runoff measured by May 2, 2015 when compared to May 2, 2016 could be a result of the establishment of vegetation throughout 2016, when compared to the little vegetation that was present during the start of 2015 (further discussed in Section 5.4). Additionally, higher intensity precipitation events, and low lying and dormant rather than taller vegetation could lead to greater quantities of runoff (discussed in Chapter 2). The high intensity precipitation events and low lying vegetation observed during Periods 3, 4, and 5 (discussed in Sections 5.5 and 5.4,respectively) could have resulted in the high measured runoff as a percentage of precipitation. The apparent effect of season vegetation changes on runoff was evident when comparing runoff results from Periods 2 and 4, where infrequent precipitation was measured during both time periods. The infrequent precipitation during Period 2 (during spring and summer when there was a dense growth of vegetation) had high intensity precipitation and Period 4 (during winter and vegetation dormancy) had low intensity precipciation (see Section 5.5). This would suggest that the promonant vegetation during Period 2 provided greater resistance to runoff than during Period 4 when the vegetation was dormant. Greater differences in runoff quantites for periods of greater precipication when compared to less precipitation suggest that more precipitation events result increase the effect that changes in vegetation has on the amount of runoff. The wide range of results for runoff as a percentage of precipitation would suggest that factors such as quantity and intensity of precipitation, vegetation density and dormancy, and others have a substantial impact on runoff quantities. It was observed that the summation (total) runoff for ET cover sections seeded with the same vegetation showed that Lysimeters 3 and 6 (bermuda seeded and sodded) produced the greatest amount of runoff. As discussed previously, a greater quantity of runoff would result in less infiltration and likely result in less percolation (consistent with percolation results discussed previously). However, a higher amount of runoff could result in a greater amount of erosions; therefore, it is essential for the vegetation to provide substantial surface coverage to prevent erosion.

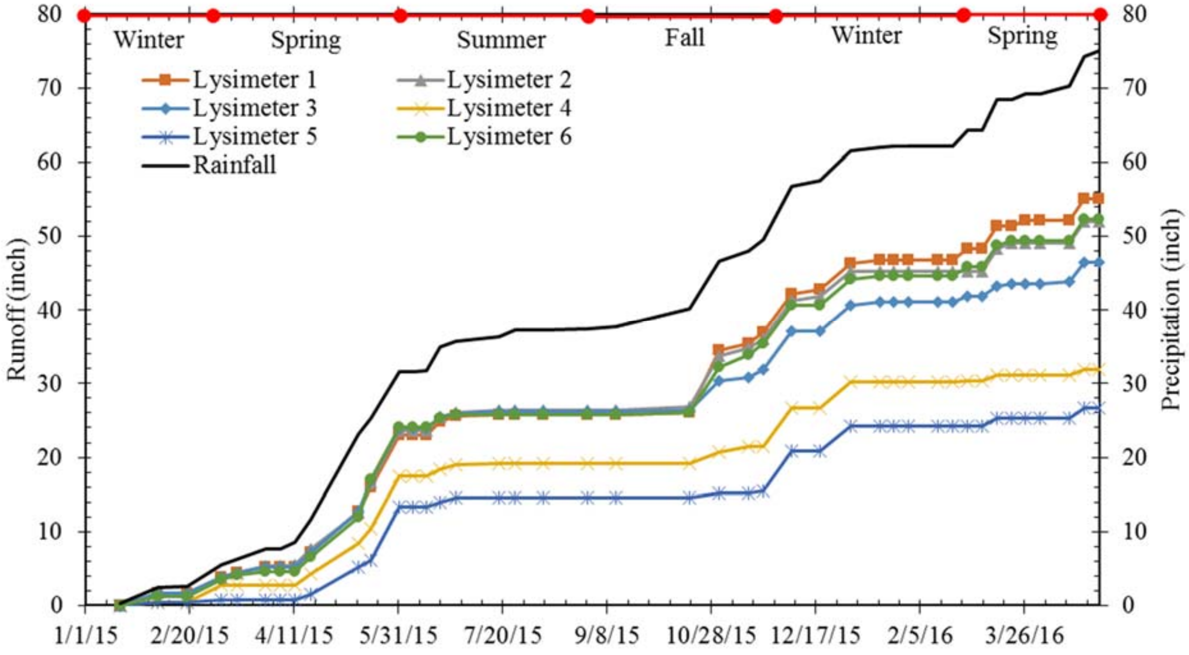

Figure 5.28: Comparison between cumulative runoff and precipitation.

Table 5.6: Runoff (inch) [percentage of precipitation] results for each time period.

ET Cover Section (Approximate Slope)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)
1 (2%)	25.54 [68.3]	0.49 [11.1]	16.82 [96.6]	3.92 [85.0]	8.34 [64.7]
2 (2%)	26.14 [69.9]	0.74 [16.7]	14.95 [85.9]	3.46 [75.1]	6.71 [52.1]
3 (2%)	25.93 [69.4]	0.49 [11.1]	10.74 [61.7]	3.92 [85.0]	5.44 [42.2]
4 (25%)	18.94 [50.7]	0.25 [5.6]	7.53 [43.3]	3.46 [75.1]	1.73 [13.4]
5 (25%)	14.49 [38.8]	0.00 [0.0]	6.29 [36.1]	3.46 [75.1]	2.47 [19.2]
6 (25%)	25.76 [68.9]	0.25 [5.6]	14.70 [84.5]	3.92 [85.0]	7.70 [59.8]
Precipitation	35.77	4.44	17.40	4.61	12.89

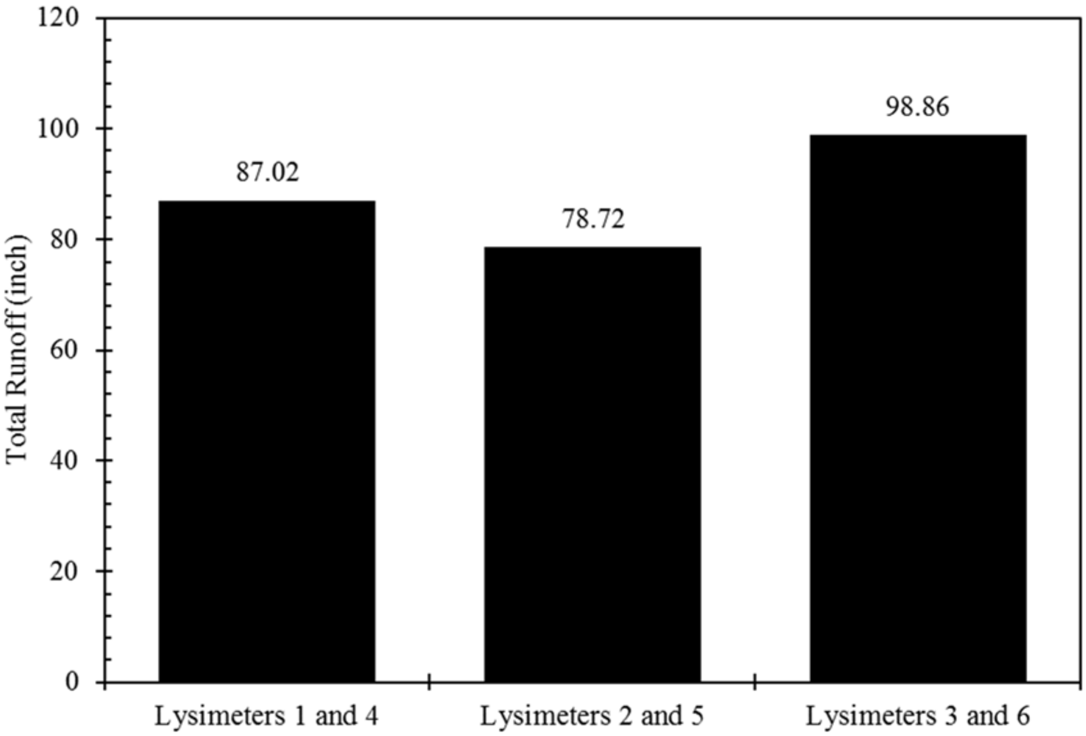

Figure 5.29: Comparison between total runoff for ET cover sections seeded with the same vegetation for the monitoring period.

Table 5.7: Comparison of yearly runoff (inch) [percentage of precipitation] for ET cover sections.

ET Cover Section (Approximate Slope)	2015 (1/1/15 to 12/31/15)	2015 (1/1/15 to 5/2/15)	2016 (1/1/16 to 5/2/15)
1 (2%)	42.85 [72.35]	12.67 [64.31]	12.26 [70.07]
2 (2%)	41.83 [70.64]	12.53 [63.60]	10.17 [58.13]
3 (2%)	37.17 [62.76]	12.67 [64.31]	9.36 [53.50]
4 (25%)	26.71 [45.11]	8.41 [42.69]	5.19 [29.67]
5 (25%)	20.78 [35.09]	5.20 [26.40]	5.93 [33.91]
6 (25%)	40.71 [68.74]	12.01 [60.96]	11.62 [66.41]
Precipitation	59.2	19.7	17.5

5.3.3 *Evapotranspiration*

Cumulative evapotranspiration was calculated by the Water Balance Equation (Equation 2.2)[13] for each ET cover section, cumulative potential evapotranspiration (PET), and cumulative precipitation is

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[13] It should also be noted that it was assumed that the amount of precipitation utilized in the Water Balance Equation for each ET cover system was equal.

provided in Figure 5.30. Calculated ET and P/ET results for each period are provided in Table 5.8 and Table 5.9, respectively[14]. Additionally, total evapotranspiration and average P/ET results for the entire monitoring period and each for ET cover sections seeded with the same vegetation are provided in Figure 5.31 and Figure 5.32, respectively. Finally measured ET from two (2) ETgage™ placed on the top and inclined sections at the site is provided in Figure 5.33. P/ET (or P/PET) provides an understanding of when water is expected to accumulate in the cover system (i.e., high values of P/ET) or when water is expected to be removed from the cover system (i.e., values close to zero). Additionally, Albright et al. (2004) suggested that water will begin accumulating in the cover system for climates which do not have snow or frozen ground when P/PET exceeds 0.34 and 0.97 for fall-winter and spring-summer, respectively.

It was observed that the inclined sections (Lysimeter 4, 5, and 6) have greater cumulative measured ET when compared to the top sections (Lysimeters 1, 2, and 3). As the cumulative ET was estimated based on the other measured parameters, these results were likely caused by a number of components as discussed previously. However, the larger amount of estimated ET in Lysimeter 4 and 5 than the other ET cover sections was likely a result of smaller quantity of runoff measured. This result corresponds with observations made by Nyhan et al. (1997). Nyhan et al. (1997) observed that evaporation tended to increase with an increase in slope, suggesting that this result was likely because large slopes can intercept greater amounts of solar radiation when compared to shallower slopes. Additionally, the quantity and speed of the wind flowing across the top and inclined section on the landfill may vary, resulting in variation in the evaporation. Both the PET and ET results for all of the ET cover section followed seasonal trends, where PET and ET was at a maximum during summer and minimum during the winter. This result is consistent with statements made in literature and discussed in Chapter 2.

The calculated ET as a percentage of PET ranged from 9.0% to 90.8%, with an average of 47.3%. This wide range of values is likely a result of multiple factors which have an effect on runoff, percolation, precipitation, and soil water storage. It was observed that during Periods 2 and 4 (periods of low

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[14] Instrumentation issues prevented the change in soil storage and as a result ET from being calculated for several lysimeters and time periods. These are indicated as “N/A” in the tables.

precipitation) that the PET tended to overestimate the measured ET, as the average ET for each period was 55% (Period 1), 36% (Period 2), 57% (Period 3), 38% (Period 4), and 46% (Period 5). This result would suggest that PET has a better correlation with ET for periods of high precipitation.

Results for the calculated ET for each period and ET cover system had a wide range of results and the variability in the total ET for cover sections seeded with the same vegetation, suggest that a number of factors have parameters utilized to calculate ET (precipitation, runoff, change in soil water storage, and percolation) contribute to the ET results. It appears that the PET overpredicted ET during periods of low precipitation (Periods 2 and 4) when compared to periods of high precipitation (Perdios 1, 3, and 5).

Calculated P/ET results for each period and ET cover system show values above one (i.e., greater precipitation than ET) for the majority of the monitoring (Periods 1, 3, 4, and 5). It is evident that water will accumulate in the ET cover systems throughout most of the monitoring, especially considering accumulation thresholds suggested by Albright et al. (2004). The exception was Period 2, where values were less than one (1) and correspond to a time where the soil water storage in all of the lysimeters decreased (i.e, removal of water from the cover by ET). These results correspond with percolation occurring throughout most of Periods 1, 3, 4, and 5, and is evident in the greater than one (1) values estimated for the average P/ET for the cover sections seeded with the same vegetation.

Measured ET from the two (2) ETgage™ correspond to results estimated based on the ET cover system results where greater ET was observed in the inclined section when compared to the top sections.[15] Additionally, these results suggest that ET can significantly vary (4.5-inches) within a short amount of time (70-days), within a short distance (approximately 60-feet), and based on location/slope on a landfill.

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[15] ETgage™ results are outside the monitoring period and for a relatively short amount of time compared to the study period.

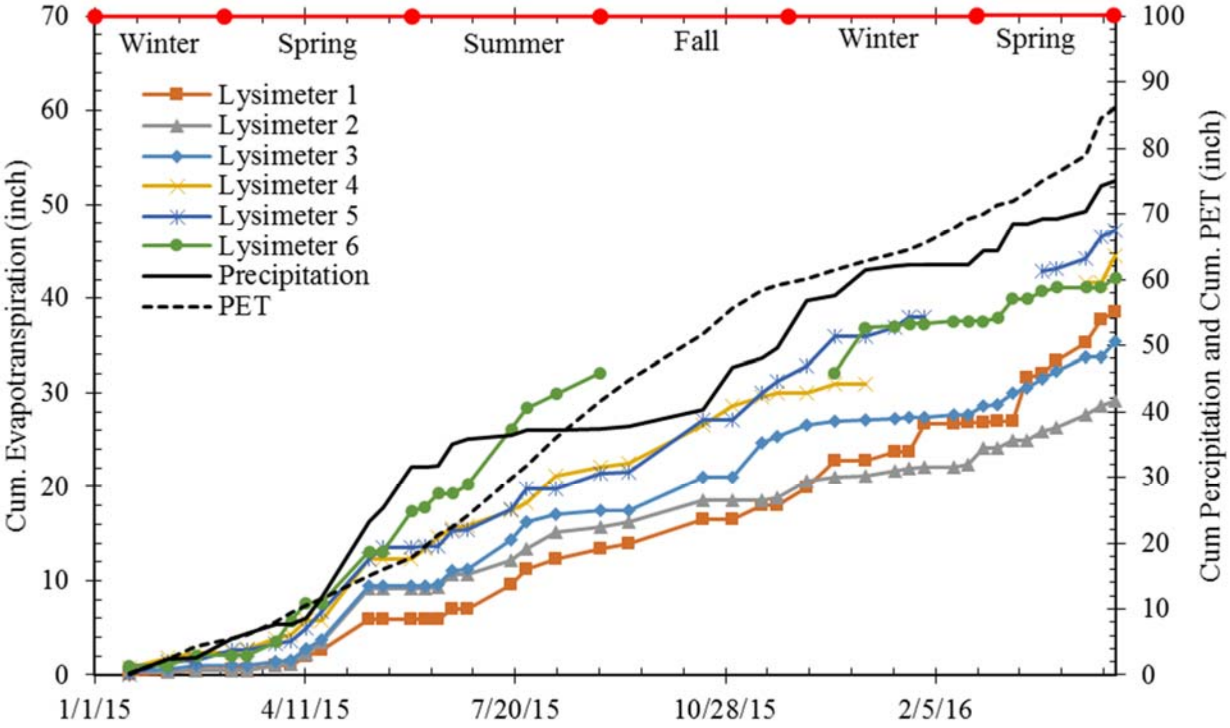

Figure 5.30: Cumulative evapotranspiration, potential evapotranspiration, and precipitation.

Table 5.8: Calculated evapotranspiration (inch) [percentage of PET] results for each time period.

ET Cover Section (Approximate Slope)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)
1 (2%)	6.97 [28.9]	9.51 [34.3]	6.23 [64.2]	4.07 [53.3]	11.79 [69.0]
2 (2%)	10.61 [44.0]	7.93 [28.6]	2.41 [24.8]	1.47 [19.2]	6.79 [40.1]
3 (2%)	11.28 [46.8]	9.70 [35.0]	6.00 [61.9]	0.68 [9.0]	7.73 [45.6]
4 (25%)	15.78 [65.4]	10.82 [39.0]	4.38 [45.2]	N/A	N/A
5 (25%)	15.49 [64.2]	11.62 [41.9]	8.81 [90.8]	N/A	N/A
6 (25%)	20.24 [83.9]	N/A	N/A	5.46 [71.6]	4.65 [27.4]
PET	24.12	27.72	9.70	7.63	16.95

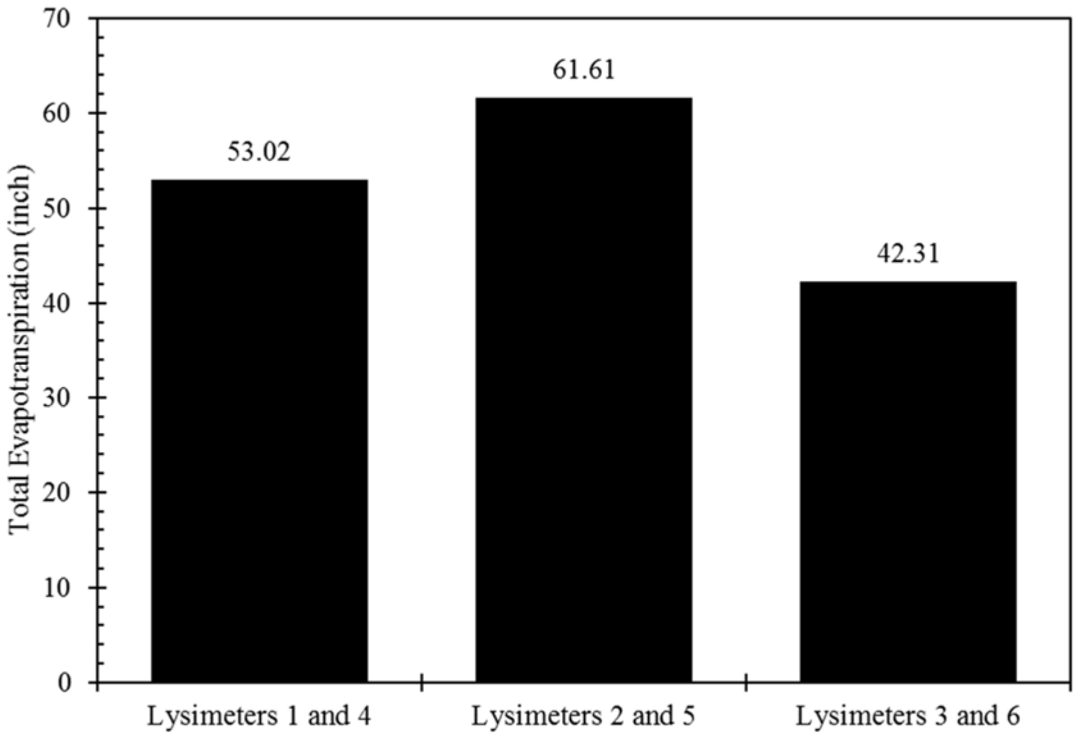

Figure 5.31: Comparison between total ET for ET cover sections seeded with the same vegetation for the monitoring period.

Table 5.9: Calculated P/ET [percentage of P/PET] results for each time period.

ET Cover Section (Approximate Slope)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)
1 (2%)	5.4 [346]	0.5 [291]	2.8 [156]	1.1 [187]	1.1 [144]
2 (2%)	3.5 [227]	0.6 [350]	7.2 [403]	3.1 [520]	1.9 [250]
3 (2%)	3.3 [214]	0.5 [286]	2.9 [162]	6.7 [1117]	1.7 [219]
4 (25%)	2.4 [153]	0.4 [256]	4.0 [221]	N/A	N/A
5 (25%)	2.4 [156]	0.4 [239]	2.0 [110]	N/A	N/A
6 (25%)	1.8 [119]	N/A	N/A	0.8 [140]	2.8 [365]
P/PET	1.55	0.16	1.79	0.60	0.76

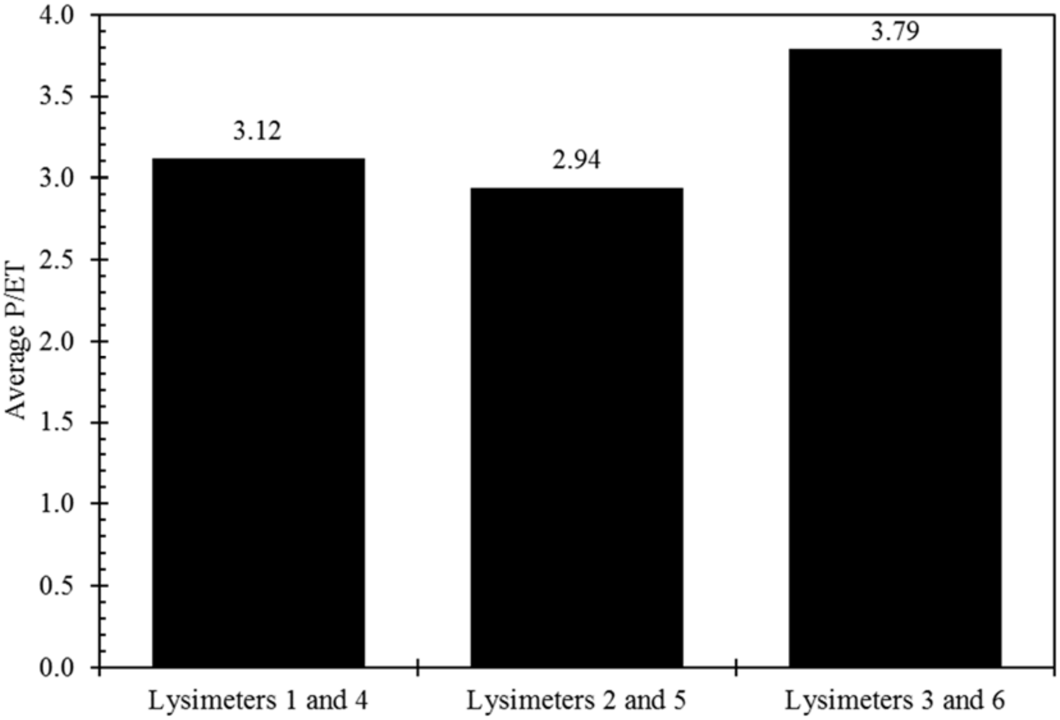

Figure 5.32: Comparison between the average P/ET for ET cover sections seeded with the same vegetation for the monitoring period.

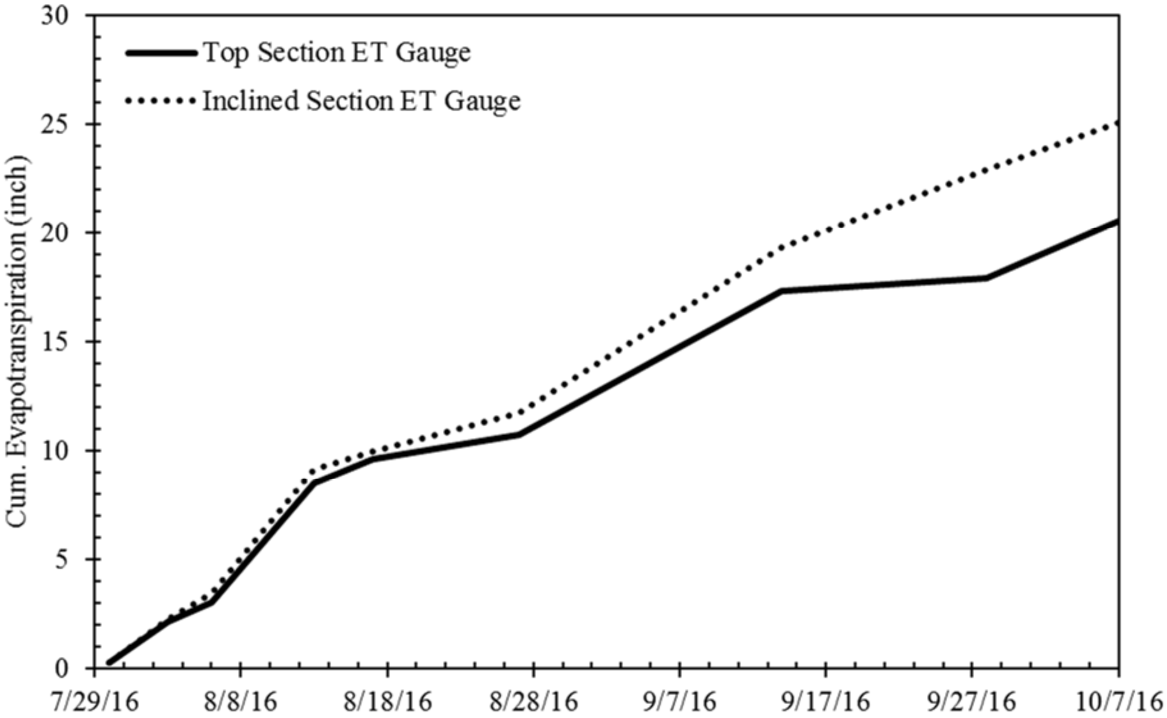

Figure 5.33: ETgage™ measured evapotranspiration.

5.3.4 *Soil Water Storage*

Soil water storage for each ET cover section and cumulative precipitation is provided in Figure 5.34. At the start of monitoring period (Period 1), varying amounts of soil water storage were measured in all of the ET cover systems. Varying amounts of soil water storage appear to be present through Period 1, after which, the water storage measured is relatively similar in all of the ET cover sections. During Period 1 (January to July 2015) of monitoring, frequent precipitation events occurred and a gradual increase in water storage was observed in all of the ET cover systems. Sharp spikes in the water storage were observed throughout the monitoring period in all of the cover systems. Additional precipitation events at the end of spring and beginning of summer appear to have caused by infiltration which was measured by an increase in water storage. During the summer of 2015 (Period 2), relatively small and infrequent precipitation events occurred and the measured water storage gradually decreases in all of the cover systems. A sharp spike in soil water storage was observed in the ET cover systems in the middle of fall (2015) when a large precipitation event occurred. During Period 3 (when frequent precipitation events occurred), a gradual decrease in the measured soil water storage was observed in the ET cover systems. Fluctuations in the soil water storage was observed for the remainder of the monitoring period (Periods 4 and 5), with the soil water storage remaining relatively high for most of the ET cover systems (with the exception of Lysimeter 4).

Different quantities of water storage at the beginning of the monitoring period was likely a result of varying amounts of water applied during the construction and irrigation phase. The gradual increase in water storage during Period 1 could be attributed to precipitation events occurring relatively frequently during this time period, with greater increases in the measured water storage when the frequency of precipitation increased. Sharp spikes observed in the water storage could be a result, in at least a small part, to the moisture sensors placed at the topsoil/storage layer boundary and at a shallow depth within the storage layer. The relative ease that the precipitated water can infiltrate through the topsoil (high hydraulic conductivity) and reach the top of the storage layer (where it is measured by that sensor) could cause spikes in the measured water storage shortly after precipitation events. Significant increases in the soil water storage of cover systems could be a result of large precipitation events (Barnswell and Dwyer, 2011). The gradual decrease in water storage over Period 2, was likely a result of ET (as vegetation was becoming established during this period) removing the water stored in the cover system during the summer and early fall of 2016. The percolation and decrease in soil water storage measured in the lysimeters during Period 3 (during a period where frequent precipitation events were observed) suggest that water was being removed from the ET cover systems by both percolation and ET. Generally, measured high soil water storage corresponded to times when percolation was measured, and suggest that percolation was flowing through the soil matrix.

A comparison between total change in soil water storage from the start of the monitoring period (January 1, 2015) to the end of the monitoring period (May 2, 2015) for ET cover section vegetated with the same mix is provided in Figure 5.35, and changes in water storage for each period is provided in Table 5.10. A greater quantity of water storage in the ET cover system is indicative of a greater amount of water infiltrated into the cover system, which could result in percolation. The soil water storage capacity (moisture content at field capacity) and minimal quantity of water stored in the cover (moisture content at the wilting point) are the limiting factors in the change in woil water storage. Additionally, the inclined section tended to have a greater increase in soil water storage over the monitoring period, indicative of greater volumes of water infiltrating into the cover soil. This results correspond well with the greater quantities of runoff and less quantity of percolation measured in the top sections when compared to the inclined sections.

The soil water storage capacity (S_c) (estimated by determining the soil water storage measured from the soil moisture sensors at times when percolation was or was not measured), the approximate maximum measured soil water storage (S_m), and estimated required thickness of storage layer for each ET cover section (S_t) is provided in Table 5.11. The required thickness of storage layer for each cover section was estimated based upon the following equation:

$$S_t = \frac{S_m * 36}{S_c} \tag{5.1}$$

The “36” in Equation 5.1 is the original thickness of the storage layer in inches, that all quantities in the equation are in inches. The equation also assumes that preferential flow pathways would not result in percolation, as the S_m and S_c are both estimated based on measurements from moisture sensors placed in the ET cover sections. The estimated required thickness of the cover can also be determined by the procedure outlined in Chapter 2 and utilizing the SWCC presented in Chapter 4. Results for the estimated required thickness of the storage layer vary between 4.4-ft to 6.9-ft, which is significantly more than the cover thickness of 3-ft utilized in this study. The range of estimated soil water storage was likely a result of changes in soil compaction during construction, variations in soil type (CH/CL soil was utilized), and/or preferential pathways. The variation in the estimated soil water storage capacity for several of the ET cover sections was a result of changes in the soil water storage when percolation was not measured throughout the monitoring period. This was likely a result of changes in the soil density observed during the monitoring period and the resulting change in the soil storage capacity of the cover system (discussection further in Section 5.4). It should be noted that these results are based upon preliminary performance monitoring during climatological conditions characterized by much greater than historic average precipitation.

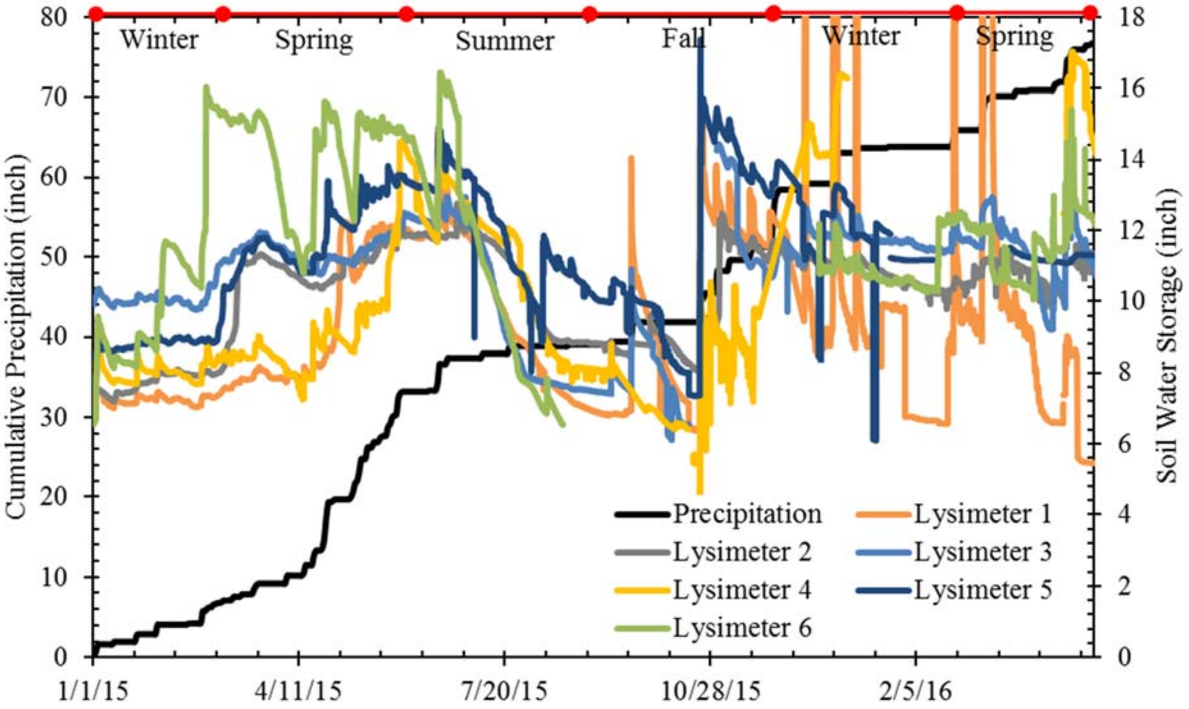

Figure 5.34: Comparison between soil water storage and cumulative precipitation.

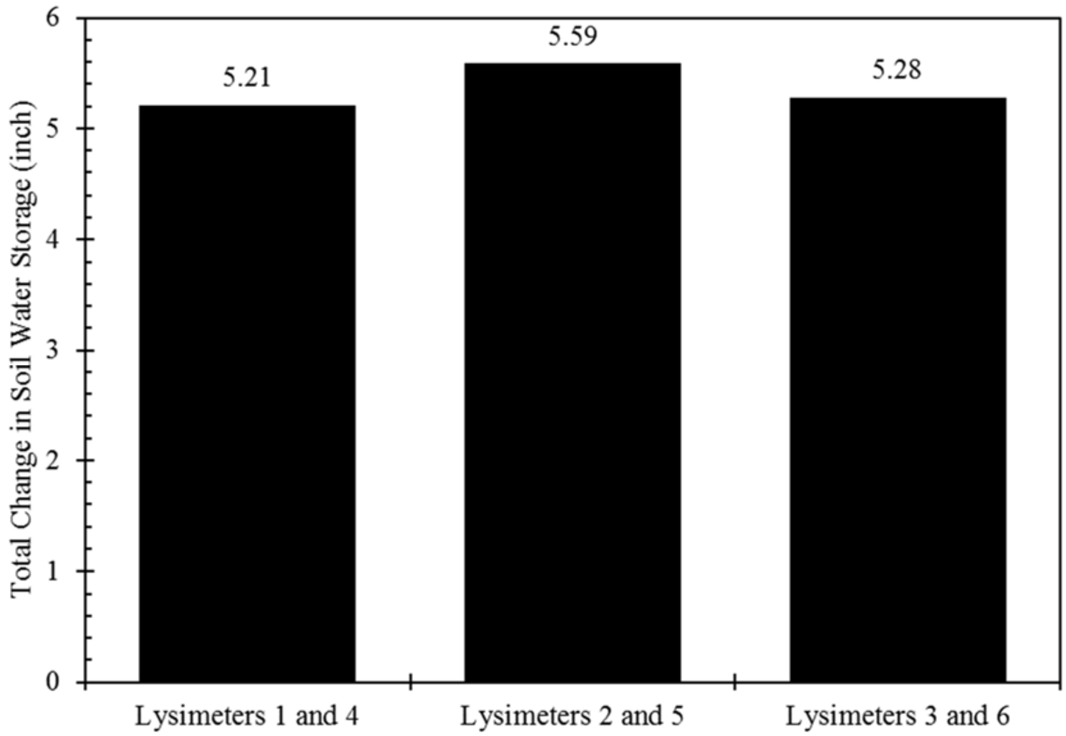

Figure 5.35: Comparison between total change in soil water storage for ET cover sections seeded with the same vegetation for the monitoring period.

Table 5.10: Change in soil water storage (inch) results for each time period and total.

ET Cover Section (Approximate Slope)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)	Total (1/1/15 to 5/2/16)
1 (2%)	4.52	-1.96	7.17	-11.71	-3.16	-1.67
2 (2%)	4.60	-2.25	1.85	-1.01	0.90	2.98
3 (2%)	1.32	-5.82	-5.22	-0.84	-0.97	1.21
4 (25%)	5.26	-2.02	5.64	N/A	N/A	6.87
5 (25%)	4.52	-2.47	-2.20	N/A	N/A	2.61
6 (25%)	5.30	N/A	NA	1.38	-0.04	4.07

Table 5.11: Summary of soil water storage for each ET Cover section.

ET Cover Section (Approximate Slope)	Estimated Soil Water Storage Capacity (inch)	Approx. Max. Measured Soil Water Storage (inch)	Estimated Required Thickness of Storage Layer (inch) [feet]	Estimated Required Thickness of Storage Layer based on SWCC (inch) [feet]
1 (2%)	7	16	82.3 [6.9]	64.3 [5.4]
2 (2%)	7.5 to 8.5	13	55.1 [4.6] to 62.4 [5.2]	52.2 [4.4]
3 (2%)	8	14.5	66.3 [5.4]	58.2 [4.9]
4 (25%)	8	16	72.0 [6]	64.3 [5.4]
5 (25%)	8.25 to 10	16	57.6 [4.8] to 69.8 [5.8]	64.3 [5.4]
6 (25%)	7	16	82.3 [6.9]	64.3 [5.4]

5.4 Vegetation and Cover Observations

Results, general discussion, and conclusions of the vegetation growth and cover observations at the surface of the cover system for the ET cover systems in each of the lysimeters is provided subsequently. The vegetation growth and cover observations could help to explain aspects of the ET cover system results and provide a greater understanding of performance of the ET cover systems.

The measured root depths for the ET cover sections in February of 2016 is provide in Table 5.12. The table is color coded such that cells with the same color were planted with the same vegetation (i.e., Lysimeters 1 and 4, Lysimeters 2 and 5, and Lysimeters 3 and 6). Holes in the cover systems were bored to obtain root depths and replace failed instrumentation. The holes were bored at the center of each ET cover section, and roots were observed and measured in these holes. The deepest root depth measured was 18-inches (Lysimeters 3 and 6) and shallowest was 7-inches (Lysimeter 5). It should be noted that the ET cover sections which had sod planted provided the deepest root depth.

The relatively shallow depth of roots measured in the ET cover systems could be a contributing factor for the relatively large amount of percolation measured. As discussed previously, roots have the ability to remove infiltrated water from the ET cover sections (transpiration). Therefore, a higher density and deeper roots will tend to increase the amount of infiltrated water that can be removed from the ET cover system. As vegetation becomes established and the roots grow deeper into the ET cover systems, it is expected that the quantity of percolation will decrease. However, it should be noted that the storage layer was compacted at a density which may be detrimental to root growth (i.e., the density of the storage layer may make it hard or impossible for roots to penetrate). This may result in the roots not penetrating deep into the cover system, and minimize the removal of infiltrated water by transpiration.

Table 5.12: Root depth measurements (2/27/2016).

Section	ET Cover Section	Root Depth (inch)
Top	1	13
	2	12
	3	14-18
Slope	4	13
	5	7
	6	13-18

During the root depth measurement procedure, it has been observed that there was a general decrease in the soil density in the ET cover systems when compared to during the initial instrumentation. At the end of the ET cover system and lysimeter construction, boring the holes for instrumentation installation was a time-consuming and difficult procedure even with a motorized augur (utilized for boring the holes). However, the auger had little difficulty boring into the cover sections during the February 2016 activities. Although this is not a quantitative measurement for the change in density, it should be noted that the density of the soil had apparently decreased from November 2014 to February 2016. This result corresponds to Anderson et al. (1993), who indicated a change in bulk density of a cover soil over time. The apparent change in soil bulk density relatively soon after construction suggest that the soil density of cover systems can change in a relatively short amount of time.

The general decrease in soil density when boring the holes in the ET cover section may lead to a higher hydraulic conductivity and could contribute to greater quantities of percolation. As indicated previously, fluctuations in the density of the cover during the monitoring period may occur because of the wetting and drying cycle in the soil. The wetting and drying cycle may cause shrinkage and swelling of the soil; therefore, resulting in the decrease in soil density when the soil swells and an increase in soil density as the soil shrinks. It is also possible that as the soil shrinks and swells, cracks or fissures may develop in the soil and could result in preferential flow channels. This would result in an increase in hydraulic conductivity, could cause greater amounts of infiltration deeper into the soil layer, and possibly result in percolation events.

The locations and pictures of several of the observed rodent burrows are provided in Figure 5.36, Figure 5.37, and Figure 5.38. The rodent burrows found in the ET cover systems may help explain the percolation events. Rodent burrows could act as preferential flow pathway for the precipitation to flow into the ET cover system and possibly increase the percolation. Additionally, it was found that the rodent burrows tend to be located near sturdy vegetation or berms. It is hypothesized that the sturdy/tall vegetation and/or berms were providing cover for the rodents from predators. Since rodent burrows may provide a potential preferential flow path for water to infiltrate into the cover system and sturdy vegetation and/or berms appear to provide cover for the rodents, it is tentatively recommended that sturdy/tall vegetation be removed from ET cover systems.

Cracking in the cover system has been observed (August 2016) in several of the ET cover sections (Figure 5.38). It was observed that the cracking occurred in areas of relatively minimal vegetation. It should be noted that these cracks generally develop in soil with high shrink/swell potential (similar to the soil placed in the storage layer) and do not typically occur in topsoil. Cracking and the resulting preferential flow pathways may cause greater infiltration and allow for runoff to directly flow into the storage layer. Without the vegetation preventing erosion of the topsoil, it is possible that the topsoil had been removed by runoff, exposing the storage layer to the atmosphere. However, extensive vegetation growth and the presence of topsoil in the majority of the study areas may have prevented cracks from being observed (although cracks may be present), and further investigation is required.

The Line-Point Intercept Method (see Chapter 2) was utilized to estimate the proportion of the ET cover sections covered by vegetation, rocks, litter, mosses, and others (total cover). Qualitative measurements (see photos provided subsequently) often accompany the quantitative measurement by the Line-Point Intercept Method as a result of the relatively large uncertainty associated with the method. A greater percentage of total coverage is correlated with greater soil and site stability. and a greater amount of obstructions to runoff (Herrick et al., 2009a). The total cover during the monitoring period (July 2015 to March 2016) for each ET cover section is provided in Figure 5.39, including an uncertainty of 20 percent[16].

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[16] Uncertainties included with the Line-Point Intercept methods were included based upon research conducted by Herrick et al., 2009. It should also be noted that the size of the lysimeters limit the amount

From the measurements and the associated uncertainty, the total coverage for all of the ET cover sections range between 64% to 100%. All of the ET cover sections showed an average cover of approximately 90%, with little variability between the cover sections. Additionally, there appears to be a trend of lower quantities of total coverage during the winter months; however, due to the uncertainty and the minimal variability, this cannot be concluded. The large total coverage for all of the ET cover sections suggest a stable soil and site stability (minimal amounts of erosions), and the vegetation is providing obstructions to minimize runoff. Additionally, this result suggest that the vegetation planted and growing on the ET cover systems are preforming well and that less successful vegetation would result in larger amounts of runoff. The predominance of vegetation in the cover sections corresponds to the qualitative results provided subsequently; however, the quantitative results are less conclusion in relation to the quantity of vegetation than the qualitative results. As stated previously, that may be related to the limited area measured by the Line-Point Intercept Method.

The percentage of bare ground was estimated by the Line-Point Intercept Method and is the proportion of the ET cover section not covered by vegetation, rocks, litter, mosses, and others. A smaller percentage of bare ground correlates to greater soil and site stability, and a greater amount of obstructions to runoff (Herrick et al., 2009a). The percentage of bare ground for each ET cover section is provided in Figure 5.40 and includes an uncertainty of 20 percent. The percentage of bare ground ranged between 0% to 36% based upon measurements and associated uncertainty. Similar to the total coverage results, the results indicate minimal amounts of erosion and relatively greater amounts of resistance to runoff.

Basal cover is the area just covered by plant bases and does not include rock cover and was estimated by utilizing the Line-Point Intercept Method. A smaller percentage of basal coverage correlates to less soil and site stability, and a smaller amount of obstructions to runoff (Herrick et al., 2009a). Additionally, greater basal coverage would tend to indicate the grasses are more predominate than shrubs, as shrubs tend to have smaller basal coverage when compared to grasses (Herrick et al., 2009a). The basal cover during the monitoring period (July 2015 to March 2016) for each ET cover section is provided

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of transits that can be completed, which would reduce the uncertainty. The uncertainty includes bias related to limited area studied by the method (along a line).

in Figure 5.41, including an uncertainty of 20 percent. From the measurements and the associated uncertainty, the basal cover for all of the ET cover sections range between 0% to 44%. The average basal coverage for the ET cover systems ranged between 8% to 18%, with Lysimeters 3 and 6 (vegetated with bermuda seed and sod) showing the greatest coverage. This result is expected as the sod was installed in half of the cover sections, providing a great amount of basal coverage from the beginning of the monitoring period. However, the uncertainty must be considered in relation to this conclusion. A seasonal basal coverage trend does not appear to be present in the quantitative results.

Monthly pictures from the corner of each lysimeter are provided in Figure 5.42 through Figure 5.56. General discussion and conclusions related to vegetation and cover observations on each of the lysimeters are provide subsequently.

Pictures from November and December of 2014 of the ET cover systems are provided in Figure 5.42 and Figure 5.43, respectively. Erosion control blankets, sod and switchgrass are present in all of the ET cover systems. It should be noted that for vegetation establishment purposes, the ET cover systems were irrigated during these months. Little time had passed from when the cover systems were planted so little growth has occurred. Ponded water on Lysimeter 3 was present in the sodded section (December 2014), likely a result of precipitation events that occurred during that time period and slight amount of subsidence in the ponded area. Ponded water on the cover system could result in greater quantities of infiltration, stored water, and possibly percolation if not removed from the cover system by ET.

Pictures from January, February, and March of 2015 of the ET cover systems are provided in Figure 5.44, Figure 5.45, and Figure 5.46, respectively. Low lying vegetation growth was present in all of the lysimeters (grass), with vegetation growing through the sodded sections. As indicated by Abichou et al. (2005), denser grass would result in more resistance to surface flow; therefore, resulting in less runoff. The lack of vegetation growth present on the cover likely would result in substantial amounts of runoff during precipitation events. This corresponds to the relatively large quantities of runoff measured during Period 1. Lysimeter 3 and 6 were sodded on half of each ET cover test section; therefore, runoff in these locations may be affected. The presense of sod during the first period of monitoring may lead to less runoff and therefore greater infiltration when compared to the other test sections that vegetation had yet to be established. The topsoil surface was relatively free of subsidence or ponded water. It should be noted that in March there appeared to be greater amounts of vegetation growth in the inclined sections when compared to the top sections. Greater amounts of vegetation were present in the ponded location in Lysimeter 3, indicative that water tended to pond in that location.

A relatively large amount of vegetation had grown from March to April (Figure 5.47). It was noted that there does seem to a higher density of vegetation present in the inclined sections when compared to the top sections, and the vegetation appeared to be taller. It is likely that the greater density of vegetation generally observed in the inclined sections had an effect on the runoff, as a greater density of vegetation could result in less runff and larger quantities of infiltration. Vegetation appeared to be very similar in all of the lysimeters, with very little of the planted vegetation present (with the exception of the sodded areas). It was indicated by Smesrud et al. (2012) that nearly all of the vegetation that was planted or seeded during construction were replaced over several years. However, it is important to note that native vegetation may take a relatively substantial amount of time to become established after seeding/planting.

The vegetation growth and height dramatically increased from April to May, especially in the top sections (Figure 5.48). It should be noted that the vegetation within the lysimeters was similar to what was observed outside of the study area. The vegetation seemed to be very similar in all of the lysimeters, likely a result of fast growing vegetation coming in from outside the lysimeters. The vegetation growing appeared to be a winter rye grass, which was planted as an erosion control measure surrounding the study area. The amount of vegetation growing within the lysimeters was likely to have an effect on runoff; therefore, affect the quantity of runoff, infiltration, and percolation. The dense vegetation likely minimized the amount of runoff and results in greater amounts of infiltration.

There was a noticeable change in the vegetation coloration in June and July of 2015 as the winter rye died off in the summer (Figure 5.49 and Figure 5.50, respectively). Based upon visual observation, all of the lysimeter appear to have nearly complete coverage of vegetation (both taller winter rye and low-lying grass are present). As a result of the high density of vegetation, runoff would have likely deceased and resulted in an increase in infiltration. It should also be noted that vegetation growth within the lysimeters was similar to outside of the lysimeters (growing on intermediate cover). In July there appeared to be greater amounts of taller vegetation present in the inclined sections. Qualtititative conclusions provided by the site visits and pictures coorespond with the quantititve measurements by the Line-Point Intercept Method.

The ET cover sections and vegetation present in August of 2015 is provided in Figure 5.51. Winter rye was still present, although seemed to had died several months ago. Vegetation in all of the lysimeters was very similar, with both low- and tall-growing vegetation. It should be noted that the inclined section lysimeters appeared to have a large amount of tall brush type vegetation and a greater density of taller vegetation growth. Subsidence was present in all of the lysimeters at this time, which likely had an effect on runoff and ponding of surface water.

Winter rye seemed to nearly not be present in December of 2015 (Figure 5.52), with much of the lysimeters covered solely by low-lying vegetation growth (grasses). There were patches of taller vegetation present in all of lysimeters, with similar vegetation growth in all of the lysimeters. It was observed that there appeared to be a substantial amounts of subsidence present throughout the lysimeters. The observed subsidence was likely a result of topsoil loss due to runoff (high intensity precipitation events occurred in October and November of 2015) or settlement. Subsidence could cause pooling of water and result in greater quantities of infiltration. It should be noted that the change in the soil water storage as a result of the subsidence (and resulting infiltration) would not be measured by the moisture sensors unless the subsidence is above or near the sensors.

In January of 2016, vegetation growth was similar to what was observed in December of 2015 (Figure 5.53). It should be noted that vegetation with thick stems were observed in all of the lysimeters (greater density in the inclined sections). It was also observed that there were rodent burrows present around the thick stemmed vegetation and near the berms. It was likely that the rodents are provided coverage with the berms and thick stemmed vegetation from predatory birds that have been seen at the site. Therefore, removal of thick stemmed vegetation during routine maintenance of ET cover system may minimize the presence of rodent burrows (as previously indicated, rodent burrows likely have a detrimental effect on the cover performance).

Figure 5.54 provides pictures of the ET cover systems from February 2016. The vegetation present at this time tended to be brown, indicating that it has gone dormant during the winter. This likely resulted in a decrease in transpiration; therefore, decrease the amount of water removed from the ET cover system. Similar to previous month, vegetation was mostly low-lying with patches of taller vegetation.

A dramatic change in the color of the vegetation present in the lysimeters was observed in March of 2016 (Figure 5.55). All of the ET cover systems were observed to have almost complete coverage of low-lying vegetation with little taller plant growth. It should be noted that greater amounts of subsidence were observed in all of the lysimeters.

Low-lying vegetation continued to provide almost complete coverage of all of the lysimeters, with very similar vegetation present in all of the lysimeters in (April of 2016) (Figure 5.56). It was observed that flowers were present in the lysimeters (with greater densities presents in Lysimeters 4 and 5). These type of flowing plant was likely growth from the seeds that were planted at the end of the construction phase (Lysimeters 1, 2, 4, and 5), as flowering plants were not present in the surrounding area. It has been noted in literature that native vegetation (which was planted) usually takes a year to begin growing, which is likely in this case.

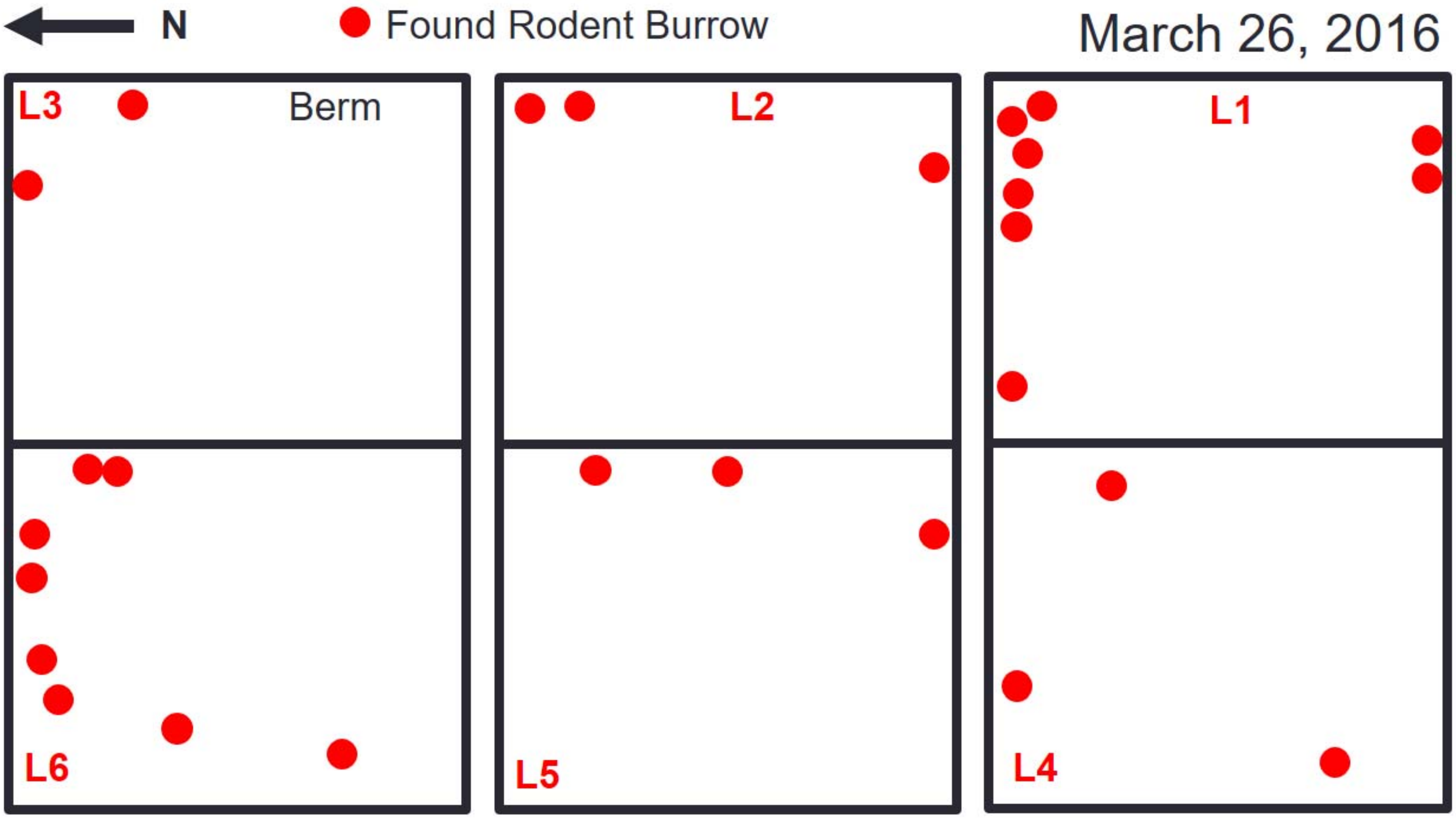

Figure 5.36: Identified rodent burrows – March 26, 2016

Figure 5.37: Rodent burrows – top row – December 2015, middle row – January 2016 and bottom row – March 2016

Figure 5.38: Rodent burrows and cracking – August 2016

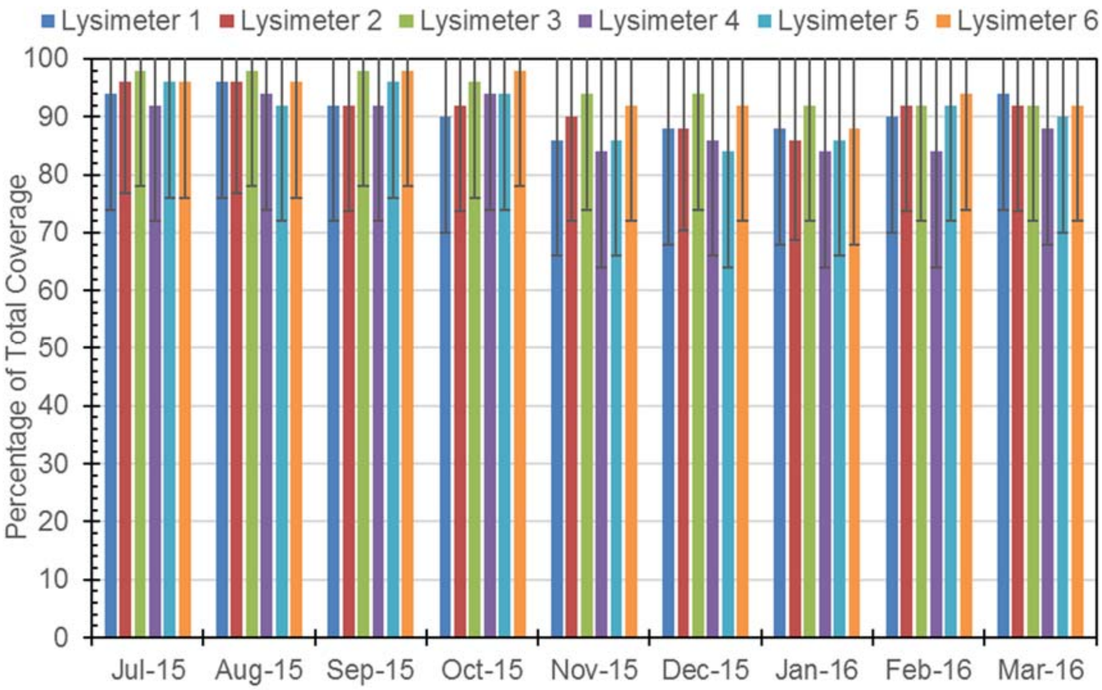

Figure 5.39: Percentage of total coverage estimated for each ET cover section by the Line-Point Intercept Method.

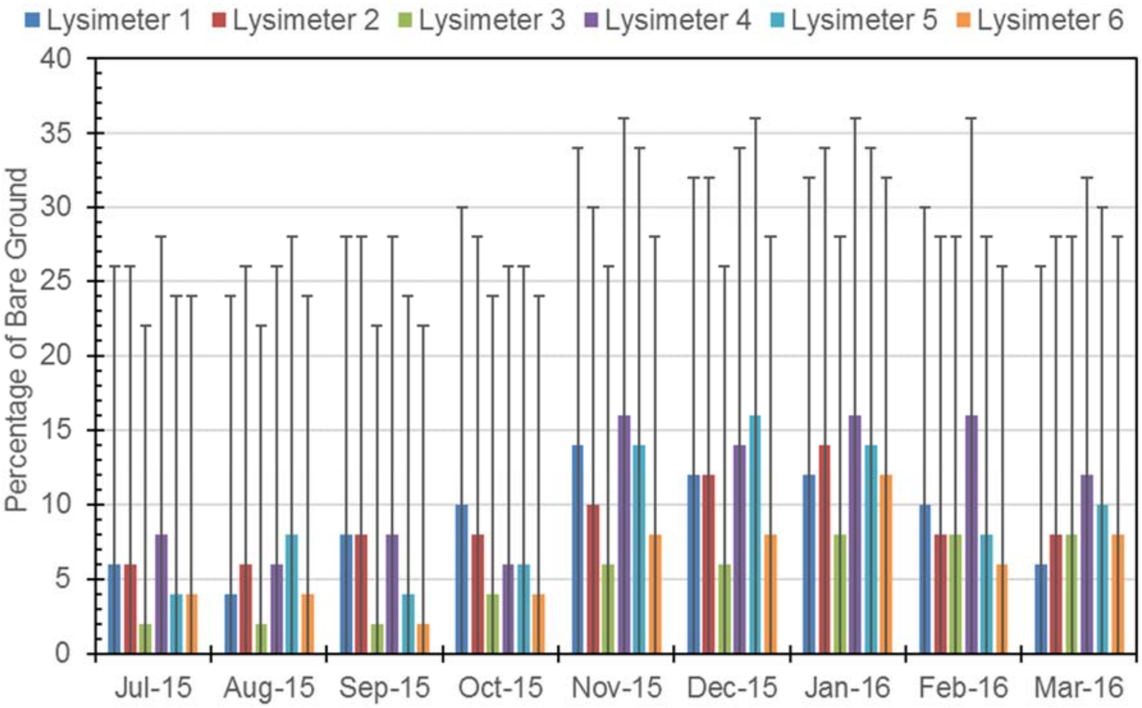

Figure 5.40: Percentage of bare ground estimated for each ET cover section by the Line-Point Intercept Method.

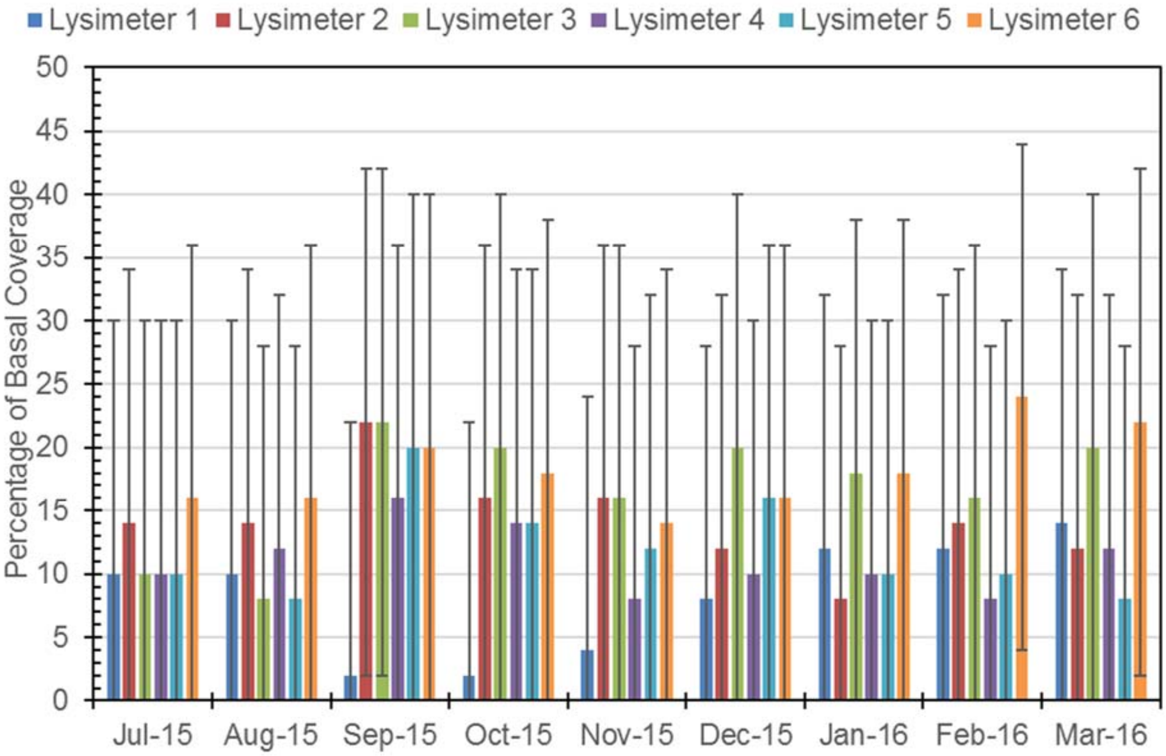

Figure 5.41: Percentage of basal coverage estimated for each ET cover section by the Line-Point Intercept Method.

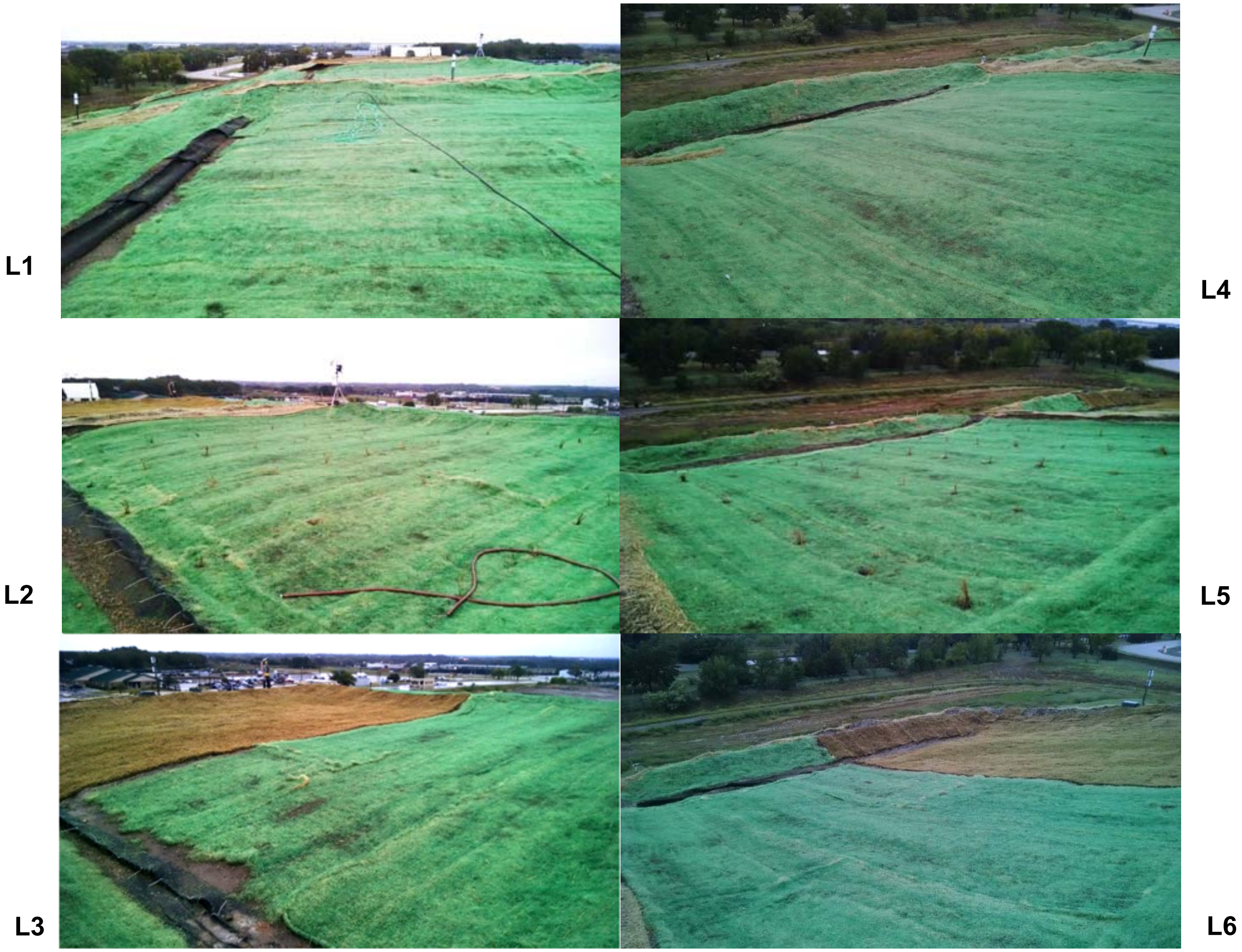

Figure 5.42: Vegetation details – November 2014

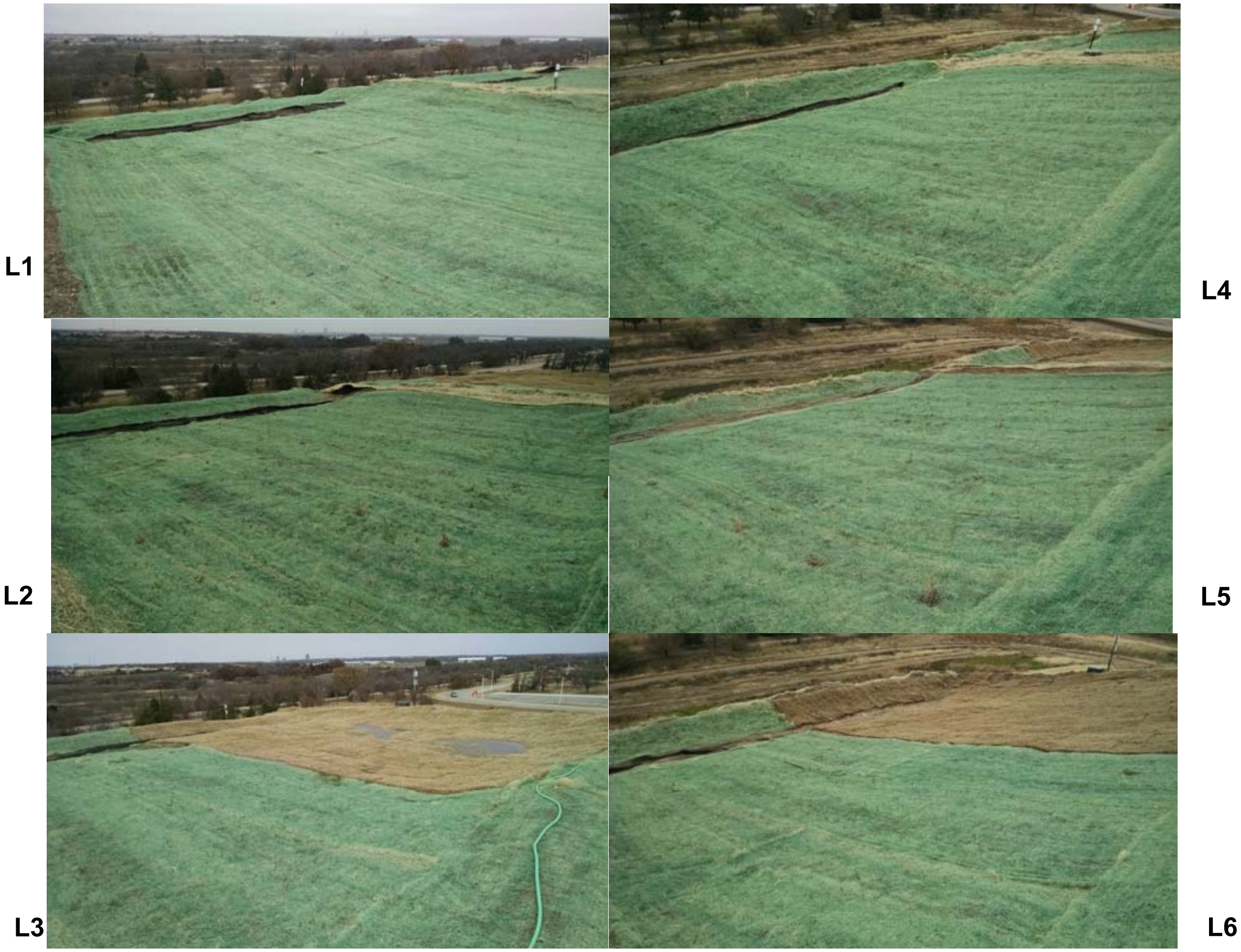

Figure 5.43: Vegetation details – December 2014

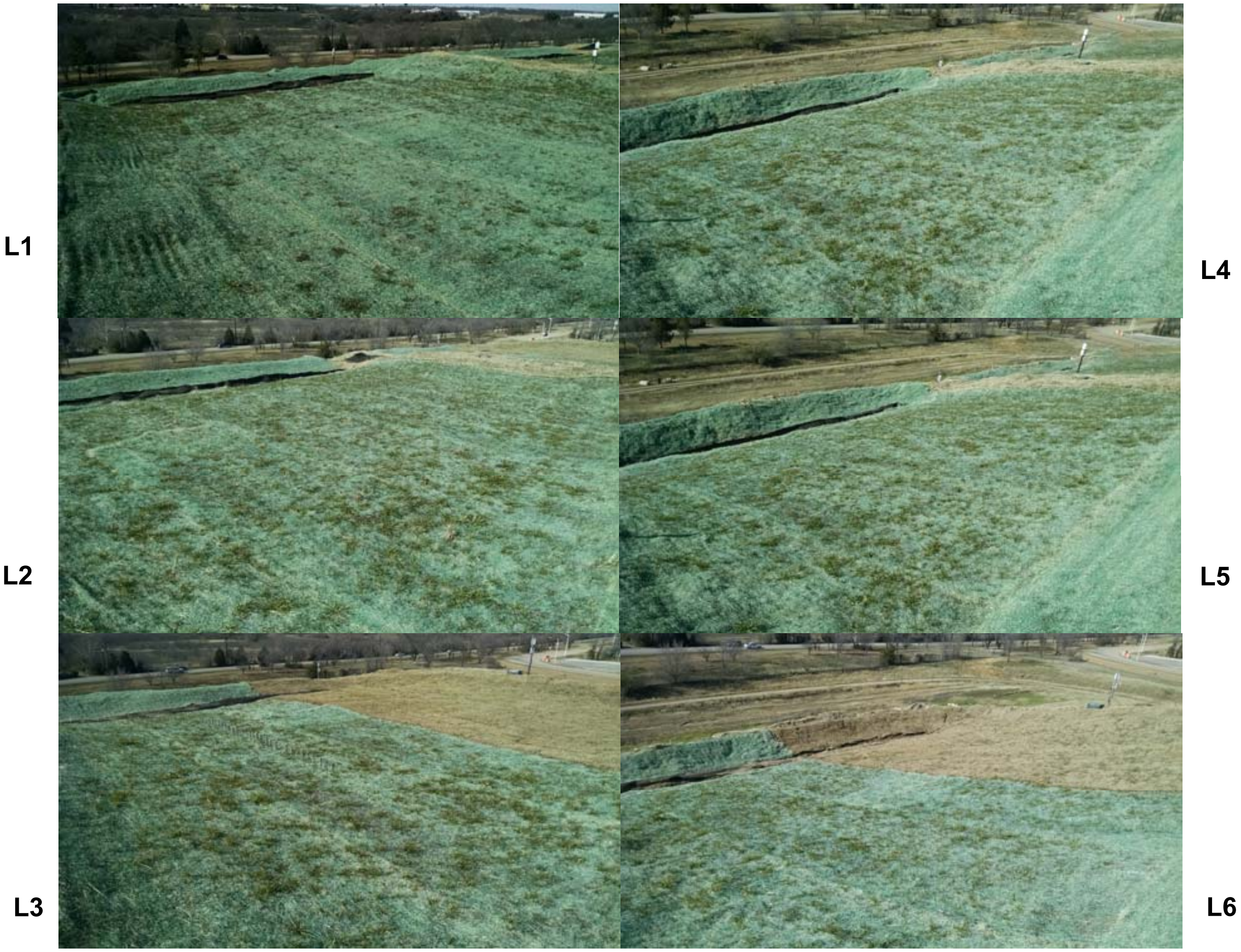

Figure 5.44: Vegetation details – January 2015

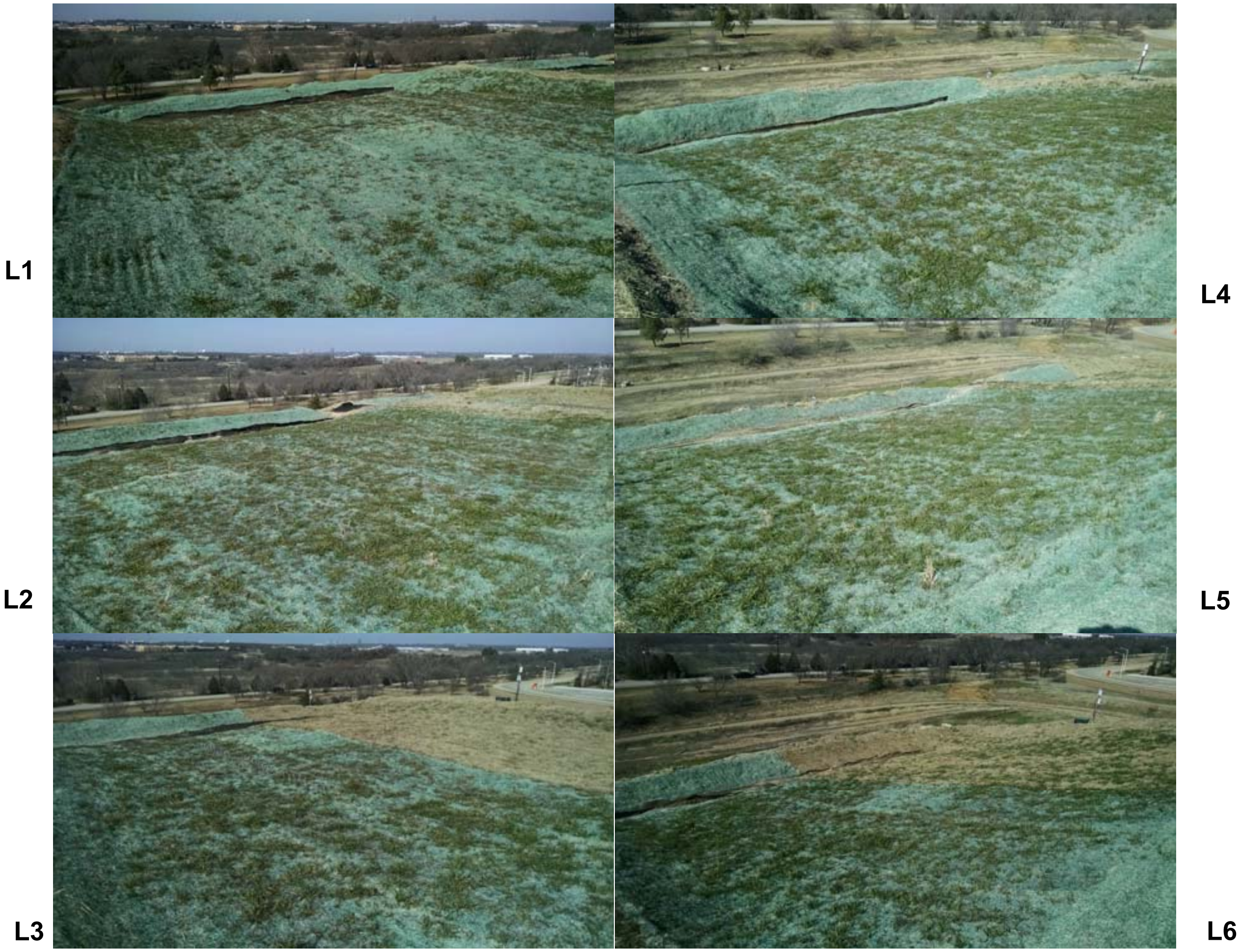

Figure 5.45: Vegetation details – February 2015

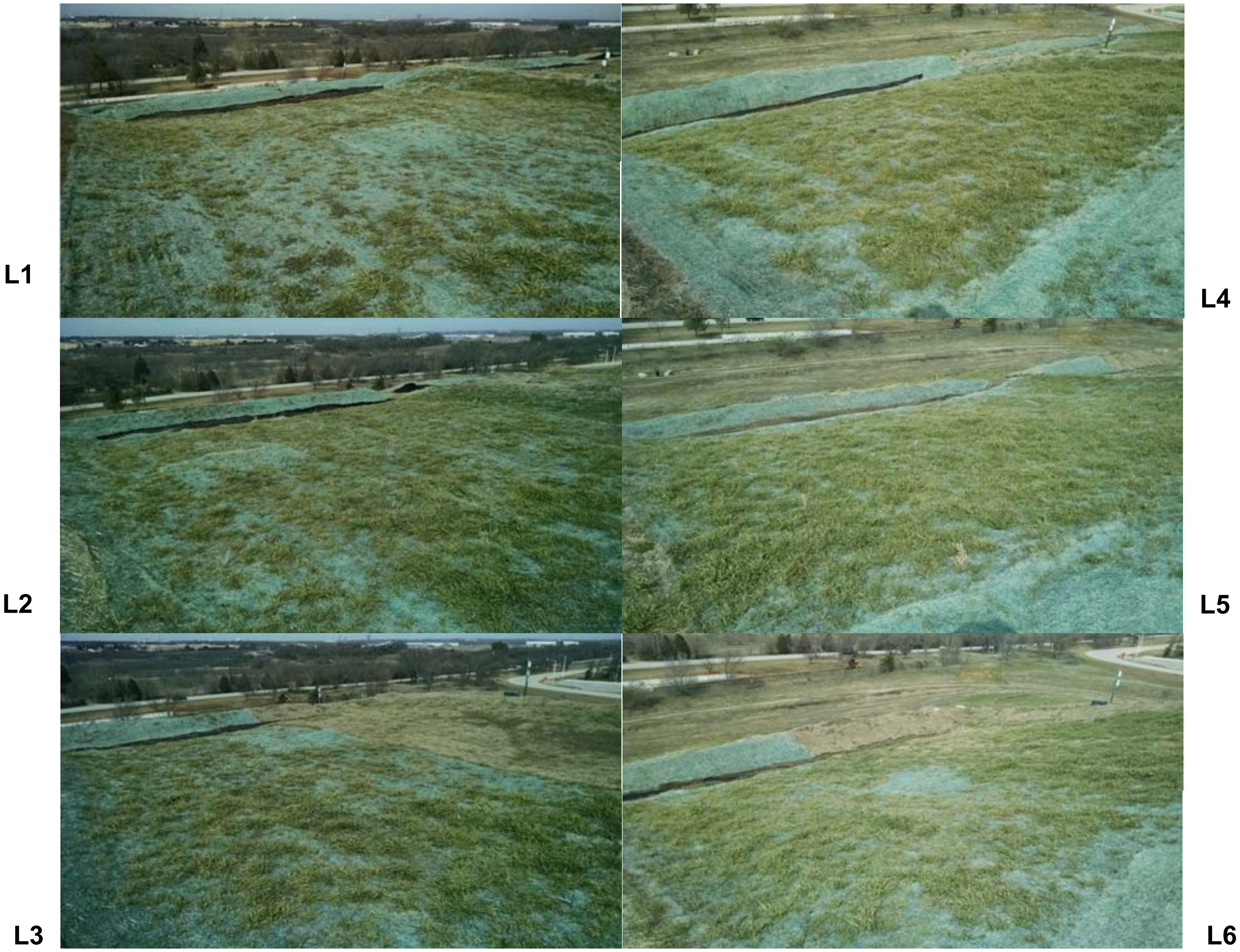

Figure 5.46: Vegetation details – March 2015

Figure 5.47: Vegetation details – April 2015

Figure 5.48: Vegetation details – May 2015

Figure 5.49: Vegetation details – June 2015

Figure 5.50: Vegetation details –July 2015

Figure 5.51: Vegetation details –August 2015

Figure 5.52: Vegetation details – December 2015


L1

L4

L2

L5

L3

L6

Figure 5.53: Vegetation details – January 2016

Figure 5.54: Vegetation details – February 2016

Figure 5.55: Vegetation details – March 2016

Figure 5.56: Vegetation details – April 2016

5.5 Climatological Monitoring

5.5.1 *Introduction*

As discussed in Chapter 2, the climatic conditions occurring at the site is one of the major contributing factors as to the performance of ET cover systems. Several climatic related factors are known to affect the performance of the evapotranspiration (ET) cover system, including the following:

- quantity and intensity of rainfall;
- air temperature;
- relative humidity; and
- wind speed.

Higher quantities of precipitation will tend to cause a greater amount water infiltrating into the ET cover system, and as a result tend to increase the amount of percolation (provided the water is not removed from the soil by ET).

5.5.2 *Precipitation*

Percolation measured at the site throughout the ET cover system monitoring period is provided in Figure 5.57 and Figure 5.58. Approximately 79.85 inches of measured precipitation was measured at the site since the end of construction (76.72-inches since January 1, 2015), with the historic average for Denton being 49.43 inches (since January 1, 2015). It should be noted that the quantity of precipitation measured at the site was approximately 27.29 inches greater than historic average. As shown in the figure, relatively large quantities of precipitation have been measured during both spring of 2015 and 2016, and the 2015 and 2016 winters (Periods 1, 3, and 5). A relatively long dry period during summer/fall of 2015 (Period 2) and a relatively short dry period were observed in winter of 2015/2016 (Period 3). As discussed previously, the large quantity and high frequency of precipitation that has been measured at the site was likely a major contributing factor in the relatively large quantity of percolation that has been observed (discussed in greater detail previously). It is suggested by the percolation and soil water storage results that the dry periods were not able to remove adequate quantities of water stored in the cover systems to prevent substantial quantities of percolation.

Figure 5.59 and Table 5.13 provide precipitation intensity throughout the ET cover system monitoring period. It should be noted that the greatest precipitation intensity measured at the site was 23 inches/hour. Almost all of the precipitation intensity results were below 3-inches per day (99.8%), with the majority being between 0 to 1-inch (77.6%). Precipitation was measured for 33.0%, 6.6%, 25.0%, 7.0%, and 27.9% of the days for Periods 1, 2, 3, 4, and 5, respectively. Therefore, Periods 1, 3, and 5 has substantial amounts of precipitation events (wet periods), while Periods 2 and 4 had comparatively small (dry periods). Additionally, greater than 1-inch of precipitation was measured 6.5%, 1.9%, 7.8%, 1.8%, and 4.4% of the days during Periods 1, 2, 3, 4, and 5, respectively. Therefore, periods of relatively high intensity precipitation (greater than 1-inch per day) correspond to periods of substantial amounts of precipitation events. Periods 2 and 4 (dry periods) almost identical amounts of high intensity precipitation days. As discussed in Chapter 2, a high intensity rainfall events will tend to cause greater runoff and result in less amount of infiltration into the ET cover system. Therefore, high intensity rainfall events will tend to decrease the amount of water stored in the cover and could result in a greater amount of percolation. These results provide quantitative values to discussion stated in the previous sections.

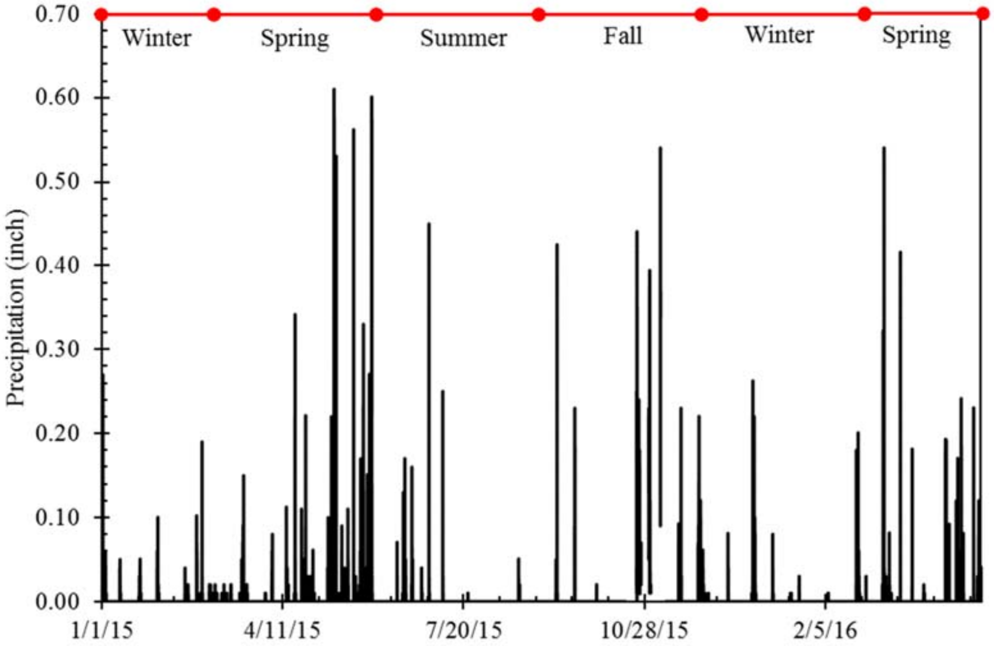

Figure 5.57: Site precipitation (site specific).

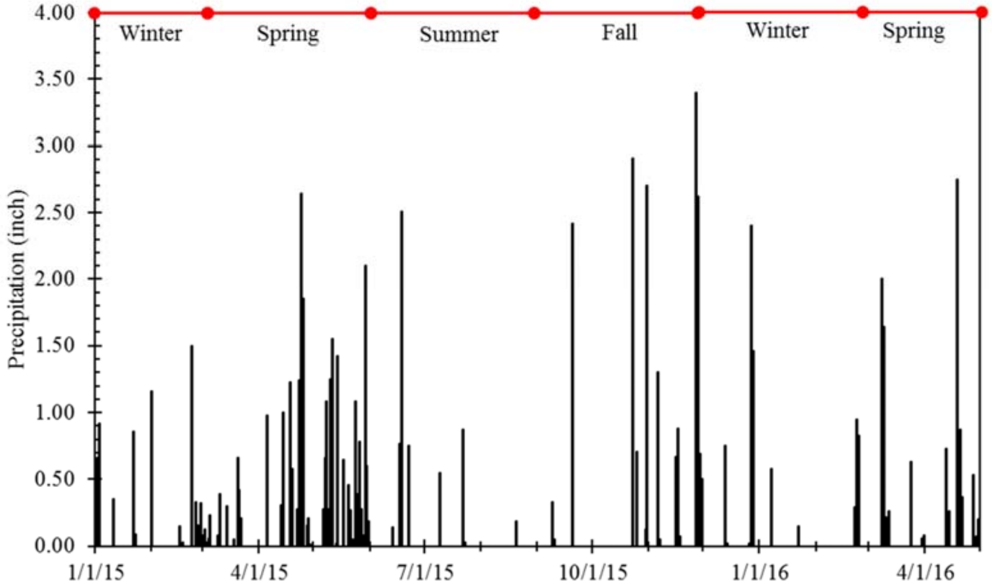

Figure 5.58: Site precipitation (NOAA).

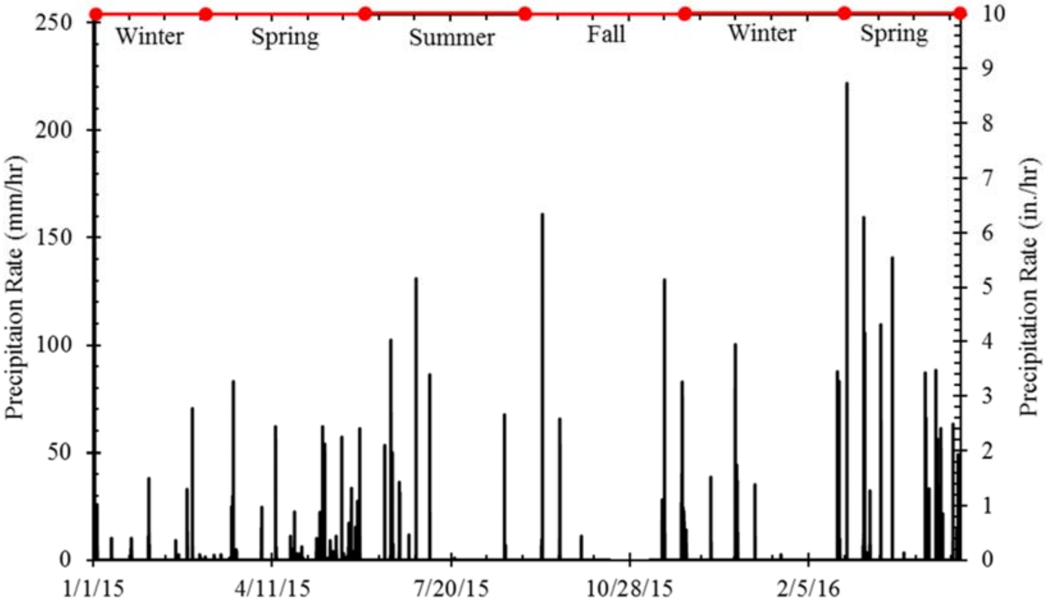

Figure 5.59: Site precipitation rate (site specific).

Table 5.13: Daily precipitation [percentage] results for each time period (NOAA).

Daily Precipitation (inch)	Period 1 (1/1/15 to 7/10/15)	Period 2 (7/11/15 to 10/24/15)	Period 3 (10/25/15 to 12/27/15)	Period 4 (12/28/15 to 2/22/15)	Period 5 (2/23/16 to 5/2/16)	Total (1/1/15 to 5/2/16)
0	128 [67.0]	99 [93.4]	48 [75.0]	53 [93.0]	49 [72.1]	377 [77.6]
0 < P ≤ 1	50 [26.2]	5 [4.7]	11 [17.2]	3 [5.3]	16 [23.5]	85 [17.5]
1 < P ≤ 2	10 [5.2]	0 [0.0]	1 [1.6]	1 [1.8]	2 [2.9]	14 [2.9]
2 < P ≤ 3	3 [1.6]	2 [1.9]	3 [1.8]	0 [0.0]	1 [1.5]	9 [1.9]
3 < P ≤ 4	0 [0.0]	0 [0.0]	1 [1.6]	0 [0.0]	0 [0.0]	1 {0.2]
5 < P	0 [0.0]	0 [0.0]	0 [0.0]	0 [0.0]	0 [0.0]	0 [0.0]
Total	191	106	64	57	68	486

5.5.3 *Atmospheric Temperature*

Atmospheric temperature measured at the site (top of the landfill) throughout the monitoring period is provided in Figure 5.60. It is shown that there is a typical fluctuation in atmospheric temperature with the changes in the season. The measurements show lower temperatures throughout the winter and higher temperatures throughout the summer.

As discussed in Chapter 2, lower atmospheric temperatures will tend to decrease the amount of potential ET; therefore, will tend to decrease the amount of water removed from the ET cover system. Therefore, greater amounts of water will tend to be removed from the cover system during the summer when compared to the winter. It has been observed that the soil water storage in the ET cover sections decreased during the summer of 2015 (Period 2) when temperatures were relatively high (causing an increase in evaporation), suggesting that ET and specifically evaporation is a major cause of water removed from the cover system.

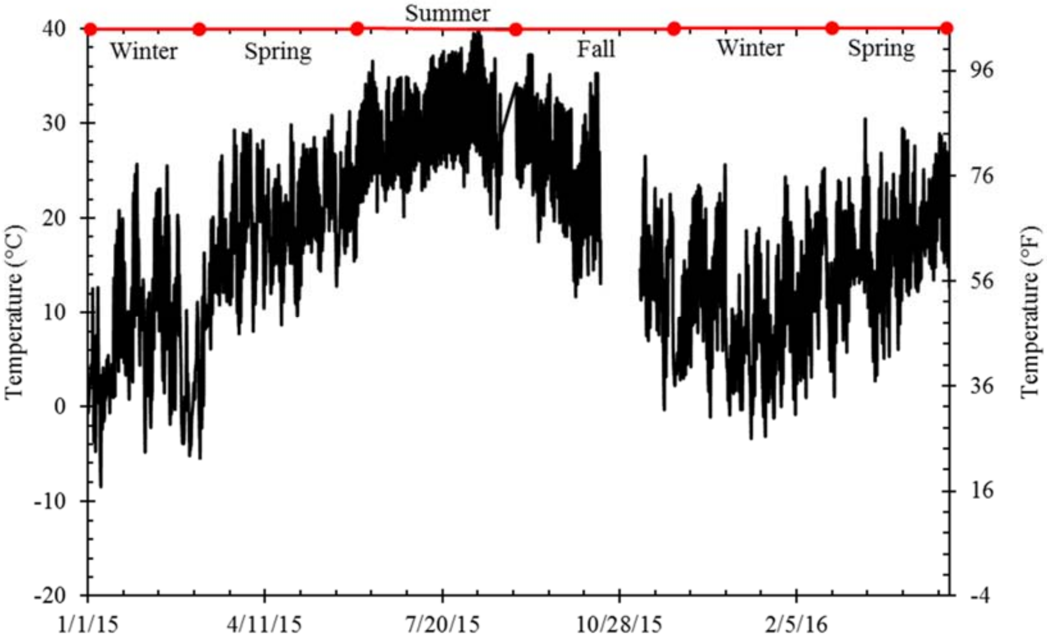

Figure 5.60: Atmospheric temperature (site specific).

5.5.4 *Relative Humidity*

Figure 5.61 provides the relative humidity measured at the site throughout the monitoring period. There does not appear to be an apparent trend in the data; however, there does appear to be slight tendency for relative humidity to be lower at the end of the summer of 2015 (Period 2).

As discussed in Chapter 2, ET will tend to be larger when relative humidity is low. The general trend of lower relative humidity observed during Period 2 could have caused an increased rate of potential ET, which could have resulted in the general decrease in soil water storage observed in the ET cover systems.

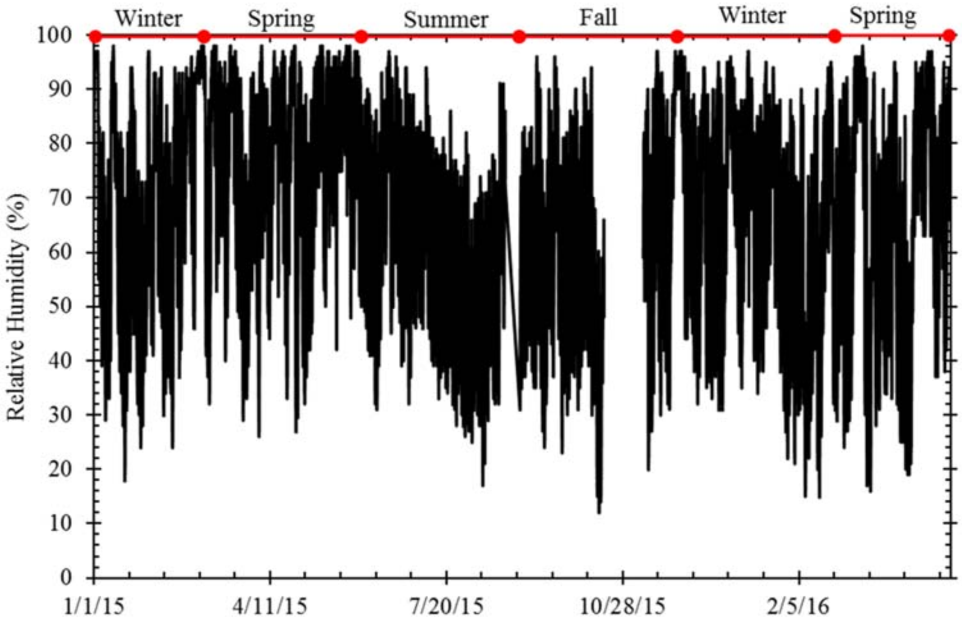

Figure 5.61: Relative humidity.

5.5.5 *Wind Speed and Direction*

The wind speed and wind direction measured throughout the monitoring period at the site is provided in Figure 5.62 and Figure 5.63, respectively. Wind speeds at the top of the landfill near the lysimeters were generally between 0 and 20 mph, with relatively little time with no wind. Wind speeds significantly fluctuated with time; however, there did not appear to be trends for each season. The average wind speed measured was approximately 7.2 mph and the maximum wind speed measured was 55 mph. The wind direction has been measured predominantly from the south and east, with the inclined section facing west.

Higher wind speeds and constant wind at the site will tend to increase the amount of water in the ET cover system removed by ET. The predominance of wind blowing from the south and east may result in less wind flowing across the inclined sections as the landfill may act as a wind barrier. This could result in less potential ET in the inclined sections and possibly result in greater percolation.

Nyhan (2005) indicated an annual trend for evaporation to decrease with a decrease in slope, and Nyhan et al. (1997) suggest that this was likely a result of larger slopes intercepting greater amounts of solar radiation when compared to shallower slopes.

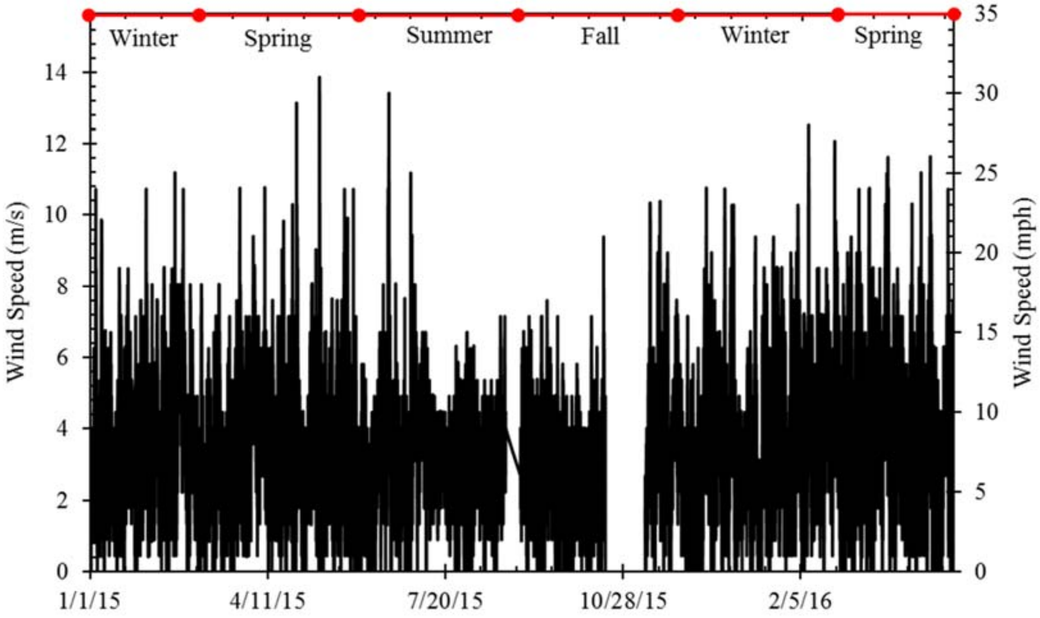

Figure 5.62: Wind speed

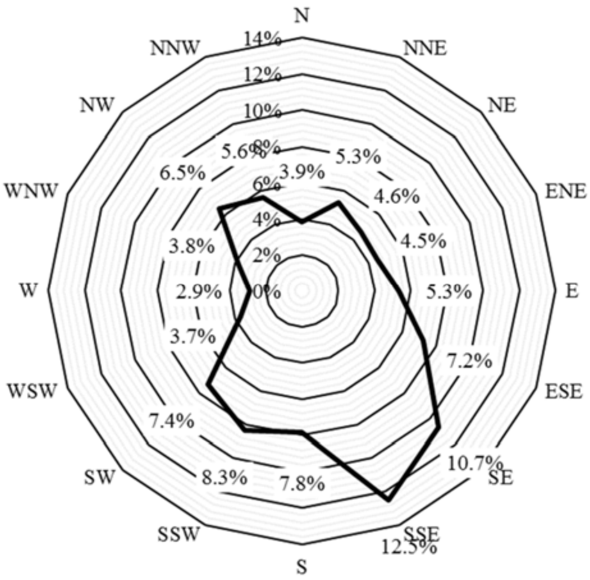

Figure 5.63: Wind rose

5.6 Summary and Synopsis

The results, trends, summary, and conclusions from the evapotranspiration (ET) cover systems tested within six (6) 40-ft by 40-ft lysimeters (as described in Chapter 4) have been discussed in this Chapter. Many factors can have an effect on the performance of ET cover system (see Chapter 2) and have been incorporated into the discussion. Preliminary percolation results do not appear to be encouraging for the performance of the cover systems, with all the ET cover systems producing substantial amounts of percolation. However, it is important to note the following:

- The results are from the short-term performance of the ET cover systems.
- There has been a large quantity of precipitation measured during the monitoring period, much greater than the historic average.
- Vegetation appears to be established; however, the roots have not been observed to extend to a great depth within the cover systems.
- Desiccation cracking and rodent burrows have been found in the cover systems, and may have resulted in preferential pathways for water to easily infiltrate into the cover system.

The ET cover systems will continue to be evaluated and their performance evaluated over a greater amount of time.

Chapter 6

Conclusions and Recommendations

6.1 Introduction

Short-term (1.3-years) performance assessment of ET cover systems at the City of Denton Municipal Solid Waste Landfill has been conducted in this study. The hydraulic and vegetation performance assessment of the ET cover systems was monitored in the field using six (6) 40-ft x 40-ft lysimeters. General conclusions and recommendations based upon this study are provided subsequently. ET cover sections vegetated with the mixture of bermuda sod and seed resulted in the lowest quantity of percolation; therefore, it can be preliminary concluded to provide the best performance. However, preliminary percolation results do not appear to be encouraging for the performance of the cover systems based upon TCEQ requirements, with all the ET cover systems producing substantial amounts of percolation. A number of factors must be acknowledged when considering this conclused, stated as follows:

- The results are from the short-term (1.3-years) performance of the ET cover systems;
- There has been a large quantity of precipitation measured during the monitoring period, much greater than the historic average;
- Vegetation appears to be established; however, the roots have not been observed to extend to a great depth within the cover systems;
- Desiccation cracking and rodent burrows have been found in the cover systems, and may have resulted in preferential pathways for water to easily infiltrate into the cover system; and
- Previous studies have indicated that it is difficult to obtain low quantities of percolation (less than 4 mm/year) in non-arid regions such as in the City of Denton.

6.2 Summary of Current Study

General results, discussion, and conclusions from monitoring the ET cover system in this study are provided as follows:

- Gradual increases were observed in soil water storage corresponding to times of relatively frequently precipitation events. The gradual increases in the measured soil water storage suggest that the water from frequent precipitation events was infiltrating into the cover soil layer, resulting in an increase in volumetric moisture content measured in the sensors placed in the storage layer.
- Sharp spikes (increases) in the soil water storage have been observed throughout the monitoring period for all of the ET cover systems. The sharp spikes (increases) in water storage may be a result of the high frequency of relatively large precipitation events and the resulting water infiltrating in the ET cover system. Additionally, the sharp spikes (increases) observed in the water storage could be a result, in at least a small part, of the moisture sensors placed at the topsoil/storage layer boundary. The relative ease that the precipitated water could infiltrate through the topsoil (high hydraulic conductivity) and reach the top of the storage layer (where it was measured by that sensor) could have caused the spikes in the measured water storage shortly after precipitation events. This conclusion corresponds with results from individual moisture sensors, where sensors located at the topsoil/storage layer boundary tended to measure an increase in volumetric moisture content shortly after precipitation events. Additionally, the sensors installed at a depth of 9-inches into the storage layer tended to measure an increase in volumetric moisture content following the increase in the moisture content observed in the sensor at the topsoil/storage layer boundary. Sensors located at deeper depths into the storage layer (at a depth of 18-inches and 27-inches) tended to measure general increases and decreases in moisture content, likely as a result of general climatological and ET conditions (e.g., frequent precipitation events). The volumetric moisture content changes measured in the sensors located throughout the storage layer were observed to be consistent in all of the ET cover systems.

- Sharp spikes (decreases) in the soil water storage have also been observed in the ET cover sections. These sharp spikes (decreases) suggest severe desiccation has occurred in the ET cover system, and ET removing water from the cover.
- It was observed in several of the ET cover sections that the quantity of water stored in the cover system at times when percolation was not measured changed throughout the monitoring period (indicative of a change in storage capacity). This could be a result of natural pedogensis processes such as insect and animal burrowing, wet-dry cycling (and resulting shrinking and swelling), changes in soil density, and/or plant root growth. Further investigation will be required prior to determine if this is hypothesis can be proven correct or incorrect.
- During times of infrequent precipitation and high potential ET, decreases in water storage and little percolation were measured in the cover systems. It is likely that the water stored in the cover system was being removed solely by ET during these dry and high potential ET time periods.
- Several of the cover sections showed a decrease in soil water storage during times of frequent precipitation events, during which time an increase in soil water storage would be expected. During these times, a large amount of percolation was measured; suggesting that the rate of removal of water by ET and percolation was greater than the rate at which water was infiltrating into the cover system.
- Throughout most of the monitoring period (in the all of the ET cover systems), the measured soil water storage has been observed to be greater than the estimate soil water storage capacity. This was likely a result of the high quantity of precipitation which occurred since monitoring began and the lack of vegetation root growth deep into the cover systems, minimizing the depth of water removal by transpiration.
- Different quantities of water storage measured at the beginning of the monitoring period was likely a result of varying amounts of water applied during the construction and irrigation phase.

- Percolation results indicate that soil water storage conditions prior to periods of high or low precipitation can significantly affect the quantity of percolation (i.e., little percolation may occur if the cover soil is completely dry followed by a period of frequent precipitation, or large amounts of percolation may occur if the cover soil is saturated followed by a period of relatively infrequent precipitation).
- The measured soil water storage in the inclined sections were generally greater than the top sections. This is likely a result the generally lower quantities of runoff measured in the inclined sections, resulting in a greater amount of infiltrated water.
- Delayed increases in soil water storage after precipitation events have been observed in the ET cover systems. This was likely caused by the low hydraulic conductivity of the storage layer (compacted clay layer) that should have required relatively large amounts of time for infiltrated water to flow through.
- Large and frequent precipitation events were measured during the monitoring period and correspond to large increases in the soil water storage in the cover systems.
- The average, minimum, and maximum percolation as a percentage of precipitation was 5.6%, 0.7%, and 12.8%, respectively.
- Issues and constraints related to the use of lysimeters for cover monitoring purposes which may affect percolation results include: 1) preferential flow along the sidewall of the lysimeters, 2) greater amounts of infiltration from the runoff collection system, and 3) the geomembrane at the bottom of the lysimeter preventing interaction between the waste system and the soil cover that would be present in an in-place cover system. The first and second constraints were minimized or eliminated during the construction of the lysimeters. Bentonite was placed along the sidewalls of the lysimeters which should prevent the preferential flow, and geomembrane was placed beneath the runoff collection system that should prevent additional infiltration from the runoff collection system. The third item cannot easily be prevented if percolation through the cover system is to be directly measured by these types of monitoring systems.

- The relatively high rate of percolation may be a result of high amounts and frequency of precipitation, minimal root penetration into the storage layer, rodent burrows, shrink/swell of the clay, preferential channels, and inadequate soil water storage capacity. Percolation events tended to occur during times when the measured water storage was greater than the estimated storage capacity of the soil; therefore, it follows that a relatively large quantity of percolation was measured (water storage was greater than the capacity for the majority of the monitoring period).
- Each of the set of lysimeters were constructed as identical as construction would allow and detrimental effects (i.e., rodent burrows and desiccation cracking) that would be present during a final landfill cover system; therefore, a comparison between ET cover sections seeded with the same vegetation can provide reliable conclusions. The measured percolation indicate that the ET cover sections vegetated with bermuda sod and seed (Lysimeters 3 and 6) reduced the total quantity of percolation by 0.53-inches and 1.2-inches for Lysimeters 2 and 5 and Lysimeter 1 and 4, respectively. Therefore, it can be concluded that the ET cover vegetation with bermuda sod and/or seed will provide the greatest performance in comparison to the other vegetation mixes.
- Percolation immediately following construction and being independent of precipitation and irrigation has been observed in the ET cover systems. This was likely a result of the cover systems being at a near-saturated condition during construction and compaction causing consolidation of the clayey cover soil.
- Results suggest that percolation events during the start of the monitoring period may be significantly affected by differences in the moisture content of the soil during the construction and irrigation phase (if applicable). Additionally, these results indicate the a substantial wet or dry period may be required to produce reliable and representative ET cover performance results.
- Yearly percolation results suggest that the presence of rodent burrows and desiccation cracking observed the second year of monitoring could produce greater quantities of

percolation. Additionally, quantities of water stored in the cover at the end of the year can substantially affect percolation results.

- The large quantity of precipitation that occurred during the monitoring period (approximately 27.22-inches greater than the historic average) could help to explain the relatively large amount of percolation measured in all of the ET cover systems.
- Percolation following shortly after precipitation events has been observed in the ET cover systems and could be caused by root channels, desiccation cracking, and/or rodent burrows penetrating the cover system. It is likely that desiccation cracking occurred during the drying of the cover system and resulted in the percolation that was measured shortly after precipitation during the periods after drying. Additionally, the tensiometers and moisture sensors showed that the soil was at or near saturated conditions during most of the monitoring period, and additional water infiltrated into a saturated cover system should theoretically result in a percolation event.
- A relatively uniform rate of percolation has been observed for the ET cover systems. This could be indicative of flow through the soil matrix (i.e., not through preferential flow paths).
- It has been suggested by the effective hydraulic conductivities and percolation results from this study that low effective hydraulic conductivities can be incorporated into the ET cover systems and still result in relatively high quantities of percolation.
- Measured percolation for the inclined sections have been observed to tend to be greater than the top sections.
- The average, minimum, and maximum runoff as a percentage of precipitation was 52%, 0%, and 97%, respectively.
- Higher intensity precipitation events tended to cause large amounts of runoff and the site had experienced many percolation events over 1-inch/hour with a maximum rainfall rate measured of 23-inches/hour.
- Incorporating a runoff collection system that is located along the entire width and at the lowest point of the lysimeters should allow for a substantial runoff capture rate. The substantial runoff capture rate may have resulted in the relatively large quantity of runoff

that was measured during the monitoring period. The runoff collection system also incorporated a geomembrane liner below the burrito wrap which was designed to prevent runoff from infiltrating into cover system in the vicinity of the collection system.

- Measured runoff for the inclined sections have been observed to tend to be lower than the top sections. This result suggests that the slope of the cover system may not play as critical role in the quantity of runoff as previously indicated in Chapter 2.
- The relatively large amounts of runoff measured during Period 1 when vegetation had yet to be established would suggest that the establishment of vegetation is critical factor affecting the quantity of runoff.
- The apparent effect of season vegetation changes on runoff was evident when comparing runoff results from Periods 2 and 4, where infrequent precipitation was measured during both time periods. The infrequent precipitation during Period 2 (during spring and summer when there was a dense growth of vegetation) had high intensity precipitation and Period 4 (during winter and vegetation dormancy) had low intensity precipitation. This would suggest that the predominate vegetation during Period 2 provided greater resistance to runoff than during Period 4 when the vegetation was dormant. Greater differences in runoff quantities for periods of greater precipitation when compared to less precipitation suggest that more precipitation events result increase the effect that changes in vegetation has on the amount of runoff.
- As of July 30, 2016, two (2) ETgage™ have been placed on the site, one (1) on the inclined section between Lysimeters 4 and 5, and another on the top section between Lysimeter 1 and 2. Measured ET from the two (2) ETgage™ correspond to results estimated based on the ET cover system results where greater ET was observed in the inclined section when compared to the top sections.[17] Additionally, these results suggest that ET can significantly vary (4.5-inches) within a short amount of time (70-days), within a short distance (approximately 60-feet), and based on location/slope on a landfill.

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[17] ETgage™ results are outside the monitoring period and for a relatively short amount of time compared to the study period.

- The gradual increase in water storage during Period 1 could be attributed to precipitation events occurring relatively frequently during this time period, with greater increases in the measured water storage when the frequency of precipitation increased.
- The gradual decrease in water storage over Period 2, was likely a result of ET (as vegetation was becoming established during this period) removing the water stored in the cover system during the summer and early fall of 2016.
- The percolation and decrease in soil water storage measured in the lysimeters during Period 3 (during a period where frequent precipitation events were observed) suggest that water was being removed from the ET cover systems by both percolation and ET.
- Generally, measured high soil water storage corresponded to times when percolation was measured, and suggest that percolation was flowing through the soil matrix.
- Results for the estimated required thickness of the storage layer vary between 4.4-ft to 6.9-ft, which is significantly more than the cover thickness of 3-ft utilized in this study. The range of estimated soil water storage was likely a result of changes in soil compaction during construction, variations in soil type (CH/CL soil was utilized), and/or preferential pathways.
- Variations in the estimated soil water storage capacity for several of the ET cover sections as indicated by changes in the soil water storage when percolation was not measured throughout the monitoring period. This was likely a result of changes in the soil density observed during the monitoring period and the resulting change in the soil storage capacity of the cover system.
- It was observed that the inclined sections (Lysimeter 4, 5, and 6) have greater cumulative measured ET when compared to the top sections (Lysimeters 1, 2, and 3). As the cumulative ET was estimated based on the other measured parameters, these results were likely caused by a number of components as discussed previously. However, the larger amount of estimated ET in Lysimeter 4 and 5 than the other ET cover sections was likely a result of smaller quantities of runoff measured. This result corresponds with observations made by Nyhan et al. (1997). Nyhan et al. (1997) observed that evaporation tended to increase with an increase in slope, suggesting that this result was likely because large

slopes can intercept greater amounts of solar radiation when compared to shallower slopes. Additionally, the quantity and speed of the wind flowing across the top and inclined section on the landfill may vary, resulting in variation in the evaporation. Both the PET and estimated ET results for all of the ET cover section followed seasonal trends, where PET and estimated ET was at a maximum during summer and minimum during the winter.

- The calculated ET as a percentage of PET when considering the periods ranged from 9.0% to 90.8%, with an average of 47.3%. This wide range of values was likely a result of multiple factors which have an effect on runoff, percolation, precipitation, and soil water storage. It was observed that during Periods 2 and 4 (periods of low precipitation) that the PET tended to overestimate the estimated ET, as the average estimated ET for each period was 55% (Period 1), 36% (Period 2), 57% (Period 3), 38% (Period 4), and 46% (Period 5). This result would suggest that PET has a better correlation with ET for periods of high precipitation.
- The gradual decrease in soil water potential during Period 1 was observed in many of the ET cover systems. This was likely due to the high frequency of precipitation events during the winter, spring, and beginning of summer in 2015. As the precipitated water infiltrates into the soil and the soil becomes more saturated, the soil water potential will tend to decrease. This result corresponds well with the general increase in water stored in the soil and the measured percolation events during this same time period.
- An increase in soil water potential was measured in the tensiometers at the topsoil and storage layer boundary and the tensiometers in the middle of the storage layer, during a time when there was a small gap in relatively large precipitation events and relatively high potential ET (e.g., spring of 2016). Larger gaps in precipitation events were observed during the times of low potential ET (e.g., winter of 2015/2016); however, a decrease in soil water potential was not measured. As is expected, it is likely that higher potential ET result in water removal from the cover system at a greater rate than during time periods of lower potential ET.
- It was observed that during drying periods (high potential ET and infrequent precipitation events), that soil water potential measured tended to be greater at the topsoil and storage

layer boundary when compared to greater depths. This suggests that the soil near the atmosphere and soil boundary will tend to dry sooner than the soil deeper in the cover system and likely an indicator that water was being removed from the cover system by ET.

- In general, the tensiometers tend to provide an accurate representation of times when percolation was measured (when soil water potential was measured to be approximately 0 kPa) and times when little/no percolation was measured (when soil water potential was greater than 0 kPa).
- Results from tensiometers and soil moisture sensors show a good correlation throughout the monitoring period (i.e., during periods of high soil water storage, the water potential indicated near or at saturated conditions). This result was expected as the sensors installed were installed in close proximity.
- The relatively shallow root system measured (2/27/2016) in the ET cover systems [18-inches (Lysimeter 3 and 6) at the deepest and 7-inches (Lysimeter 5) at the shallowest] could be a contributing factor for the relatively large amount of percolation measured. It should be noted that the ET cover sections which had sod planted provided the deepest root depth. A higher density of roots and deeper roots tend to increase the amount of infiltrated water that can be removed from the ET cover system. As the vegetation becomes established and if the roots grow deeper into the ET cover systems, it is anticipated that the quantity of percolation will decrease. It should also be noted that the storage layer was compacted at the density with may prevent or minimize vegetation growth. Therefore; transpiration may be minimized if the roots do not grow deep into the storage layer. The root depth is currently being monitored in each ET cover system.
- It has been visually observed that there tended to be a greater quantity of vegetation in the inclined sections when compared to the top sections. The greater quantity of vegetation may slow down the runoff (decreasing the quantity of measured runoff) and possibly lead to greater amounts of infiltration and percolation. The quantity of vegetation each month is currently being monitored.

- Cracking in the cover system was observed in August 2016 in several of the lysimeters. Cracking and the resulting preferential flow pathways may cause greater infiltration and allow for runoff to directly flow into the storage layer without first having to flow through the topsoil and bypassing some of the storage layer. It should be noted that these cracks generally develop in soil with high shrink/swell potential (similar to the soil placed in the storage layer) and do not typically occur in topsoil. It was observed that the cracking occurred in areas of relatively minimal vegetation. Without the vegetation preventing erosion of the topsoil, it is possible that the topsoil has been removed by runoff in these areas. However, it should be noted that extensive vegetation growth in the lysimeter may have prevented cracks from being observed throughout the lysimeters and further investigation is required.
- It was observed that there has been a general decrease in the soil density in the storage layer of the ET cover systems when compared to during the construction. This result may lead to a higher hydraulic conductivity in the storage layer and could contribute to greater quantities of percolation. Fluctuations in the density of the cover during the monitoring period may occur because of the wetting and drying cycle of the soil. The wetting and drying cycle may cause shrinkage and swelling of the soil; therefore, resulting in the decrease in soil density when the soil swells and an increase in soil density as the soil shrinks. It is also possible that as the soil shrinks and swells, cracks or fissures may develop in the soil and could result in preferential flow channels. This would result in an increase in effective hydraulic conductivity and may result in greater amounts of infiltration deeper into the soil layer and result in percolation events.
- The rodent burrows found in the ET cover systems may help explain the percolation events. The rodent burrows tend to act as preferential channels for the precipitation to flow into the ET cover system and possibly increase the percolation. Additionally, it was found that the rodent burrows tend to be located near sturdy vegetation or berms. It is hypothesized that the sturdy/tall vegetation and/or berms are providing cover for the rodents from predators. Since rodent burrows provide a potential preferential flow path for water to infiltrate into the

cover system and sturdy vegetation and/or berms seem to provide cover for the rodents, it is recommended that sturdy/tall vegetation be removed from ET cover systems.

- Vegetation appeared to be very similar in all of the lysimeters, with very little of the planted vegetation present (with the exception of the sodded areas). However, it is important to note that native vegetation may take a relatively substantial amount of time to become established after seeding/planting.
- The Line-Point Intercept Method was conducted in all of the ET cover sections and provided quantitative measurements for total cover, bare ground, and basal cover. Qualitative measurements accompanied the quantitative measurement by the Line-Point Intercept Method as a result of the relatively large uncertainty associated with the method. From the measurements and the associated uncertainty, the total coverage for all of the ET cover sections ranged between 64% to 100%. All of the ET cover sections showed an average cover of approximately 90%, with little variability between the cover sections. Additionally, there appeared to be a trend of lower quantities of total coverage during the winter months; however, due to the uncertainty and the minimal variability, this cannot be concluded. The large total coverage for all of the ET cover sections suggest a stable soil and site stability (minimal amounts of erosions), and the vegetation was providing obstructions to minimize runoff. Additionally, these results suggest that the vegetation planted and growing on the ET cover systems were preforming well and that less successful vegetation would result in larger amounts of runoff. The predominance of vegetation in the cover sections corresponds to the qualitative results; however, the quantitative results are less conclusive in relation to the quantity of vegetation than the qualitative results. This result may be related to the limited area measured by the Line-Point Intercept Method. From the measurements and the associated uncertainty, the basal cover for all of the ET cover sections range between 0% to 44%. The average basal coverage for the ET cover systems ranged between 8% to 18%, with Lysimeters 3 and 6 (vegetated with bermuda seed and sod) showing the greatest coverage. This result is expected as the sod was installed in half of the cover sections, providing a great amount of basal coverage from the beginning of the

monitoring period. However, the uncertainty must be considered in relation to this conclusion.

- Almost all of the precipitation intensity results were below 3-inches per day (99.8%), with the majority being between 0 to 1-inch (77.6%). Precipitation was measured for 33.0%, 6.6%, 25.0%, 7.0%, and 27.9% of the days for Periods 1, 2, 3, 4, and 5, respectively. Additionally, greater than 1-inch of precipitation was measured 6.5%, 1.9%, 7.8%, 1.8%, and 4.4% of the days during Periods 1, 2, 3, 4, and 5, respectively.
- Subsidence was observed on the ET cover sections and have resulted in ponded water. The observed subsidence was likely a result of topsoil loss due to runoff or settlement. Ponded water on the cover system could result in greater quantities of infiltration, stored water, and possibly percolation if not removed from the cover system by ET. It should be noted that the change in the soil water storage as a result of the subsidence (and resulting infiltration) would not be measured by the moisture sensors unless the subsidence is above or near the sensors.
- Vegetation dormancy observed during the Winter of 2016 likely resulted in a decrease in transpiration; therefore, decrease the rate at which water was removed from the ET cover system.
- Flowering plants were observed at the end of the testing section and were likely growth from the seeds that were planted at the end of the construction phase (Lysimeters 1, 2, 4, and 5).

6.3 Limitations of the Study

The major limitations of this study are provided as follows:

- The ET cover system was monitored at only one (1) location.
- The evaluation of the cover system was conducted over a relatively short amount of time.
- All of the ET cover systems used the same soil schematic, with varying types of vegetation.
- Modeling has not been conducted as a comparison or fit to measured results.
- The study utilized climatic conditions during the time of monitoring.
- Relatively small area tested in comparision to full-scale cover systems

6.4 Recommendations for Future Studies

Several topics have been identified and recommended for further study as follows:

- Further monitoring utilizing and expanding upon the current study to evaluate the performance of the ET cover systems for long-term performance.
- Additional ET cover performance assessment studies are recommended as follows:
    - Conduct similar studies in other geographic locations to evaluate other climates.
    - Conducting the same study in a different location(s) at the City of Denton Landfill to evaluate changes (if any) in performance at the same landfill.
    - Conduct the same study but varying the direction that the cover sections are facing to evaluate changes (if any) in performance.
    - Utilizing other ET cover system schematic(s) (e.g., varying soil depth, varying soil type, varying soil density, varying vegetation, etc.).
    - Identify other possible monitoring systems that would provide reliable cover performance assessment results with minimal cost (e.g., relatively small-scale lysimeters).
    - Conduct a similar study but recreating large storm events, drier climatic conditions, or other variations in cover performance parameters (i.e., having more control of climatic conditions during the study).
- Comparison of monitoring and modeling and model fitting to monitoring results is suggested. Additionally, several models can be utilized as a tool for comparisons and model fitting to monitoring results.
- The current study identified that preferential flow may be a cause of excessive percolation. A study is suggested to identify the impact of preferential flow on the performance of cover systems and how preferential flow can be minimized.
- Problems with data collection have been identified in this study resulting in lost data. Improved instrumentation is required to prevent such loss of data during other similar studies.

Appendix A

ET Cover Daily Construction Activities

Construction Activities June 16th

The following occurred during the first day (June 16th) of the ET Cover construction

- The top soil was stripped in the top section only (Figure A.1).
- The embankment base of the embankment was almost competed on the top section only (Figure A.2).
- It appeared as through some of the existing pipes along the existing cover near the test section were moved in anticipation of the ET Cover construction.

Figure A.1: Top soil stripped and base embankment constructed after day 1.

Figure A.2: Embankment base after day 1.

A.1 Construction Activities June 17th

The following occurred during the second day (June 17th) of the ET Cover construction:

- The top soil was stripped and removed in the inclined section (Figure A.3 and Figure A.4).
- Base of the embankment was placed and compacted for both the top and inclined sections (Figure A.5). Note: water was utilized (from the City of Denton water truck) on the top section to achieve a satisfactory embankment base compaction (Figure A.6).
- It was decided to use the gray clay for the remainder of the embankment (both the top and inclined sections) in anticipation of geomembrane placement and excavation (i.e., the gray clay shall provide a sufficient sidewall for the lysimeters and not require additional excavation).
- The gray clay was placed into piles near the slope edge and sprayed with water (from the City of Denton water truck) prior to spreading and compaction (Figure A.7). These clay piles were then spread and compacted in the inclined section (Figure A.8). **Note:** the gray clay was obtained from the location shown in Figure A.9.
- Stakes/markers were placed near gas wells to avoid hitting them with machinery Figure A.10.

- There was concern over the timing of the staking at the site, but it was determined that the surveyor should be present Wednesday (June 18th).

Figure A.3: Stripping of top soil from the inclined section.

Figure A.4: Removal of top soil from the inclined section.

Figure A.5: Placement and compaction of the embankment base in the top section.

Figure A.6:Water application to the top section for compaction purposes.

Figure A.7: Placing the gray clay on the test section prior to spreading and compaction.

Figure A.8: Spreading and compacting the gray clay in the inclined section.

Figure A.9: Excavating the gray clay for transportation to the test section.

Figure A.10: Marker placed to avoid hitting a vertical leachate injection pipe.

A.2 Construction Activities June 19th

The following occurred during the fourth day (June 19th) of the ET Cover construction:

- There was a meeting at 1 pm between the contractors, City of Denton, and the University ofTexas at Arlington to finalize details of the construction plan and get everyone on the same page (Figure A.11 and Figure A.12). Several items were discussed in this meeting:
    - The embankment shall be constructed to a 4-foot height (possibly completed by the following Thursday) and then excavation for the lysimeters shall be conducted (estimated to take a few days).
    - Construction of the embankment may require more time than anticipated due to the high soil clay content; therefore, requiring additional water application to achieve adequate compaction.
    - It was decided that the top section excavation and lysimeter construction shall be completed first, then once completed, the inclined section shall be completed.
    - Staggering/offsetting between the top and bottom lysimeters for each test section shall be allowed. This may allow for easier construction, and shall be allowed because the top and bottom lysimeters of each test section are not to be connected.
    - Boundaries between the edge of the embankment and the lysimeters shall be 10-feet, and should allow a gap of approximately 10-feet between lysimeters. Additionally, the 10-foot gap on the outside boundaries shall be heavily compacted to ensure that the lysimeter sidewalls do not fail.
    - Clay rich soils can be found on the side of the borrow pit that the contractors are currently digging (Figure A.13). Excavation shall stop when the borrow pit embankment is at an elevation equal to the surrounding area.
    - The leachate injection well at the middle and top of the test section was determined to not cause issues with the lysimeter locations. This was most likely due to the change in the grade break location during the construction of the embankment, and provided approximately 48-feet between the grade break and the leachate injection well.

- Embankment construction began for the day after the completion of the meeting. The same as previous days, water was manually applied to the inclined section and the City of Denton water truck was used to apply water to the top section. The embankment construction wasconcentrated on the inclined section (Figure A.14).
- The surveyor came to the site and provided a point with a set elevation and stakes placed 10-feet outside of the existing boundary stakes (Figure A.15). He also spoke with the contractors to ensure that he provided them with all of the surveying related activities that they required.

Figure A.11: Discussion between the City of Denton (David Dugger) and the University of Texas at Arlington.

Figure A.12: Discussion between the City of Denton, constructors, and UTA.

Figure A.13: Excavation from the borrow pit to utilize as the embankment.

Figure A.14: Embankment construction on the inclined section.

Figure A.15: 10-foot boundary offset stakes placed by the surveyor.

A.3 Construction Activities June 20th

The following occurred during the fifth day (June 20th) of the ET Cover construction:

- Construction of the embankment progressed in a similar fashion as previous days (i.e., transporting soil by dump truck, moving/compacting the soil by the bulldozer, and applying water for adequate compaction) (Figure A.16 and Figure A.17). The embankment construction progressed at rapid pace (faster than what was estimated the previous day), and the contractors were trying to complete the embankment construction by the end of this day or by noon tomorrow (June 21st). Water was also applied to the temporary access road for dust control purposes (Figure A.18).

- Soil was taken from the north side of the borrow pit (same as previous days) (Figure A.19).
- The embankment on the top section was completed (3-foot of clayey soil and approximately 18-inches of other sandier soil) (Figure A.20 and Figure A.21). The depth was verified (by the contractors) by utilizing a survey instrument and point checking at several locations on the top section (Figure A.22 and Figure A.23).
- Several boundary stakes were hit during the embankment construction and may not have been replaced in their exact location (can verify by measuring from the stakes which were placed 10-feet outside of the test section boundary).
- The leachate injection well near the top section was slightly covered by the embankment, with no evidence of damage (Figure A.24).
- It appeared as though the gas collection well north of the top section was raised (Figure A.25).
- Other interesting/relevant pictures are provided in Figure A.26, Figure A.27, and Figure A.28.

Figure A.16: Water application to ensure adequate compaction.

Figure A.17: Transporting soil by dump truck and moving/compacting soil by bulldozer.

Figure A.18: Water application to the temporary access road.

Figure A.19: Obtaining embankment soil from the borrow pit on the fifth day.

Figure A.20: Top section embankment completion one (1).

Figure A.21: Top section embankment completion two (2).

Figure A.22: Embankment height verification one (1).

Figure A.23: Embankment height verification two (2).

Figure A.24: Leachate injection well slightly covered by the embankment.

Figure A.25: Gas collection well, north of the test section.

Figure A.26: View of the inclined section embankment from the bottom of the landfill slope.

Figure A.27: View of the inclined section embankment from the top section.

Figure A.28: View of the inclined section from the south.

A.4 Construction Activities June 21st

The following occurred during the sixth day (June 21st) of the ET Cover construction:

- Construction of the embankment progressed in a similar fashion as previous days (i.e., transporting soil by dump truck, moving/compacting the soil by the bulldozer, and applying water for adequate compaction) (Figure A.29, Figure A.30, and Figure A.31). Embankment height was verified in a similar fashion as previous days (Figure A.32).
- Much less soil (when compared to previous days) was transported from the borrow pit to the embankment location. The soil that was obtained came from the same location as previous days (Figure A.33). The contractors planned on filling in the hole in the borrow pit and leveling to enhance runoff and avoid standing water.
- The inclined section embankment was completed, resulting in the completion of the entire embankment.
- Staking the lysimeter/excavation locations should begin in the Monday morning (June 23rd), beginning with the north most top section excavation and progressing south. Once these are completed, then the inclined sections can be staked and excavated. This shall

allow for ease of construction and for excavation to commence as soon as the lysimeter/excavation locations are staked.

- The existing pipe on the south side of the embankment may need to be relocated for construction purposes.
- The remaining construction plan is to excavate 3-feet of the embankment and thoroughly compact the underlying soil in preparation for the geomembrane, geotextiles, and cover soil.
- Other interesting/relevant details are provided in Figure A.34, Figure A.35, Figure A.36, and Figure A.37.

Figure A.29: Inclined section embankment construction and water application.

Figure A.30: Inclined section embankment construction one (1).

Figure A.31: Inclined section embankment construction two (2).

Figure A.32: Embankment height verification.

Figure A.33: Obtaining embankment soil from the borrow pit on the sixth day.

Figure A.34: View of the top section during the sixth day of ET Cover construction.

Figure A.35: View of the inclined section (south side) from the top section on the sixth day.

Figure A.36: View of the inclined section from the south on the sixth day (near completion).

Figure A.37: View of the inclined section from the toe of the landfill slope on the sixth day (near completion).

A.1 Construction Activities June 23rd

The following occurred during the seventh day (June 23rd) of the ET Cover construction: There was rain during the morning, and conditions were too wet to continue construction.

A.2 Construction Activities June 24th

The following occurred during the eighth day (June 24th) of the ET Cover construction:

- Photographs showing the embankment at the beginning of the eighth day are shown in Figure A.38 and Figure A.39.
- The surveyor was present at the beginning of the day and marked the corners and grade break of the excavation/lysimeter area (Figure A.40). He also noted a few locations that did not have adequate embankment height.
- The borrow pit was modified to enhance runoff and avoid any pooling of water at that location (Figure A.41).
- There was a meeting in the morning between the City of Denton (COD), contractors, and the University of Texas at Arlington (UTA), and the following was mentioned:
    - Several locations were noted on the embankment that needed to be raised, mostly on the south side of the embankment.
    - The contractors can construct a ramp to get in and out of the excavation
    - It was decided that the top of the section will be excavated, base compacted, and slope prepared, then the COD staff can place the geomembrane/geocomposite drain.
    - COD will have a company verify that the subgrade and each lift will meet the 1.0 x 10^{-7} cm/sec permeability requirement.
    - A little confusion occurred about the height of the compacted clay layer and may have resulted in the clay embankment only being 3-feet, rather than 4- to 5-feet.
    - The soil that will be used within the excavation/lysimeter is already present in the embankment; therefore, little (if any) additional soil will be required.
    - It was request by COD that the edge of the embankment be cleaned-up for appearance purposes.
- Immediately following the meeting, the edges of the embankment at the east and west were modified and compacted (Figure A.42 and Figure A.43).

- Stakes were placed at each marker (placed by the surveyor), and line strung between the stakes to identify the excavation boundaries (Figure A.44).
- Excavation of the embankment for the lysimeter began on the top section in the north (Figure A.45). The excavated soil was placed on the edges of the embankment and down the inclined section (Figure A.46). At least two (2) of the top test sections were excavated (Figure A.47 and Figure A.48).
- A skid-steer (with wheels) was used to finalize the slope and compact the excavation and lysimeter subgrade (Figure A.49).
- A laser level was used in the excavation to verify the slope and height requirements of the test section subgrade (Figure A.50).
- Rainfall event and clay soil notes are as follows:
  - Extensive desiccation cracking was seen throughout the embankment (Figure A.51 and Figure A.52).
  - The top section was notably wetter than the side slope, and did not dry until approximately 11 am (approximately 24-hours after the rainfall event).
  - No significant loss of embankment soil or gullies was observed on the embankment as a result of the rainfall event the previous day.

Figure A.38: Photograph of the embankment at the beginning of the eight day- one (1).

Figure A.39: Photograph of the embankment at the beginning of the eighth day- two (2).

Figure A.40: Surveyor marking the edges of the embankment/lysimeter.

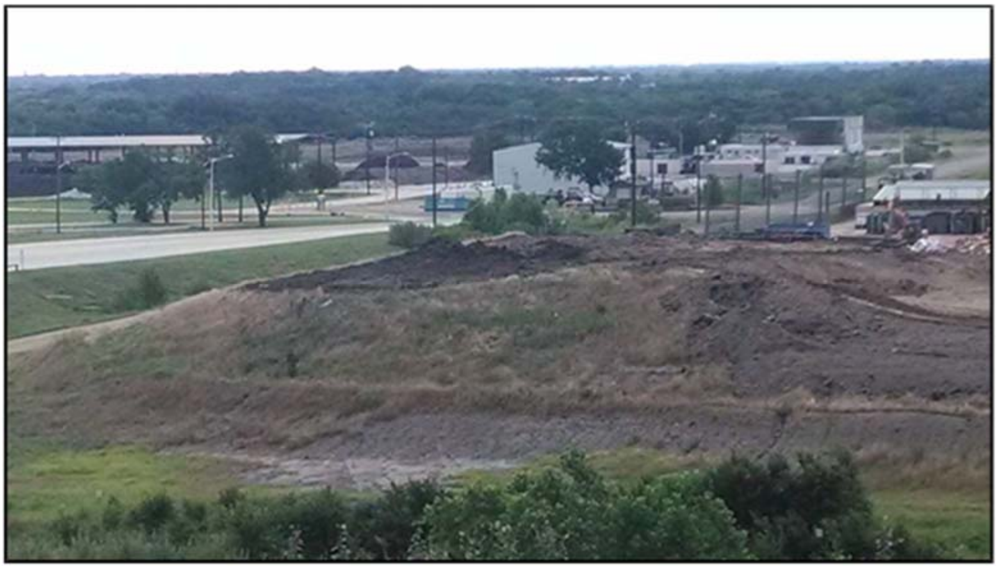


Figure A.41: Borrow pit modification.

Figure A.42: Embankment edge modification by the excavator.

Figure A.43: Embankment modification by bulldozer.

Figure A.44: Staking and marking the edges of the excavation area.

Figure A.45: Beginning of the excavation of the top section.

Figure A.46: Excavation and placement of soil on the embankment.

Figure A.47: Test section excavation nearing completion.

Figure A.48: Two (2) of the top test sections nearing completion of the excavation.

Figure A.49: Finalizing the lysimeter subgrade by a skid-steer.

Figure A.50: Subgrade slope and height verification by laser level.

Figure A.51: Evidence of desiccation cracking on the surface of the embankment-one (1).

Figure A.52: Evidence of desiccation cracking on the surface of the embankment-two (2).

A.3 Construction Activities June 25th

The following occurred during the ninth day (June 25th) of the ET Cover construction:

- Conditions were very wet (ponding within the excavation occurred) from a storm event that occurred this morning (Figure A.53). Made moving around the site a challenge and should help with the compaction of the clay.

- During excavation of the embankment, waste was unearthed in the south top section (Figure A.54, Figure A.55, and Figure A.56). It was decided to place an additional 1-foot of clay on the embankment to ensure that the construction within the excavation was in accordance with the original plans (Figure A.57). A significant portion of the soil that was excavated from the embankment was utilized to construct the 1-foot addition, and additional soil from the borrow pit for subsequent construction may be required.
- Additional soil was placed on the leachate injection pipe near the top section to construct a pathway for construction equipment (Figure A.58).
- A skid-steer and compactor were used to ensure compaction at the base of the south top section (Figure A.59).
- A storm in the afternoon halted construction.
- Additional photographs from the activities of the ninth day are shown in Figure A.60, Figure A.61, and Figure A.62.

Figure A.53: Ponding as a result of a rainfall event in the morning.

Figure A.54: Waste that was unearthed in the south top section excavation-one (1).

Figure 3: Waste that was unearthed in the south top section excavation-two (2).

Figure A.55:Waste that was unearthed in the south top section excavation-three (3).

Figure A.56: Construction of an additional 1-foot of embankment around the excavation areas.

Figure A.57:Embankment addition construction and view of the top section excavations.

Figure A.58:View of the leachate injection pipe.

Figure A.59: Compaction and gradation of the south top section.

Figure A.60: View of the test section from the bottom of the landfill slope on the ninth day.

Figure A.61: Construction of the test section on the ninth day.

Figure A.62: Mr. Dugger (City of Denton) speaking with the contractors.

A.4 Construction Activities June 26th

The following occurred during the tenth day (June 26th) of the ET Cover construction:

- The 2% slope was constructed along the top of the subgrade in each of the top section lysimeters (Figure A.63). Additionally, the subgrade was slightly graded toward the edge of the embankment for drainage pipe purposes at the base of the slope. The north and middle top sections were graded to allow drainage to the north and the south top section was graded towards the south.
- A 2-foot high by 2-foot long berm was created at the top of the slope at the excavation/lysimeter edge in each of the top sections (Figure A.64).
- During subgrade construction, water was manually sprayed onto the subgrade soil to ensure adequate compaction (Figure A.65 and Figure A.66).
- The sheep-footed compactor was utilized in a back and forth motion over the entire subgrade in each top sections, after water application (Figure A.67).
- The skid-steer was used to finalize the appropriate slopes and to smooth any ridges and imperfections (Figure A.68). Additionally, the skid-steer was utilized to construct the berms and help with the subgrade compaction effort.
- The laser level was utilized to ensure the appropriate subgrade slopes (Figure A.69).
- D&S was contacted for nuclear density testing on the near completed subgrade to ensure adequate compaction effort (Figure A.70). One (1) nuclear density test was completed within each excavation/lysimeter, and it was found that all subgrades had greater than 95% compaction. It was concluded that the contractors will contact D&S for nuclear density testing when appropriate [i.e., when the subgrade and each lift is completed with one (1) test for each lysimeter top section and one (1) test for each lysimeter inclined section].

- Tomorrow morning (June 27th), the ramps which were construction in each excavation/lysimeter shall be removed and be ready for geomembrane placement by the City of Denton. This is anticipated to not require substantial time and the north top section shall be ready for geomembrane placement early in the morning. The middle and south top sections require additional smoothing/slope adjustments, but this process should not require substantial time. The inclined section on the south side shall be the next lysimeter to be excavation.

Figure A.63: Nearly completed lysimeter subgrade.

Figure A.64: Berm construction by a skid-steer.

Figure A.65: Water application to the subgrade of the middle and south top section lysimeters.

Figure A.66: Water application to the subgrade of the north top section lysimeter.

Figure A.67: Subgrade compaction by a sheep-footed compactor.

Figure A.68: Subgrade finalization by a skid-steer.

Figure A.69: Slope verification by the laser level.

Figure A.70: Nuclear density test on the subgrade by D&S.

A.5 Construction Activities June 27th

The following occurred during the eleventh day (June 27th) of the ET Cover construction:

- The middle berm (on the top section side) between the top and inclined sections were constructed for all the top sections (Figure A.71 and Figure A.72). This shall allow the City of Denton (COD) staff to place the geomembrane.
- Construction ramps (within the lysimeter) were removed and the berms on the east side of the top sections were finalized (Figure A.73).
- The subgrade showed signs of cracking and warping as a result of drying of the clay soil (Figure A.74, Figure A.75, and Figure A.76). As a result, it was determined to finalize the subgrade just prior to the geomembrane placement and place a small amount of sandy soil in low-lying areas (Figure A.77 and Figure A.78). This shall eliminate any areas where water can pool on the lysimeter bottom while maintaining the appropriate slope, and the sandy soil is sufficiently fine and

graded to not puncture the geomembrane (Figure A.79). Additionally, any large particles shall be removed prior to geomembrane placement to eliminate the risk of puncturing the geomembrane.

- As the geomembrane is approximately 22-feet wide, two (2) sheets will need to be placed along the lysimeter bottom and welded down the center. The sidewalls shall be another piece of geomembrane, and will overlap and be welded to the geomembrane sheets on the subgrade. It was decided to begin geomembrane placement on Monday (June 30th).

Figure A.71: Constructed middle berm details for the top section.

Figure A.72: Construction of the middle berm.

Figure A.73: Subgrade berm finalization for a top section.

Figure A.74: Subgrade details at the beginning of the eleventh day.

Figure A.75: Desiccation cracking of the subgrade at the beginning of the eleventh day.

Figure A.76: Subgrade cracking at the beginning of the eleventh day.

Figure A.77: Subgrade with sandy soil in low-lying areas.

Figure A.78: Nearly completed top section subgrades.

Figure A.79: Sandy material provided by the COD.

A.6 Construction Activities June 30th

The following occurred during the twelfth day (June 30th) of the ET Cover construction:

- The geomembrane in the North top section was placed and welded. Welds were done in the middle of the lysimeter (to connect the geomembranes on the subgrade) and near the sidewall (to connect the sidewall geomembranes to the subgrade geomembranes) (Figure A.80 through Figure A.86). Approximately 6-feet of geomembrane was left outside of the lysimeter area. Two (2) geomembrane sections were placed at the lysimeter subgrade and smaller (approximately 11-feet wide) geomembrane sections were placed on the sidewalls (only those sidewalls oriented east to west).
- It will probably take another two (2) days to complete the geomembrane placement for the top section lysimeters.
- Tires were placed on the geomembrane at the top of the embankment to anchor it to the ground (Figure A.87).
- Soil that was present on the subgrade geomembrane was swept away from the welding area (Figure A.88). Large soil particles were removed from the lysimeter area.
- The edge of the geomembrane (where they were welded) was cleaned with glass cleaner to provide an adequate welding surface (Figure A.89).
- The geomembrane at the Northeast and Southeast corners of the lysimeter needed to be cut and welded to obtain an adequate lysimeter (Figure A.90).
- The finished product at the end of the twelfth day is shown in Figure A.91, Figure A.92, and Figure A.93.

Figure A.80: Welding of the geomembrane by the City of Denton (COD) staff.

Figure A.81: Welding of the geomembrane by the University of Texas at Arlington (UTA)-one (1)

Figure A.82: Welding of the geomembrane by UTA-two (2).

Figure A.83: Welding of the geomembrane by UTA-three (3).

Figure A.84: Welding the geomembrane along the sidewall by the COD staff.

Figure A.85: Sidewall geomembrane welding to subgrade geomembrane by COD staff.

Figure A.86: Sidewall geomembrane welding and cleaning of welding area.

Figure A.87: Tires placed on the geomembrane on the top of the embankment.

Figure A.88: Sweeping away soil from welding area.

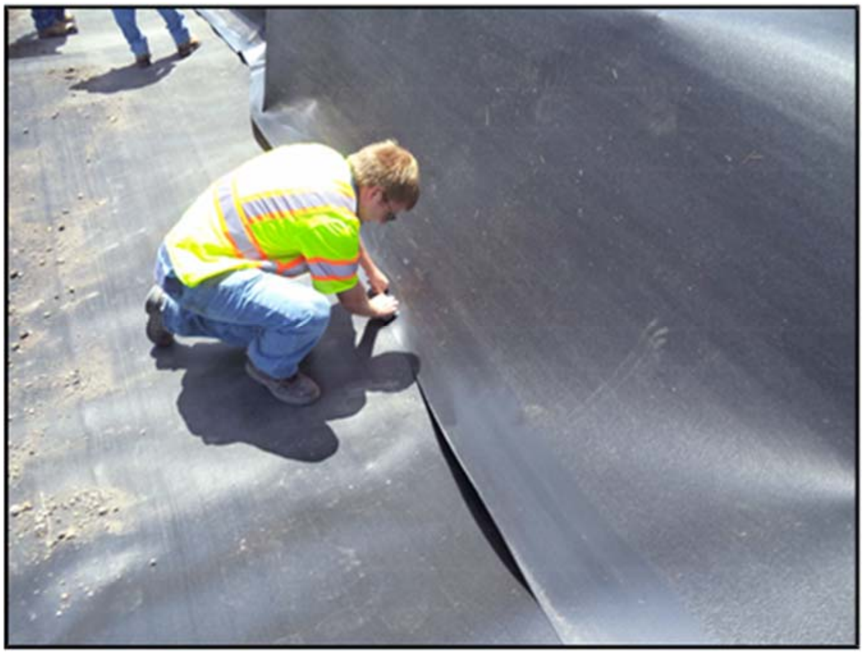


Figure A.89: Cleaning welding area.

Figure A.90: Geomembrane welding in the Southwest corner.

Figure A.91: Geomembrane placed in the North top section lysimeter-one (1).

Figure A.92: Geomembrane placed in the North top section lysimeter-two (2).

Figure A.93:Geomembrane placed in the North top section lysimeter-three (3).

A.7 Construction Activities July 1st

The following occurred during the thirteenth day (July 1st) of the ET Cover construction:

- Geomembrane placement commenced in the same manner as yesterday (June 30th); however, the geomembrane was placed within the middle top lysimeter.
- Removal of large soil clots, rocks, and imperfections on the subgrade was completed prior to the geomembrane placement to prevent puncturing the geomembrane and maintain the required slope (Figure A.94).
- The subgrade geomembranes were completely welded together (Figure A.95 and Figure A.96).
- During the welding of the North sidewall to the subgrade geomembrane, the welding gun stopped working and could not be fixed. As a result, only half of the sidewall weld was completed and construction stopped for the day (Figure A.97). A replacement welding gun is being transported to Denton from Houston and should arrive tomorrow (July 2nd) morning.
- Photographs of the North top lysimeter when the geomembrane is cool (preventing many of the wrinkles seen in yesterday's photographs) are shown in Figure A.98, Figure A.99, and Figure A.100.

Figure A.94: Removing soil clots and rocks from the subgrade.

Figure A.95: Geomembrane placed during the thirteenth day and welding details.

Figure A.96:Welding of the subgrade geomembrane.

Figure A.97: Geomembrane placed during the thirteenth day.

Figure A.98: North top lysimeter geomembrane details-one (1).

Figure A.99: North top lysimeter geomembrane details-two (2).

Figure A.100: North top lysimeter geomembrane details-three (3).

A.8 Construction Activities July 2nd

The following occurred during the fourteenth day (July 2nd) of the ET Cover construction:

- As a result of problems encountered with the extrusion welder the previous day (July 1st), a new extrusion welder was brought from Houston and arrived late in the morning (Figure A.101).
- Construction commenced at approximately noon, and resumed in the middle top section lysimeter.
- The middle top section geomembrane welds were completed with a similar procedure that was used the previous two (2) days (i.e., removing soil near the welding area, cleaning of the welding surface, and welding the geomembrane with the extrusion welder). This process is shown in Figure A.102 and Figure A.103.
- Relevant photographs of the top section lysimeters are provided in Figure A.104, Figure A.105, and Figure A.106. Note that the geomembrane has expanded due to the high outside temperature, and caused excessive wrinkles to appear.

Figure A.101: Replacement extrusion welder (MINI-Z – Extrusion Welder from Polyweld U S A).

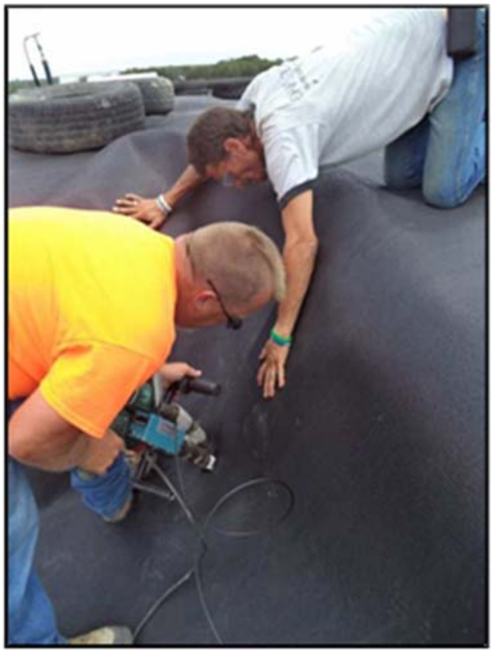


Figure A.102: Welding of the sidewall geomembrane.

Figure A.103: Construction of the sidewall geomembrane for the middle lysimeter.

Figure A.104: Middle top section geomembrane details from the Northwest.

Figure A.105: Middle top section geomembrane details from the Southeast.

Figure A.106: North top section geomembrane details from the Northwest.

Figure A.107: North top section geomembrane details from the Southeast.

A.9 Construction Activities July 3rd

The following occurred during the fifteenth day (July 3rd) of the ET Cover construction:

- A large rainfall event occurred early in the morning, and more rainfall was expected throughout the day. As a result, construction was not conducted today.
- The result of the rainfall event(s) for the North Top Section at approximately 9:30 am is provided in. Note that the rainwater is substantially pooled in the Northwest corner (as intended), and that several wrinkles were present and prevented some of the water from flowing to that corner (should be removed prior to geocomposite drain placement).
- The result of the rainfall event(s) for the Middle Top Section at approximately 9:30 am is provided in Figure A.108, Figure A.109, and Figure A.110. Note that the rainwater is substantially pooled in the Northwest corner (as intended), and

that less wrinkling was present and prevented some of the water from flowing to that corner (should be removed prior to geocomposite drain placement).

- The result of the rainfall event(s) for the South Top Section at approximately 9:30 am is provided in Figure A.111 and Figure A.112. Note that the rainwater is substantially pooled in the Southwest corner (as intended even without the geomembrane), and that a small section has pooled water (should be removed prior to geomembrane placement).

Figure A.108: North Top Section lysimeter after the morning rainfall event(s)-one (1).

Figure A.109: North Top Section lysimeter after the morning rainfall event(s)-two (2).

Figure A.110: North Top Section lysimeter after the morning rainfall event(s)-three (3).

Figure A.111: Middle Top Section lysimeter after the morning rainfall event(s)-one (1)

Figure A.112: Middle Top Section lysimeter after the morning rainfall event(s)-two (2).

Figure A.113: Middle Top Section lysimeter after the morning rainfall event(s)-three (3).

Figure A.114: South Top Section lysimeter after the morning rainfall event(s)-one (1).

Figure A.115: South Top Section lysimeter after the morning rainfall event(s)-two (2).

A.10 Construction Activities

- The placement of geomembrane in the South top section started today.
- Water was still present in middle and North top sections, accumulated from the rain on Friday.
- The wrinkles were present in very less amount in the early morning, but it increased with the sunlight in both the middle and North top sections. Randall Morris said it is not easy to write off the wrinkles.
- After lunch they started doing the sidewalls.
- Ami came, and she mentioned that the boots are not there yet and the work tomorrow with the pipes may be delayed.
- We took Randall's contact number and we will contact him tomorrow before going.

Figure A.116: North Top Section lysimeter on Monday (after Friday morning rainfall).

Figure A.117: Middle Top Section lysimeter on Monday (after Friday morning rainfall).

Figure A.118: South Top Section lysimeter (Construction has begun).

Figure A.119: South Top Section lysimeter.

Figure A.120: South Top Section lysimeters

Figure A.121: South Top Section lysimeters (after completion)

Figure A.122: South Top Section lysimeters (after completion) corner1.

Figure A.123: South Top Section lysimeters (after completion) corner2.

Figure A.124: South Top Section lysimeters (after completion) corner 3

Figure A.125: South Top Section lysimeters (after completion) corner 4

A.11 Construction Activities

- The boots were supposed to arrive today but they did not reach Denton.
- Ami told me that the manufacturers are not producing the boots anymore and now Randall was asked to prepare them on site.
- In their workshop they prepared 3 boots for the top sections.


(a)


(b)

Figure A.126: The prepared boots outside the workshop.

A.12 Construction Activities

- The construction was discontinued due to the presence of rainwater on the top sections.
- The water was pumped out from the sections.

Figure A.127:: North Top Section lysimeter on Wednesday.

Figure A.128: Middle Top Section lysimeter on Wednesday.

Figure A.129: South Top Section lysimeter on Wednesday.

Figure A.130: North Top Section lysimeter (pumping out water)

Figure A.131: Middle Top Section lysimeters (pumping out water).

A.13 Construction Activities

- The excavation in the north and middle sections started in the morning for the placement of the drainage pipes.
- The outlet for the middle section is now constructed as such that both the north cell drainage pipe and the middle section drainage pipe will go down the north side.
- The pipe caps for the perforated pipes were fixed.

- Boots are placed both in the middle and north cell and they are not yet completely welded. After backfilling the boots will be welded.

Figure A.132: North Top Section lysimeters, the membranes are pulled to dig the drainage.

Figure A.133: Perforated pipes on site, the caps being welded.

Figure A.134: Boots placed in the north lysimeters.

Figure A.135: The geotextile placed below the perforated pipes. Burritos to be made tomorrow.

A.14 Construction Activities July 14th

The following occurred during the twenty-first day (July 14th) of the ET Cover construction:

- The geocomposite drain (i.e., the geonet sandwiched between geotextiles) was placed only on the bottom of the lysimeter (to cover the majority of the bottom) and slightly up the berms (on the east and west sides of the lysimeters) (Figure A.136).
- Adjacent geocomposite drain sheets were overlapped and held together with zip-ties (Figure A.138, Figure A.139, and Figure A.140). These zip-ties went through both of the geocomposite drains [i.e., through the two (2) layers of geotextiles and geonet on each of the geocomposite drains].
- Geotextile sheets were cut to the appropriate size (Figure A.141) and then placed along the sidewalls on the north, south, and east sides each of the lysimeters (Figure A.142). The geotextiles were placed to overlap the geocomposite drain and joined with zip-ties (Figure A.143 and Figure A.144). Geotextile along the sidewalls was placed in an effort to protect the geomembrane during soil placement, while minimizing the flow of water along the sidewall (reason why the geocomposite drain was not placed in those locations).
- The placement of the geotextile and geocomposite drain was completed by the end of the day in the three (3) top sections. The top section lysimeters that are ready for soil placement are shown in Figure A.145 through Figure A.150.

Figure A.136: Placement of the geocomposite drain in a lysimeter-one (1).

Figure A.137: Placement of the geocomposite drain in a lysimeter-two (2).

Figure A.138: Placing adjacent geocomposite sheets together in preparation for zip-ties.

Figure A.139: Joining adjacent geocomposite sheets together with zip-ties.

Figure A.140: Joining adjacent geocomposite sheets by COD and UTA personal.

Figure A.141: Cutting the geotextile to the appropriate size for placement in the lysimeter.

Figure A.142: Placement of the geotextile on the sidewall.

Figure A.143: Joining the geotextiles to the geocomposite drain along a sidewall.

Figure A.144: Joining the geotextiles to the geocomposite drain along a sidewall by UTA.

Figure A.145: South top section lysimeter ready for soil placement-one (1).

Figure A.146: South top section lysimeter ready for soil placement-two (2).

Figure A.147:Middle top section lysimeter ready for soil placement-one (1).

Figure A.148: Middle top section lysimeter ready for soil placement-two (2).

Figure A.149: North top section lysimeter ready for soil placement-one (1).

Figure A.150: North top section lysimeter ready for soil placement-two (2).

A.15 Construction Activities July 15th

The following occurred during the twenty-second day (July 15th) of the ET Cover construction:

- The geomembrane and geocomposite drain were folded along the west side of the top section lysimeters to accommodate excavation of the inclined sections (Figure A.151).
- A string line was placed along all three (3) inclined sections near the middle berm and shall allow for alignment of the inclined sections (if constructed correctly). The top of the berms was set to between 2- to 3-feet (Figure A.152), and 40-feet were measured for each of the inclined lysimeters.
- Excavation of the inclined sections began and the excavated soil was placed in the top section lysimeters (Figure A.152, Figure A.153, and Figure A.154). **Note:** the inclined sections shall be extended approximately 3-feet west, to ensure the lysimeter remains 40-feet in length.

- The surveyors came and shot the elevations in the top section lysimeters (Figure A.156).
- A ramp was constructed in the southeast corner of the south top section lysimeter to allow a skid-steer to spread the 1st layer of soil (Figure A.157).
- The contractors were told to do the following while placing the 1st soil layer in the lysimeter:
    - Do not go on top of the liner,
    - Try and remove the wrinkles in the liner system while placing the soil, and
    - Try and compact the soil such that the soil clots are removed.
- Soil that was placed by the excavator was prepared and compacted by a skid-steer (Figure A.157 and Figure A.158).
- The 1st layer was disturbed by the excavator in preparation for watering in the south top section lysimeter (Figure A.160).
- Water was placed on the 1st layer after disturbing the soil in the south top section lysimeter for approximately 40-minutes (Figure A.161). **Note:** after water placement, several inches of the 1st layer was excavated and the soil was dry at a depth of approximately 2-inches. The soil pile on the middle top section lysimeter was watered prior to layer preparation and compaction.
- It was decided by the contractors to place a large amount of water on the soil in the south and middle top section lysimeters, and allow the water to infiltrate into the soil (to ensure compaction). Construction shall begin again tomorrow morning.
- The 8-inch lifts were marked along the sidewall in the middle top section lysimeter to ensure proper lift thicknesses (Figure A.162).

- Excavation of the south inclined lysimeter was nearly completed (too much soil was excavated in the west and will need to be addressed), and the middle inclined lysimeter excavation began (Figure A.163 and Figure A.164).

Figure A.151: Folding of the geomembrane and string line placement.

Figure A.152: Excavation of an inclined section and soil placement in the top section lysimeter.

Figure A.153: Excavation of the south inclined section lysimeter-one (1).

Figure A.154: Excavation of the south inclined section lysimeter-two (2).

Figure A.155: Surveyors taking an elevation in the bottom of a lysimeter.

Figure A.156: Ramp construction in the south top section lysimeter.

Figure A.157: 1st soil layer preparation and compaction in the south top section lysimeter-one (1).

Figure A.158: 1st soil layer preparation and compaction in the south top section lysimeter-two (2).

Figure A.159: Disturbing of the 1st soil layer in the south top section lysimeter.

Figure A.160: Water placement on the 1st layer of the south top section

Figure A.161: Water placement on the soil pile in the middle top section lysimeter.

Figure A.162: Lift thicknesses marking in the middle top section lysimeter.

Figure A.163: South inclined section lysimeter excavation at the end of the day.

Figure A.164: Middle inclined section lysimeter excavation at the end of the day.

A.16 Construction Activities July 16th

The following occurred during the twenty-third day (July 16th) of the ET Cover construction:

- The lower berms in the south and middle inclined sections were constructed with a gentle slope and compacted by the excavator (Figure A.165 and Figure A.166).
- Upper berms and soil surface for the subgrade were constructed in the south and middle inclined sections by a skid-steer and excavator.
- General directions given to the contractors about the inclined test sections were as follows:
    - Construct the sidewalls straight,
    - Slope the berms at a gentle slope to allow for relative ease of geomembrane placement, and
    - Ensure that there is enough depth of excavation to place 1-feet of subgrade soil and 3-feet of compacted clay.

- The soil layer in the south top section (which was wetted for approximately 40-minutesyesterday) was still fairly wet, and approximately 2-inches was dug into the soil layer and therewas evidence of water infiltration (dry yesterday and damp this morning) (Figure A.168 and Figure A.169)
- The middle top section soil (that had less water applied), was relatively dry on the surface butthe soil was damp about 4-inches into the pile (Figure A.170 and Figure A.171).
- Soil was placed in the north top section lysimeter, but water was not applied (Figure A.172).
- The embankment downslope of the inclined sections may need to be compacted or soil addedfor stability purposes (Figure A.173).
- The south and middle inclined sections were prepared for subgrade placement and excavationstared by the end of the day. Details at the end of the day are shown in Figure A.174 through Figure A.178.

Figure A.165: Lower berm construction with an excavator.

Figure A.166: Lower berm details in the south inclined section.

Figure A.167: South inclined test section preparation.

Figure A.168: Details of the soil placed in the south top section (morning).

Figure A.169: Damp soil from excavating into the south top section (morning).

Figure A.170: Details of the soil placed in the middle top section (morning).

Figure A.171: Damp soil from excavating into the middle top section (morning).

Figure A.172: Soil placement in the north top section.

Figure A.173: Details of the downslope embankment.

Figure A.174: End of the day details of the north inclined section.

Figure A.175: End of the day details of the middle inclined section-one (1).

Figure A.176: End of the day details of the middle inclined section-two (2).

Figure A.177: End of the day details of the south inclined section-one (1).

Figure A.178: End of the day details of the south inclined section-two (2).

Figure A.179: Details of the inclined sections at the end of the day.

A.17 Construction Activities July 17th

The following occurred during the twenty-fourth day (July 17th) of the ET Cover construction:

- Due to the rainfall event, construction did not continue today.
- Water was flowing from all of the pipes and gullies were evident of significant water flow (Figure A.180 through Figure A.191).
- Slight amount of storage in the lysimeters near the boot (due to the boot not being at the lowest point in the lysimeter), stored water was conservatively estimated at 2-ft^3 and should not significantly affect results. More water was stored in the south and north top sections when compared to the middle top section.
- A gully was present from the south inclined section and should be addressed.
- Other details of the test section during the rainfall event are shown in Figure A.189 through Figure A.191.

Figure A.180:: Flow of water from the south top section.

Figure A.181: Gully formed by the flow of water from the south top section.

Figure A.182: Flow of water from the north top section.

Figure A.183: Gullies formed by the flow of water from the middle and north top sections.

Figure A.184: Flow of water from the middle top section.

Figure A.185: North top section details during a rainfall event.

Figure A.186: Middle top section details during a rainfall event.

Figure A.187:: South top section details during a rainfall event.

Figure A.188: Gully from the south inclined section.

Figure A.189: Details of the south inclined section during a rainfall event.

Figure A.190: Details of the middle inclined section during a rainfall event.

Figure A.191: Details of the north inclined section during a rainfall event.

Figure A.192: Details of the inclined section from the west.

Figure A.193: Details of the south top section during a rainfall event.

A.18 Construction Activities July 18th

The following occurred during the twenty-fifth day (July 18th) of the ET Cover construction:

- It was not raining when I was at the site, so water was not flowing from the piping system (with the exception of a slight amount of water flowing from the south top section lysimeter) (Figure A.194, Figure A.195, and Figure A.196).
- Little (if any) water remained on the geocomposite drains within each of the top section lysimeters, except for the stored water near the boot (Figure A.197 and Figure A.198). Again, more water was stored in the north and south top section lysimeters when compared to the middle section (Figure A.199, Figure A.200, and Figure A.201).
- The geomembrane on the edge of the northeast side of the middle top section lysimeter had been disturbed by the wind, and had folded over into the lysimeter (Figure A.202).
- Standing water was present on the soil piles/layers within each lysimeter (Figure A.203, Figure A.204, and Figure A.205).
- I spoke with the contractors about their construction plans, and they told me they were planning on continuing the construction on Monday (i.e., not working today or Saturday).
- Additional details are provided in Figure A.206 through Figure A.211.

Figure A.194: Pipe details from the north top section lysimeter (no flow seen).

Figure A.195: Pipe details from the middle top section lysimeter (no flow seen).

Figure A.196: Pipe details from the south top section lysimeter (trickling flow seen).

Figure A.197: Geocomposite drain details in a lysimeter (mud, not water present near the soil pile on the geocomposite drain).

Figure A.198: Geocomposite drain and mud (not mud ridden water) details in a lysimeter.

Figure A.199: Details of the north top section lysimeter (near piping system).

Figure A.200: Details of the middle top section lysimeter (near piping system).

Figure A.201: Details of the south top section lysimeter (near piping system).

Figure A.202: Geomembrane disturbance by the wind in the middle top section.

Figure A.203: Soil pile details in the north top section lysimeter after a rainfall event.

Figure A.204: Soil pile details in the middle top section lysimeter after a rainfall event.

Figure A.205: Soil layer details in the south top section lysimeter after a rainfall event.

Figure A.206: South inclined section details after a rainfall event.

Figure A.207: Middle inclined section details after a rainfall event.

Figure A.208: North inclined section details after a rainfall event.

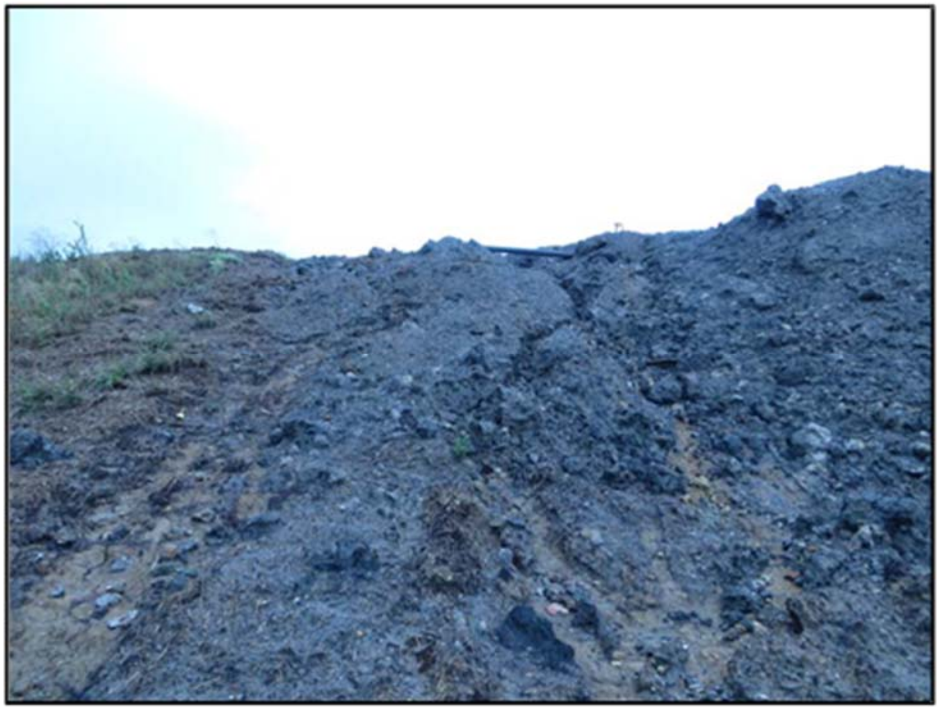


Figure A.209: Downslope embankment details after a rainfall event.

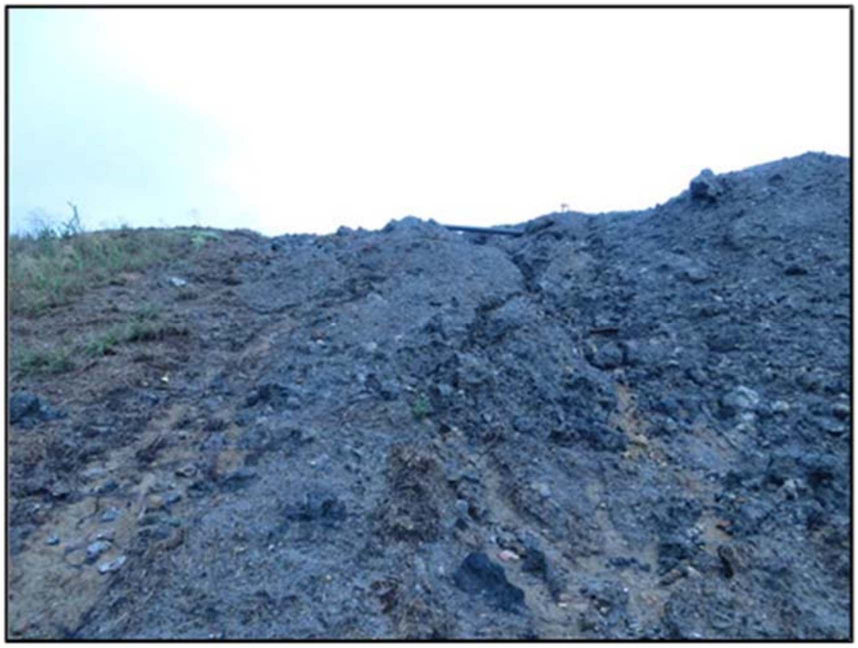


Figure A.210: Gullies formed by water from the north and middle top section lysimeters.

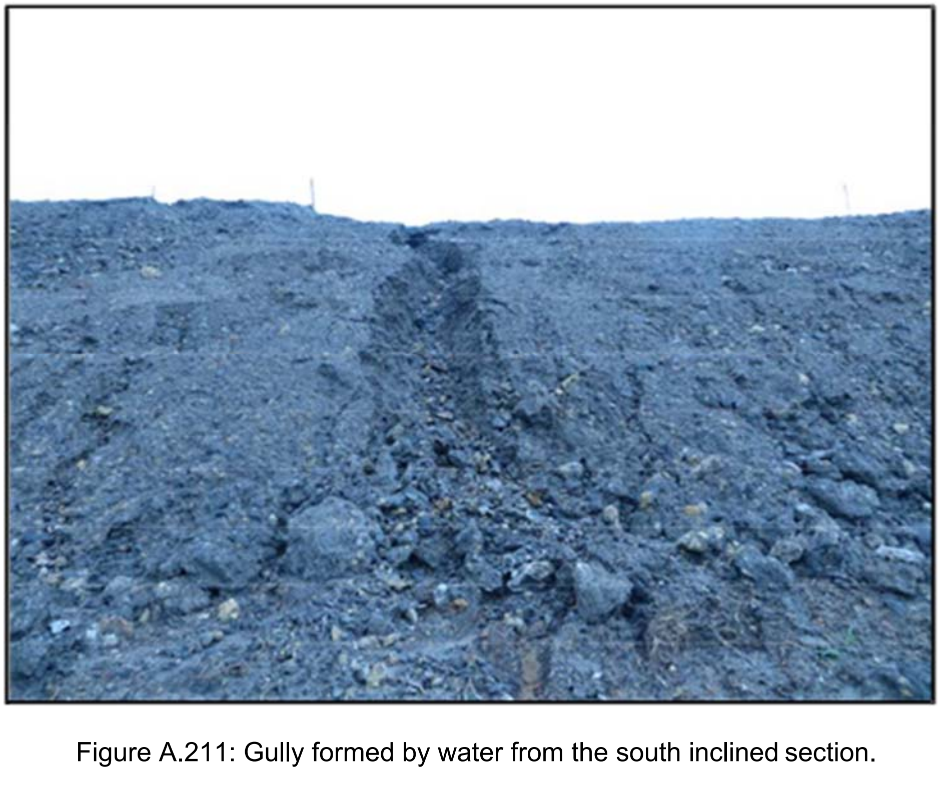


Figure A.211: Gully formed by water from the south inclined section.

A.19 Construction Activities July 21st

The following occurred during the twenty-sixth day (July 21st) of the ET Cover construction:

- A large amount of desiccation cracks was seen in the south top test section of the first coversoil layer (Figure A.212 and Figure A.213).
- Additional details of prior to the day´s construction are shown in Figure A.214 through Figure A.224.
- Construction began early in the afternoon.
- The first soil layer was placed on the north top section (Figure A.225).
- The sheep-footed compactor was run in a back-and-forth motion over the first soil layer in thesouth top section (Figure A.226 and Figure A.227).

Figure A.212: Desiccation cracks present in the south top test section-one (1).

Figure A.213: Desiccation cracks present in the south top test section-two (2).

Figure A.214: Soil pile in the middle top section lysimeter.

Figure A.215: Soil pile in the north top section lysimeter.

Figure A.216: North inclined test section current excavation progress.

Figure A.217: Middle inclined test section current excavation progress.

Figure A.218: South inclined test section current excavation progress.

Figure A.219: Embankment below the inclined sections.

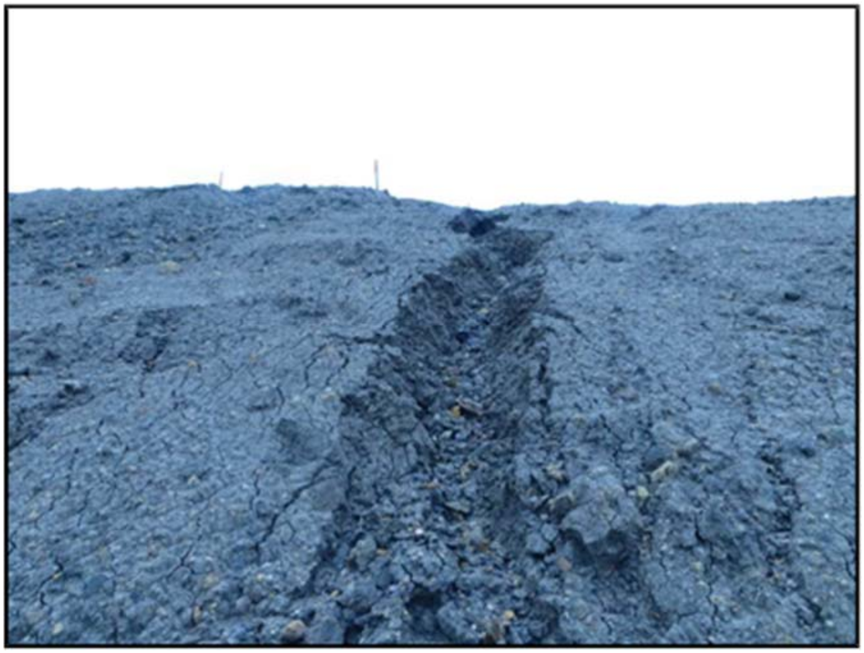


Figure A.220: Drainage gully from the south inclined section.

Figure A.221: South top section details.

Figure A.222: Middle top section details.

Figure A.223: North top section details.

Figure A.224: Drainage gullies form the middle and north top sections.

Figure A.225: First soil layer placement on the north top section.

Figure A.226: Sheep-footed compactor on the south top section-one (1).

Figure A.227: Sheep-footed compactor on the south top section-two (2).

A.20 Construction Activities July 22nd

The following occurred during the twenty-seventh day (July 22nd) of the ET Cover construction:

- Lower berms in the north and middle inclined sections were reconstructed (Figure A.228).
- A skid-steer was used to spread the first soil layer over the middle top section (Figure A.229).
- A skid-steer was used on all three (3) of the first soil layers in the top sections (Figure A.230, Figure A.231,and Figure A.232).
- The percolation pipe from the middle top section was covered with soil and I marked the outletof the pipe from the north top section (Figure A.233).

- The geomembrane and geocomposite drain were pulled over into the inclined sections to complete the first layer soil placement in the top sections (Figure A.234 and Figure A.235).
- Holes in the geomembrane (on the top berm of the north inclined section) and geocomposite drain (near the top of the middle berm between the top and inclined sections) (Figure A.236, Figure A.237, and Figure A.238). Can be fixed and imperfections in the geomembrane near the holes were investigated and none were found.
- Gravel and clay was found and removed near the percolation pipe in the north top section (Figure A.239).
- The water truck from the City of Denton was driven by the contractors to a position that it may flip (Figure A.240, Figure A.241, and Figure A.242). The water had to be removed and the excavator used to pull the water truck out of that position.
- Nuclear density tests were conducted on the first layers in the top sections [two (2) in the south and one (1) each of the middle and north test sections]. Confusion about the required cover soil density began when D&S (density testers) had different requirements (85% max density and dry of optimum) than what was originally thought (95% max density). Shall be remedied in the morning.

Figure A.228: Reconstruction of the lower berms in the inclined sections.

Figure A.229: Skid-steer used to spread the first soil layer.

Figure A.230: Sheep-footed compactor used in middle top section.

Figure A.231: First soil layer after compaction in the south top test section.

Figure A.232: Sheep-footed compactor used in north top section.

Figure A.233: Percolation pipe outlets.

Figure A.234: Geosynthetics pulled over into an inclined section.

Figure A.235: Pulling over the geosynthetics into the inclined sections.

Figure A.236: Locations of the holes in the geomembrane (circled by the paint).

Figure A.237: Hole in the geomembrane-one (1).

Figure A.238: Hole in the geomembrane-two (2).

Figure A.239: Removal of soil near the percolation pipe.

Figure A.240: City of Denton water truck´s back wheels lifting off of the ground.

Figure A.241: Removal of water from the water truck to avoid flipping.

Figure A.242: Excavator used to move the water truck.

A.21 Construction Activities July 23rd

The following occurred during the twenty-eighth day (July 23rd) of the ET Cover construction:

- It was decided to proceed with 95% compaction effort without a moisture content requirement.
- It was emphasized to the contractors to do the following:
    - Keep the soil moist to avoid desiccation cracking, with emphasis on when they place the subsequent soil lift.
    - To avoid turning sharply, creating ruts, or hitting the liner system when placing the soil lift or in general.
    - Place the 1-foot of subgrade soil in the inclined sections.
    - Ensure that the inclined sections are square and have 40-foot lengths.
    - Ensure that the sidewalls are straight and preferably tapered (for ease of geomembrane placement.

  - Ensure that the sidewalls are compacted to avoid soil falling when the geomembrane is placed.
  - Ensure that the embankment below the inclined sections is stable.
- D&S shall test all six (6) lysimeters at the same time (subgrade in the inclined sections and 1st soil layer in the top sections) to ensure the 85% compaction effort.
- A roadway was placed for the water truck near the top sections to effectively apply water to the top test sections (Figure A.243). Additionally, the water truck was left near the middle top section overnight

The sheep-footed compacted was rolled over the top sections to achieve a compaction effort of 95% (the top sections failed to achieve such a density the previous day, but the moisture content was wet of optimum) (Figure A.244).

- Water was applied to the top sections early in the afternoon and at the end of the day to avoid desiccation cracking (Figure A.245).
- The lower section subgrades were modified by the excavator (Figure A.246) and compacted by the sheep-footed compactor (Figure A.247).
- Special attention was paid to verify that the contractors did not compromise the liner systems.
- Soil samples were taken from 1st soil layer in the middle and north top sections (Figure A.248).

Figure A.243: Roadway construction for the water truck.

Figure A.244: 1st soil layer compacted by the sheep-footed compactor.

Figure A.245: Water application to the 1st soil layer in a top section.

Figure A.246: Modification of the inclined section subgrade by the excavator.

Figure A.247: Compaction of the subgrade by the sheep-footed compactor.

Figure A.248: Taking a soil sample from the middle top section

A.22 Construction Activities August 4th

The following occurred August 4th for the ET cover construction:

- The cover soil on the top sections was adjusted (and shall be finalized after the inclined sectioncover soil is placed) in accordance to the surveyor's stakes (Figure A.249).
- Water remained at the bottom of the inclined sections from the rainfall events of the previousweeks, so the excavator was used to remove some of the soil and water (Figure A.250).
- The geomembrane between the top and inclined sections was flipped to the top sections inpreparation for subgrade adjustment (Figure A.251).
- The middle berms (between the inclined and top sections) were adjusted but not completed bya skid-steer (
- Figure A.252).

Figure A.249: Cover soil adjustment in a top section by a skid-steer.

Figure A.250: Removal of soil and water from the bottom of an inclined section.

Figure A.251: Geomembrane placement for subgrade and middle berm complection

Figure A.252: Middle berm adjustment by a skid steer.

A.23 Construction Activities August 5th

The following occurred August 5th for the ET Cover construction:

- Water remained in the bottom of the inclined sections; therefore, the damp soil was removed by the skid-steer and excavator, and drier soil was put in its place (Figure A.253 and Figure A.254).
- Subgrade in the inclined sections was finalized by the skid-steer (Figure A.255). Note: little sandy soil was placed due to the excessive slope present and to try and avoid sharp/pointed rocks near the geomembrane.
- The ramps in the inclined sections were removed by the excavator and the subgrade was adjusted (as best as possible) in those areas (Figure A.256).
- Soil clods and other subgrade imperfections were removed from the inclined sections by hand (Figure A.257).
- A laser-level was used to verify the correct slope at the bottom of the inclined sections in preparation for the drainage pipe (Figure A.258).

- The surveyor came and took subgrade, inclined section, and cover soil elevations (Figure A.259).
- Details of the subgrade in the inclined sections are provided in Figure A.260 through Figure A.265.
- The subgrades were prepared such that the COD and UTA can place the liner system.

Figure A.253: Removal of water and damp soil from an inclined section by a skid steer.

Figure A.254: Removal of water and damp soil from an inclined section by an excavator.

Figure A.255: Subgrade finalization in an inclined section by a skid-steer.

Figure A.256: Removal of the construction ramps in an inclined section by an excvator.

Figure A.257: Removal of subgrade imperfections in an inclined section.

Figure A.258: Slope verification in the bottom of an inclined section by a laser-level.

Figure A.259: Surveyor taking a subgrade elevation in an inclined section.

Figure A.260: South inclined section subgrade details-one (1).

Figure A.261: South inclined section subgrade details-two (2).

Figure A.262: Middle inclined section subgrade details-one (1).

Figure A.263: Middle inclined section subgrade details-two (2).

Figure A.264: North inclined section subgrade details-one (1).

Figure A.265: North inclined section subgrade details-two (2).

A.24 Construction Activities August 6th

The following occurred August 6th for the ET Cover construction:

- Rocks and soil clods were removed from the inclined section subgrades to avoid puncturing the geomembrane (Figure A.266).
- Adequate amounts of geomembrane for the inclined sections were rolled-out and cut for all inclined sections (Figure A.267).
- Holes and imperfections were checked in each of the geomembrane sheets (Figure A.268).
- Welding of the geomembrane in the south inclined section began (Figure A.269).

Figure A.266: Removing rocks and soil clods from the subgrade prior to geomembrane placement.

Figure A.267: Rolling of geomembrane to the appropriate length.

Figure A.268: Checking for holes and imperfections in the geomembrane.

Figure A.269: Welding of the geomembrane in the south inclined section.

A.25 Construction Activities August 7th

The following occurred August 7th for the ET Cover construction:

- The boots for the inclined sections were constructed with the following procedure:
    1. A small geomembrane sheet was cut to approximately 1.5- by 1.5-feet.
    2. The 4-inch HDPE pipe was used to trace a circle in the geomembrane sheet (Figure A.270).
    3. The circle was cut-out in preparation for the 4-inch HDPE pipe to be inserted (Figure A.271).
    4. The 4-inch HDPE pipe was inserted into the hole in the geomembrane sheet and thiswas placed into the 6-inch HDPE pipe in preparation for welding (Figure A.272).
    5. The 4-inch HDPE pipe was heated to properly weld the geomembrane sheet to the HDPEpipe (Figure A.273).

6. The pipe and geomembrane sheet were welded together with the welding gun (Figure A.274 and Figure A.275).
7. The pipe and sheet were flipped over and welded for an adequate seal.
8. This process was repeated for the remaining two (2) boots.

- Welding of the geomembrane in the south inclined section began; however, the weldermalfunctioned and we are still waiting for a new one to be delivered.

Figure A.270: Tracing the pipe to effectively cut the hole in a geomembrane sheet.

Figure A.271: Cutting the hole in the sheet for the 4-inch HDPE pipe.

Figure A.272: Placing the geomembrane sheet and 4-inch pipe in a 6-inch pipe in preparation of welding.

Figure A.273: Heating the 4-inch HDPE pipe in preparation of welding it to the geomembrane sheet.

Figure A.274: Welding the geomembrane sheet to the 4-inch HDPE pipe.

Figure A.275: Results of the welding procedure.

A.26 Construction Activities August 8th

The following occurred August 8th for the ET Cover construction:

- A replacement welder did not arrive, so geomembrane welding did not occur.
- Sodium bentonite (to place between the sidewalls and cover soil to prevent the flow of waterdown the sidewall) was located and can be purchased from a store in McKinney.

A.27 Construction Activities August 11th

The new welder had not arrived yet; therefore, construction did not progress.

A.28 Construction Activities August 12th

The following occurred August 12th for the ET Cover construction:

- Welding continued in the south inclined section.
- Some of the welding separated along the seam in the middle berm and required rewilding. Sandbags were made and placed below the weld to prevent

separation (Figure A.276). The sandbagging seemed to work and rewelding was not required the rest of the week.

- In anticipation of the boot placement, only slightly over half of the required welds for the south inclined section were completed.
- Water was placed on the on the middle inclined section prior to geomembrane placement (Figure A.277).
- Geomembrane was placed, but not welded in the middle inclined section (Figure A.278).

Figure A.276: Sandbag placement along the middle berm.

Figure A.277: Water application to the middle inclined section.

Figure A.278: Geomembrane placement in the middle inclined section.

A.29 Construction Activities August 13th

The following occurred August 13th for the ET Cover construction:

- Welding of the geomembrane continued in the middle inclined section.
- Similar to the south incline section, slightly only half of the geomembrane was welded in anticipation to boot placement.
- Water was applied to the north inclined section prior to the geomembrane placement.
- The geomembrane was placed and welding began in the north inclined section.
- Additional sandbags were made and placed in the lysimeter and along the edges to prevent wind damage.

A.30 Construction Activities August 14th

The following occurred August 14th for the ET Cover construction:

- Welding of the geomembrane continued and was finished in the north inclined section.
- Soil near the boot was removed with the excavator and the boot and perforated pipe was placed in the north inclined section (Figure A.279, Figure A.280, and Figure A.281).
- The remainder of the required welds in the north inclined section was completed.

Figure A.279: Cutting the HDPE pipe in preparation for welding.

Figure A.280: Welding of the HDPE pipe.

Figure A.281: Boot placement in an inclined section.

Figure A.282: North inclined section with geomembrane and HDPE piping system in place.

A.31 Construction Activities August 15th

The following occurred August 15th for the ET Cover construction:

- A roadway was constructed below the inclined section for the excavator in preparation of the boot and “burrito” placement.
- The remainder of the required welds in the south inclined section was completed.
- Soil was excavated and the boot and HDPE pipe in the middle inclined section was constructed (Figure A.283).
- The remainder of the required welds in the middle inclined section was completed.
- Additional sandbags were made and placed to prevent wind damage to the geomembrane.

Figure A.283: Middle inclined section with geomembrane and HDPE piping system in place.

A.32 Construction Activities August 16th

The following occurred August 16th for the ET Cover construction:

- Soil was excavated and the boot and HDPE pipe in the south inclined section was constructed (Figure A.284).

- The welds and the imperfections in the geomembrane in all of the inclined sections werechecked and repaired with the welder.
- The geocomposite drain in for the “burrito” was cut to 7.5 by 37-foot wide sections (Figure A.285). The roadway was adjusted in the bottom of the inclined sections were adjusted in anticipationof the burrito construction.

Figure A.284: South inclined section with geomembrane and HDPE piping system in place.

Figure A.285: Cutting the geocomposite drain.

A.33 Construction Activities August 18th

- Sandbags were made in anticipation of the “burrito wrap” construction.
- The geocomposite drain for the “burrito wrap” was placed in the middle and north inclined sections (Figure A.286).
- Sandbags were placed below the geocomposite in the middle and north inclined sections to form an arc (hopefully making the “burrito wrap” construction easier) (Figure A.287).
- A roadway below the inclined sections was constructed to effectively place the granular material in the “burrito wrap” in each of the inclined sections (Figure A.288 and Figure A.289).
- Several pictures after the rain event on Sunday are provided in Figure A.290, Figure A.291, and Figure A.292.

- Outflow from the percolation pipes was evident from each of the inclined sections as a result of the rainfall.

Figure A.286: Geocomposite drain and sandbag placement for the “burrito wrap.”

Figure A.287: Sandbag placement for the "burrito wrap."

Figure A.288: Roadway constructed below the south and middle inclined sections.

Figure A.289: Roadway constructed below the north inclined section.

Figure A.290: After rainfall event details of the south inclined section.

Figure A.291: After rainfall event details of the middle inclined section.

Figure A.292: After rainfall event details of the north inclined section.

A.34 Construction Activities August 19th

- The roadway below the north inclined section was completed.
- The “burrito wraps” were constructed in all of the inclined sections (Figure A.293 through Figure A.296).
- Geocomposite drain was cut to appropriate size (40-foot length) to cover the bottom of the inclined section lysimeters (Figure A.297).
- The geocomposite drain was placed in the south inclined section and zip-tied (Figure A.298 and Figure A.299).

Figure 8: Granular material placement in a "burrito wrap."

Figure A.293: Placing zip-ties to secure the "burrito wrap."

Figure A.294: Completed “burrito wrap” in the north inclined section.

Figure A.295: Completed “burrito wrap” in the middle inclined section.

Figure A.296: Nearly completed “burrito wrap” in the south inclined section.

Figure A.297: Cutting the geocomposite drain to appropriate size.

Figure A.298: Placing a zip-tie at the intersection of two (2) geocomposite drain sheets.

Figure A.299: Geocomposite drain placed in the south inclined section.

A.35 Construction Activities August 20th

- The geocomposite drain was placed and zip-tied in the middle and south inclined sections.
- The geotextile (i.e., felt) was removed from the geocomposite and placed on the sidewalls of each inclined section (to protect the geomembrane), these were zip-tied to the geocomposite drain (Figure A.300).
- The inclined lysimeter with all of the geosynthetics placed (i.e., geomembrane, geocomposite drain, and geotextile) are shown in Figure A.301, Figure A.302, Figure A.303.
- The contractors were contacted and told that the site was ready for compacted clay placement.

Figure A.300: Removal of the geotextile from the geocomposite drain.

Figure A.301: All of the geosynthetics placed in the south inclined section.

Figure A.302: All of the geosynthetics placed in the middle inclined section.

Figure A.303: All of the geosynthetics placed in the north inclined section.

A.36 Construction Activities August 21st

- Items and tires were gathered and removed from the site by the COD and UTA.

- The contractors came and began constructing an entrance ramp into the southeast cover of the south top section (Figure A.304).
- The surveyor came out and took elevations at the top of the geocomposite in the inclined sections.
- The liner was hit and cut by the contractors in the south top section (southeast cover) and requires a patch to be welded (Figure A.305).
- Soil was placed between the top sections to protect the liner during inclined section soil placement (Figure A.306).
- Ramps were constructed in the north and south inclined sections in anticipation of soil placement (Figure A.307).
- A skid-steer was used to place the soil in the inclined section lysimeters and was also used to compact the soil because the clay was slightly wet (Figure A.308).
- The soil was taken from the borrow pit as shown in Figure A.309.
- Special attention was paid to not hit the liner or the “burrito wrap” in the lysimeters.
- The first 8-inch compacted clay lift was completed in the north and south inclined sections (Figure A.310 and Figure A.311).

Figure A.304: Entrance ramp constructed in the southeast corner of the south top section.

Figure A.305: Liner cut details in the southeast corner of the south top section.

Figure A.306: Geosynthetic protection soil placed on the top sections.

Figure A.307: Entrance ramp construction for soil placement in an inclined section.

Figure A.308: 1st soil layer placed in the north inclined section.

Figure A.309: Obtaining soil from the borrow pit.

Figure A.310: 1st soil layer placed in the south inclined section.

Figure A.311: 1st soil layer placed in the north inclined section.

A.37 Construction Activities August 22nd

- The cut in the geomembrane in the south top section was repaired by the COD and UTA.

- More soil was placed on the entrance ramp in the south top section to prevent another incident with the liner.
- More soil was also placed between the top section lysimeters to prevent the contractors from hitting the liner.
- Soil was placed in the middle inclined lysimeter (1st 8-inch layer) and compacted.
- The north and south inclined sections were compacted again with the skid-steer.
- The skid-steer made a hole in the liner in the south inclined section (northeast corner) and was fixed by UTA and the contractors (Figure A.312).
- Soil was taken from the borrow pit as shown in Figure A.313.
- D&S came out and conducted nuclear density tests on the 1st soil layer in the inclined sections, all tests passed the 95% compaction effort requirement (Figure A.314).
- The 2nd soil layer in the south inclined section began being placed.

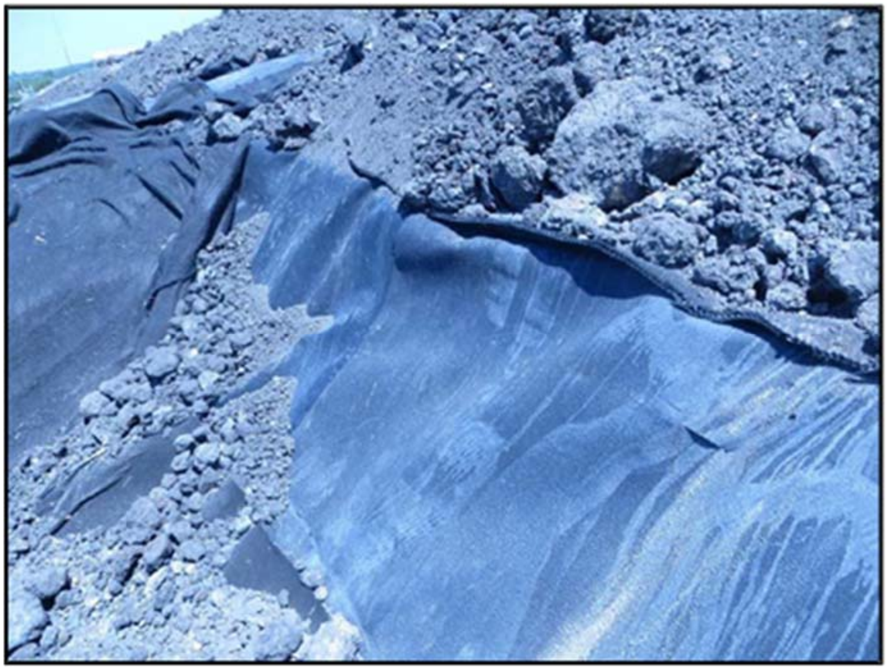
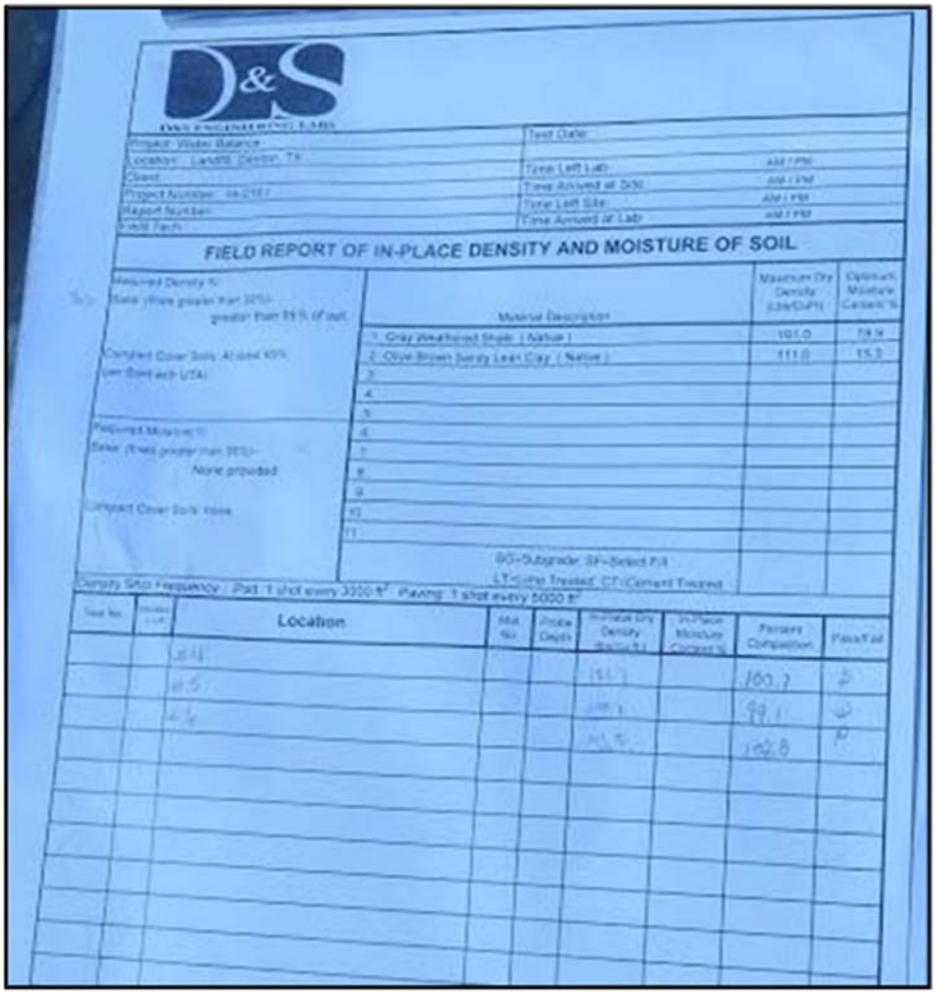


Figure A.312: Cut in the liner.

Figure A.313: Obtaining soil from the borrow pit.



FIELD REPORT OF IN-PLACE DENSITY AND MOISTURE OF SOIL

Project: Water Balance

Location: Landfill, Denton, TX

Test Date:

Material Description	Maximum Dry Density	Optimum Moisture Content %
1. Gray Weathered Shale (Native)	101.0	19.9
2. Olive Brown Sandy Lean Clay (Native)	111.0	15.5

Location	Percent Compaction	Pass/Fail
	100.7	P
	99.1	P
	102.8	P

Figure A.314: Nuclear density results for the 1st soil layer.

A.38 Construction Activities August 25th

The following occurred August 25th for the ET Cover construction:

- Desiccation cracks were found in the first 8-inch lift in the inclined sections; therefore, the skid-steer was used to scrape off the top of the layer and remove the cracks (Figure A.315).
- The second soil lift was placed in the north and middle inclined sections.
- A separation in the weld was found in the middle inclined section (northeast corner) and was repaired by the COD (Figure A.316).

- Water was applied to the top of the second 8-inch lift and was left to soak in overnight (Figure A.317).
- The contractors tried to compact the inclined section with a dump truck (against myrecommendation) and got stuck. Had to be pulled out by another dump truck (Figure A.318).
- Details at the end of the day of the inclined sections are provided in Figure A.319, Figure A.320, and Figure A.321.

Figure A.315: Desiccation cracks found in the top of the soil layer.

Figure A.316: Results of re-welding the separation in the liner.

Figure A.317: Applying water to an inclined selection.

Figure A.318: Trying to get the dump truck unstuck.

Figure A.319: End of the day details of the north inclined section.

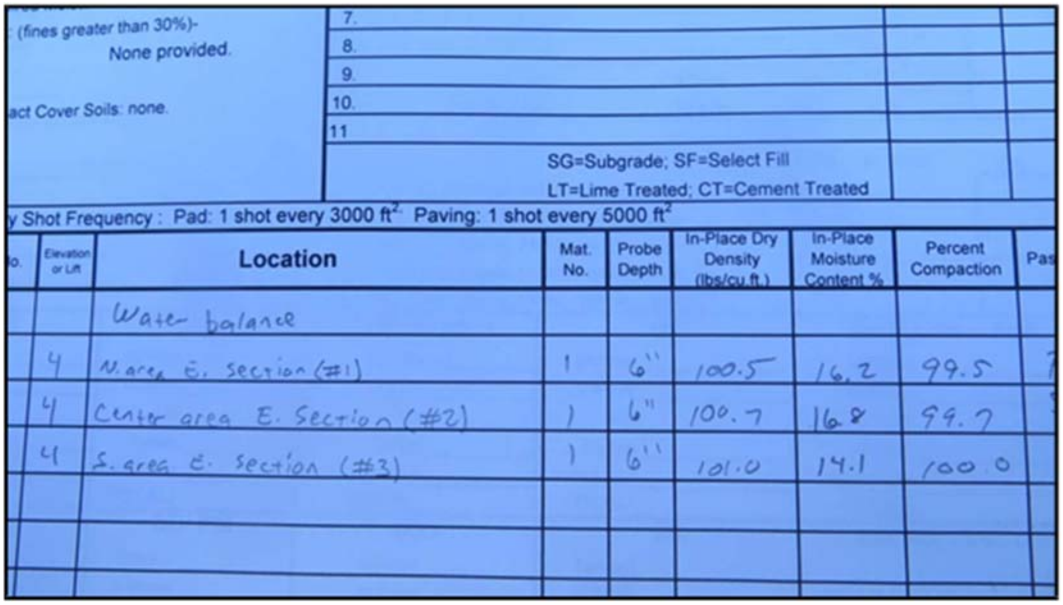
Figure A.320: End of the day details of the middle inclined section.

Figure A.321: End of the day details of the south inclined section.

A.39 Construction Activities August 26th

The following occurred August 26th for the ET Cover construction:

- The skid-steer was used to compact the 2nd soil layer prior to nuclear density testing.
- Several compacted clay lifts were completed (up to approximately 3-feet) by the end of the day.
- D&S came to conduct nuclear density tests at the completion of each lift (results shown in Figure A.322 and Figure A.323).
- Soil was taken from the borrow pit from the location shown in Figure A.324.
- End of the day details of the inclined sections are shown in Figure A.325, Figure A.326, and Figure A.327.



(fines greater than 30%)-
None provided.

act Cover Soils: none.

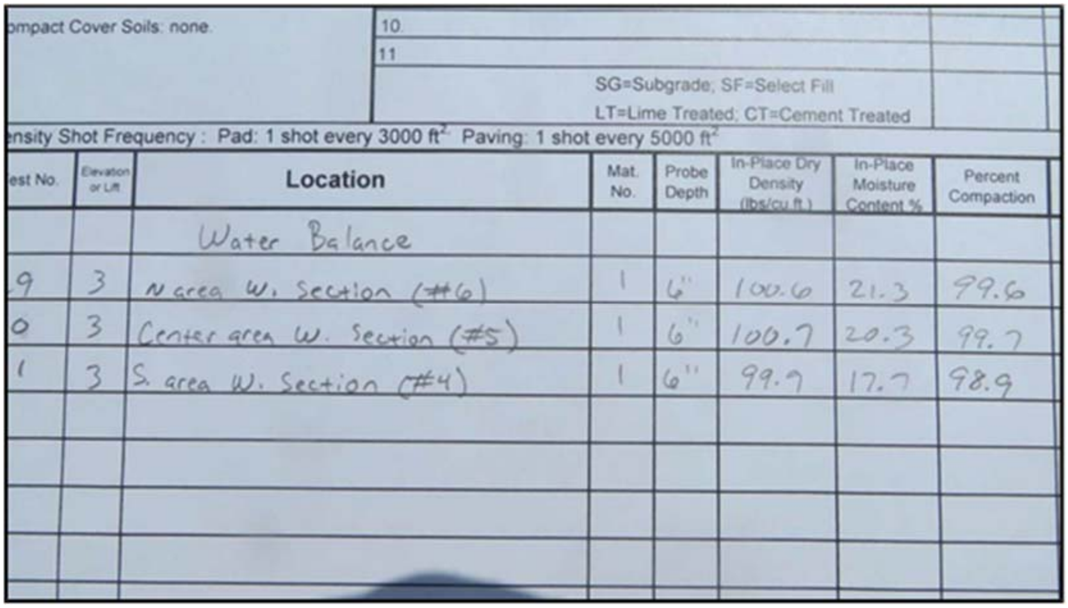
7.
8.
9.
10.
11

SG=Subgrade; SF=Select Fill
LT=Lime Treated; CT=Cement Treated

y Shot Frequency : Pad: 1 shot every 3000 ft² Paving: 1 shot every 5000 ft²

o.	Elevation or Lift	Location	Mat. No.	Probe Depth	In-Place Dry Density (lbs/cu ft.)	In-Place Moisture Content %	Percent Compaction	Pas
		Water balance						
	4	N. area E. section (#1)	1	6''	100.5	16.2	99.5	
	4	Center area E. Section (#2)	1	6''	100.7	16.8	99.7	
	4	S. area E. section (#3)	1	6''	101.0	14.1	100.0	

Figure A.322: Second soil lift nuclear density testing results.



ompact Cover Soils: none.

10

11

SG=Subgrade; SF=Select Fill

LT=Lime Treated; CT=Cement Treated

nsity Shot Frequency : Pad: 1 shot every 3000 ft^2 Paving: 1 shot every 5000 ft^2

est No.	Elevation or Lift	Location	Mat. No.	Probe Depth	In-Place Dry Density (lbs/cu ft.)	In-Place Moisture Content %	Percent Compaction
		Water Balance					
9	3	N area W. Section (#6)	1	6"	100.6	21.3	99.6
0	3	Center area W. Section (#5)	1	6"	100.7	20.3	99.7
1	3	S. area W. Section (#4)	1	6"	99.9	17.7	98.9

Figure A.323: Third soil lift nuclear density testing results.

Figure A.324: Location of soil removal from the borrow pit.

Figure A.325: End of the day details of the north inclined section.

Figure A.326: End of the day details of the middle inclined section.

Figure A.327: End of the day details of the south inclined section.

A.40 Construction Activities August 27th

The following occurred August 27th for the ET Cover construction:

- The surveyor came and took elevations in the inclined sections to verify the 3-feet of compacted clay.
- D&S also came to test the 4th soil lift that was placed the previous day.
- No other construction occurred.

A.41 Construction Activities August 28th

The following occurred August 28th for the ET Cover construction:

- Soil was removed by the COD and UTA around the outer edges of the north and middle top sections in preparation for bentonite placement and putting the sidewalls vertical (Figure A.328 and Figure A.329).

Figure A.328: Removing soil from the lysimeter boundaries-one (1).

Figure A.329: Removing soil from the lysimeter boundaries-two (2).

A.42 Construction Activities August 29th

The following occurred August 29th for the ET Cover construction:

- Morning rainfall caused construction to not occur today.

A.43 Construction Activities August 30th

The following occurred August 30th for the ET Cover construction:

- Stakes were placed by UTA to ensure that the 3-foot of compacted clay requirement is achieved (Figure A.330).
- There was a wet spot in the middle top section and the contractor ran a dump truck into it (Figure A.331).
- Compacted clay was placed to achieve the 3-foot thickness requirement.

Figure A.330: Stake and soil placement in the inclined sections.

Figure A.331: Results of the dump truck running into a wet spot.

A.44 Construction Activities September 2nd

The following occurred September 2nd for the ET Cover construction:

- Stakes were placed around the boundaries of some of the north and middle top sections, and the inclined sections; and the topsoil sidewalls were placed vertical (Figure A.332 and Figure A.333).
- Soil was removed from the west side of the middle and south inclined sections in preparation of bentonite and topsoil sidewall placement (Figure A.334).

Figure A.332: Topsoil sidewall placement in an inclined section.

Figure A.333: Topsoil sidewalls placed vertical between inclined sections.

Figure A.334: Soil removal in an inclined section boundary.

A.45 Construction Activities September 3rd

The following occurred September 3rd for the ET Cover construction:

- Sodium bentonite were placed around the boundaries of some of the north and middle topsections, and the inclined sections; and the topsoil sidewalls were placed vertical (Figure A.335 and Figure A.336). The bentonite used is shown in Figure A.337.
- Soil was placed on the bentonite (Figure A.338).
- The site was cleaned in anticipation of the topsoil placement.
- End of the day details are provided in Figure A.339 though Figure A.343.

Figure A.335: Placing sodium bentonite around the edges of a lysimeter-one (1).

Figure A.336: Placing sodium bentonite around the edges of a lysimeter-two (2).

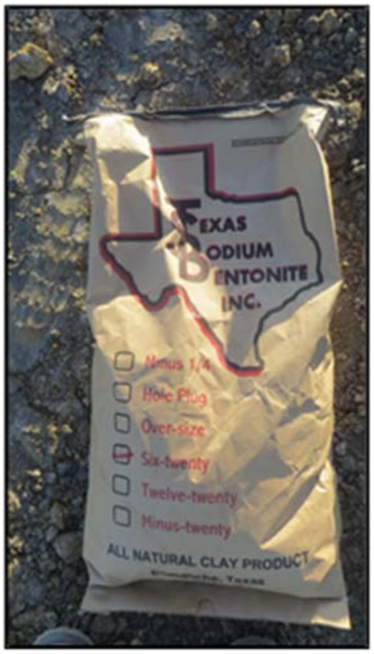


Figure A.337: Sodium bentonite details.

Figure A.338: Placing soil on the sodium bentonite.

Figure A.339: End of the day details of the top sections.

Figure A.340: End of the day details of the south inclined section.

Figure A.341: End of the day details of the middle inclined section.

Figure A.342: End of the day details of the middle and north top sections.

Figure A.343: End of the day details of the north inclined section.

A.46 Construction Activities September 4th

The following occurred September 4th for the ET Cover construction:

- Topsoil sidewalls were adjusted to accommodate topsoil placement.
- Stakes were placed in the top sections to approximate the top of the compacted clay based on previous surveying results.
- Construction did not begin until early afternoon.
- The surveyor came and gave elevations and required cut/fill in the inclined sections. UTA then placed stakes at elevation locations and marked required cut/fill.
- The contractor adjusted the north and middle inclined sections and the north top section (Figure A.344).
- Water was applied to the inclined sections by the water wagon to achieve adequate compaction and left to sit overnight (Figure A.345).

Figure A.344: Adjusting the compacted clay in the north top section.

Figure A.345: Applying water to the north inclined section.

A.47 Construction Activities September 5th

The following occurred September 5th for the ET Cover construction:

- Beginning of the day details of the inclined sections are shown in Figure A.346, Figure A.347, and Figure A.348.
- Desiccation cracking was present in the inclined sections (Figure A.349).
- The liner was hit twice (fortunately between the top sections in both cases) (Figure A.350 and Figure A.351).
- String lines were placed in the south and middle inclined sections by UTA to help achieve the 3-foot compacted clay requirement (Figure A.352).
- Soil was placed in the inclined sections and cut from the top sections (wherever necessary).
- End of the day details are provided in Figure A.353 through Figure A.356.

Figure A.346: Beginning of the day details of the south inclined section.

Figure A.347: Beginning of the day details of the middle inclined section.

Figure A.348: Beginning of the day details of the north inclined section.

Figure A.349: Desiccation cracks present in an inclined section.

Figure A.350: Cut in the liner between the south and middle top sections.

Figure A.351: Cut in the liner between the north and middle inclined sections.

Figure A.352: String line placed to achieve the 3-foot of compacted clay requirement.

Figure A.353: End of the day details of the south inclined section.

Figure A.354: End of the day details of the middle inclined section.

Figure A.355: End of the day details of the north inclined section.

Figure A.356: End of the day details of the top sections.

A.48 Construction Activities September 6th

The following occurred September 6th for the ET Cover construction:

- The COD and UTA made adjustments to some of the corners of the topsoil sidewalls in the inclined sections (required cutting and welding the liner) (Figure A.357).
- The surveyor came out (was at the landfill already) and took elevations in all lysimeters and marked required cut/fill. Cut/fill requirements for the compacted clay are shown in Figure A.358.
- UTA placed stakes at the surveying locations and marked required cut/fill.
- End of the day details are provided in Figure A.359 through Figure A.364.

Figure A.357: Adjustments made to an inclined section corner.

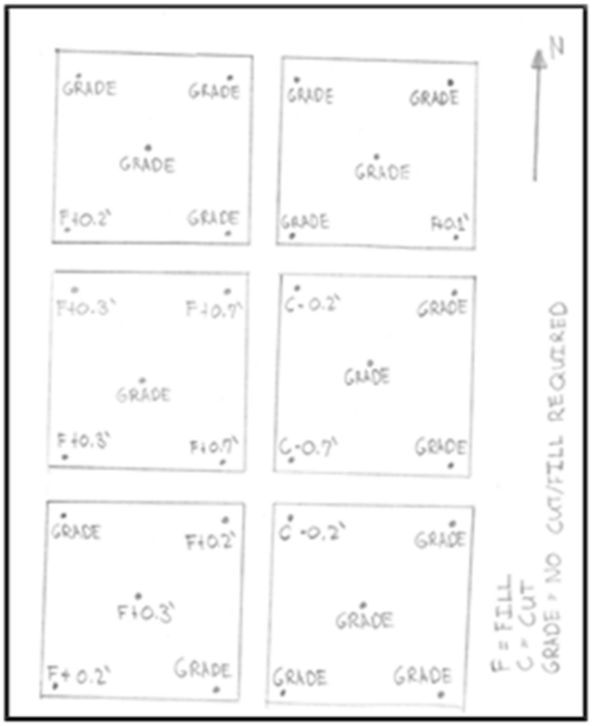


Figure A.358: Cut/fill requirements for the compacted clay.

Figure A.359: End of the day details of the south inclined section.

Figure A.360: End of the day details of the south top section.

Figure A.361: End of the day details of the middle top section.

Figure A.362: End of the day details of the middle inclined section.

Figure A.363: End of the day details of the north top section.

Figure A.364: End of the day details of the north inclined section.

A.49 Construction Activities September 8th

The following occurred September 8th for the ET Cover construction:

- The clay was compacted and adjusted to achieve the 3-foot requirement.
- The liner was cut in the berm between the top and inclined middle sections (Figure A.379 and Figure A.381). This was then repaired by UTA and the contractors.
- Topsoil was placed in the north top and inclined sections, and the inclined middle section (Figure A.382 and Figure A.383).
- The sidewall was messed-up in the north top section when the topsoil was being placed, andhad to be adjusted (Figure A.384).

Figure A.365: Cut in the berm between the top and inclined middle sections-one (1).

Figure A.366: Cut in the berm between the top and inclined middle sections-two (2).

Figure A.367: Repair of the cut in the liner.

Figure A.368: Topsoil placed in the north inclined section.

Figure A.369: Topsoil placed in the north top section.

Figure A.370: Messed-up sidewall in the north top section.

A.50 Construction Activities September 9th

The following occurred September 9th for the ET Cover construction:

- Topsoil was placed and adjusted to the 1-foot requirement in the middle and south sections (Figure A.371 through Figure A.374).
- The skid-steer got stuck in the south inclined section near the sidewall (Figure A.375). The area was checked for punctures in the liner and the sidewall was adjusted.
- Topsoil was not placed near the berm between the top and inclined sections, for sidewall construction purposes.

Figure A.371: Topsoil placed in the middle inclined section.

Figure A.372: Topsoil placed in the middle top section.

Figure A.373: Topsoil placed in the south inclined section.

Figure A.374: Topsoil placed in the south top section.

Figure A.375: Skid-steer stuck in the south inclined section.

A.51 Construction Activities September 10th

The following occurred September 10th for the ET Cover construction:

- Soil was placed to the east and west of the lysimeters, up to near the top of the sidewalls (Figure A.376 and Figure A.377).
- The embankment west of the inclined sections was modified for stability purposes (Figure A.378).
- Soil was removed near the middle berm in the north section, for sidewall construction purposes(Figure A.379).
- Percolation pipes were uncovered north of the lysimeters (Figure A.380).

Figure A.376: Placing soil near the sidewalls.

Figure A.377: Placing soil near the sidewalls and adjusting the embankment.

Figure A.378: Embankment below the lysimeters after adjustment.

Figure A.379: Removing soil for sidewall construction.

Figure A.380: Removing soil near the percolation pipes.

A.52 Construction Activities September 11th

The following occurred September 11th for the ET Cover construction:

- Berms were constructed at the bottom of the inclined sections out of clay (for drainage purposes), and an inlet was cut to accommodate the runoff collection pipe (Figure A.381).
- Six (6) boots were constructed with methods similar to those used previously (Figure A.382).
- Liner was placed in the runoff inlet and geocomposite drain placed on top, in all of the inclined sections (Figure A.383).
- The boots in all of the inclined sections were welded in placed and the liner (previously placed in the runoff inlet) was welded to the sidewall (Figure A.384).
- The burrito wraps were constructed in the inclined sections.

Figure A.381: Berm constructed in an inclined section.

Figure A.382: Boot construction.

Figure A.383: Liner and geocomposite drain placement.

Figure A.384: Welding the boot and liner to the sidewall.

A.53 Construction Activities September 12th

Rainfall occurred September 12th so no construction occurred.

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