THESIS

HYDROLOGIC COMPARISON OF PRESCRIPTIVE AND WATER BALANCE COVERS

Submitted by

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ABSTRACT

HYDROLOGIC COMPARISON OF PRESCRIPTIVE AND WATER BALANCE COVERS

The objective of this study was to compare the water balance of prescriptive and water balance cover (WBC) designs for Larimer County Landfill (LCL) via hydrologic modeling. A prescriptive cover is designed to limit percolation into underlying waste via a low permeability layer, whereas a WBC is designed to limit percolation via storing infiltrated precipitation and subsequently releasing the water through evaporation and transpiration. Guidance on WBC designs in Colorado are based on geographical location of the site and particle-size distribution of the available cover soils. Soil characteristics and engineering properties were determined from exhumed samples for a completed closure phase of LCL (Phase 1) and two borrow areas (Borrow Area 3 and Borrow Area 4). Hydrologic modeling was completed using VADOSE/W to predict the percolation rate through the prescriptive and water balance covers. The wettest ten consecutive years on record with a sufficiently complete meteorological data set (1992-2002) were selected for the analysis. Vegetation parameters were assigned to represent the revegetated state observed in Phase 1 and the natural conditions observed in the borrow areas. Predicted percolation through a prescriptive cover was < 0.1 to 2.2 mm/yr, depending on assumed saturated hydraulic conductivity. Evaporation was the primary process for removing water from the prescriptive cover models. Predicted percolation through the WBC models ranged from 6.3 to 11.3 mm/yr depending on the borrow area soil and vegetation parameters. Transpiration was the primary process for removing water from the WBC models. Within all of the regulatory acceptable cover models' evapotranspiration removed 94 to 102% of the precipitation received during the ten years modeled. Results of this study indicate that either a prescriptive cover with a total thickness of 106.7 cm (3.5 ft) or a WBC with a thickness of 76.2 cm (2.5 ft) will meet regulations for final closure cover at LCL.

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CHAPTER 1: PROBLEM STATEMENT

Final covers at landfills are designed and constructed to reduce the amount of percolation into the underlying waste after closure. Larimer County Landfill (LCL) currently has a prescriptive final cover constructed over four phases of the landfill based on designs approved by the Colorado Department of Public Health and Environment (CDPHE), Hazardous Materials and Waste Management Division. The CDPHE adheres to the Colorado Code of Regulations (CCR) 1007-2, Part 1, Part B, Section 3.5.3, which has the same requirements for final closure covers specified in the Code of Federal Regulations (CFR) Title 40, Subpart 258.60. The CFR requires "an infiltration layer that contains a minimum 18-inches of earthen material" with "a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} centimeters per second (cm/s), whichever is less". Additionally, the CFR regulation requires "an erosion layer that contains a minimum 6-inches of earthen material that is capable of sustaining native plant growth." The specific requirements for final closure covers in the CCR and CFR regulations lends to the nomenclature of a prescriptive cover.

Per both the CFR and CCR regulations, an alternative final cover, such as a water balance cover (WBC), may be approved if equivalency in percolation is demonstrated. Water balance covers have been demonstrated to achieve hydraulic equivalency to prescriptive covers through numerical modeling and field-scale experiments (Dwyer and Reavis, 2002; Zornberg et al. 2003; Schnabel et al. 2012), and have received regulatory approval for construction (Zornberg et al. 2003; McGuire et al. 2009). Water balance covers are typically constructed as a monolithic layer of loosely compacted on-site soils. A required thickness of the cover can be determined via empirical methods, numerical modeling, or field-scale experiments, and construction quality assurance is implemented to verify the soil classification is consistent with the evaluated soil.

Prescriptive final covers rely on a hydraulic barrier to reduce percolation whereas WBC rely on the storage of water within the soil pore space and subsequent release of water through evaporation and transpiration to reduce percolation. The hydraulic performance of a prescriptive cover is typically measured through permeability testing on samples of the cover collected using drive or push samplers immediately following construction. Evaluating the hydraulic performance immediately after construction does not account for pedogenesis that occurs post-closure. Pedogenesis alters the hydrologic properties of cover soils, whereby the saturated hydraulic conductivity (k_s) can increase with time (Othman and Benson 1992; Albright and Benson 2001; Benson et al. 2007). The increase in k_s for a prescriptive cover can result in noncompliance by exceeding the regulatory maximum k_s. Water balance covers offer more resilient hydraulic performance because they do not rely on a hydraulic barrier, but instead rely on available storage within the soil matrix that is less likely to be negatively affected by pedogenesis (Benson et al. 2007). The maintained soil water storage capacity, along with other features such as maturing vegetation with thicker and deeper roots, allow a WBC to maintain or potentially improve hydraulic performance with regards to reducing percolation throughout post-closure.

The objective of this project was to compare the effectiveness of a prescriptive earthen final cover and a WBC in mitigating percolation at the Larimer County Landfill, located in northern Colorado, via variably saturated flow modeling. Modeling of both cover types was conducted for a 10 year period using local meteorological data and the finite element modeling program VADOSE/W (GeoSlope 2016). Model input parameters for the soil layers were based on laboratory test results of soils sampled from the existing final prescriptive cover as well as from on-site borrow areas that would be used to construct a potential WBC. The main hypothesis of the research was that a WBC at LCL could provide hydraulic equivalency to the existing prescriptive final cover. Furthermore, the WBC may be more effective at reducing

percolation during post-closure if the hydraulic conductivity of the prescriptive cover has increased since construction as part of pedogenesis.

CHAPTER 2: INTRODUCTION TO WATER BALANCE COVERS

The hydrologic performance of a soil cover can be summarized by the equation:

$$P = R + E + T + S + P_r \qquad\qquad (2.1)$$

where P is precipitation, R is runoff, E is evaporation, T is transpiration, S is change in soil water storage, and P_r is percolation. The nomenclature of "water balance cover" is chosen because the percolation through a cover can be minimized by balancing the rearranged Eq. 2.1 as Eq. 2.2.

$$P_r = P - R - E - T - S \qquad\qquad (2.2)$$

Water balance covers reduce percolation by relying on the storage of infiltrated precipitation and subsequent release back to the atmosphere through the processes of evaporation and transpiration. Water balance covers are also referred to as store-and-release covers or evapotranspirative (ET) covers.

Water balance covers are constructed using lower compaction effort than a prescriptive cover. The lower compaction effort retains more pore space for water storage within the soil matrix. More pore space aids in root growth by providing pathways for water and roots, which increases the transpiration contribution within the water balance equation. The additional pore space also increases evaporation by allowing more solar energy into the soil and requiring less energy to remove water upwards through the cover as a gas. Runoff is decreased with the lower compaction effort, which can increase the amount of precipitation entering the water storage layer within the WBC and result in increased percolation.

Water balance covers are typically constructed as a monolithic cover using on-site soils to provide cost savings versus importing or amending on-site soils to meet permeability requirements of a prescriptive cover. Ideally the on-site soils would be fine textured with low plasticity and less than 15 % gravel. The ideal particle-size distribution depends on the site conditions, including climate, vegetation, and slopes. Water balance covers typically have a

nutrient rich soil layer (e.g., topsoil) placed above the cover to assist in vegetation growth. The compaction effort applied during construction is recommended to be between 80 and 90 % of the maximum dry density (ρ_{dmax}) as determined by standard Proctor (Albright et al. 2010). This compaction effort is enough to reduce erosion and settlement to tolerable levels while still providing more pore space within the soil versus a prescriptive cover.

A prescriptive cover is a multi-layer cover consisting of an infiltration layer beneath the erosion layer. The infiltration layer is commonly a clay soil compacted to 95 % of ρ_{dmax} and 0 to 2 % above optimum moisture content (w_{opt}) as determined by standard Proctor. This compaction effort with a clay soil tends to meet the permeability requirement of $k_s < 1 \times 10^{-5}$ cm/s. The extra effort of compaction and moisture conditioning adds to the construction cost. If on-site soils cannot achieve the permeability requirement, soil may need to be amended with clay or new soil imported that meets the permeability requirement, resulting in additional cost to the project.

Compacted clay soils are susceptible to formation of macropores due to desiccation, freeze-thaw cycles, and root penetration. The macropore structure of a surficial soil naturally forms from pedogenesis and can create pathways for percolation and further root penetration. These processes can result in an increase in k_s up to three orders of magnitude when compared to the measured rates immediately following construction (Othman and Benson 1992; Albright and Benson 2001; Benson et al. 2007). The erosion layer of a prescriptive cover is intended to protect against these natural processes that cause cracking within a compacted clay layer and is typically constructed with available on-site fill. Finally the prescriptive cover is capped with topsoil similar to a WBC. The compaction effort within these upper two layers is less stringent than the infiltration layer as there are no performance specifications to meet per regulations.

Water balance covers have been demonstrated to reduce percolation to acceptable regulatory standards in numerous projects (Zornberg et al. 2003; Albright et al. 2004; Fayer and Gee 2006; Schnabel et al. 2012; McGuire et al. 2009; Apiwantragoon et al. 2014; Zhang and Sun 2014). The successful implementation of a WBC described by McGuire et al. (2009) is of

particular interest because of the similar geographical and climate conditions to LCL (site was approximately 193 km (120 mi) south of LCL). As part of the study, eleven WBC were constructed and measured percolation rates in a lysimeter ranged from 1.9 x 10^{-10} to 5.1 x 10^{-10} cm/s from 2001 to 2005. The average annual precipitation over that period at the site was 36.6 cm (14.4 in), which is similar to the average annual precipitation of 38.4 cm (15.1 in) in Fort Collins (CSU 2017). The measured percolation rates were in agreement with the model results using input parameters obtained from laboratory testing of local borrow soils.

The CDPHE is the regulatory agency for landfills in Colorado and has published guidance for design, construction, and development of WBC in Colorado (CDPHE 2013). The CDPHE guidance offers a streamlined design approach for WBC based on "Ecozones" delineated throughout the state as shown in Fig. 2.1 and based on cover soil particle size distribution as shown in Fig. 2.2. The CDPHE guidance provides recommendations of construction moisture content, cover soil density, and vegetation. Larimer County Landfill is in Ecozone 3 (Fig. 2.1) and the thickness of acceptable WBC ranges from 76.2 to 122 cm (2.5 to 4 ft) depending on the soil composition.

The required thickness of a WBC can be estimated using an empirical method outlined by Albright et al. (2010). This method uses a ratio of precipitation to potential evapotranspiration (P/PET) developed from site climate data to estimate required storage for a WBC. The monthly values of P/PET are compared to empirical thresholds and if a given monthly value exceeds the thresholds, required storage in that month is summed to calculate a total required storage. The total required soil water storage (S_r) can then be converted to a soil layer thickness (L) as shown in Eq. 2.3:

$$L \geq \frac{S_r}{\theta_c - \theta_m} \tag{2.3}$$

where θ_c is the volumetric water content at field capacity (soil suction = 33 kPa) and θ_m is the volumetric water content at the wilting point (soil suction = 1,500 kPa).

The average monthly P/PET from 1981 through 2010 (WRCC 2017) for Fort Collins, Colorado along with P/PET thresholds identified by Albright et al. (2010) for required storage are shown in Fig. 2.3a. The average annual P/PET ratio in Fort Collins was 0.17, with a minimum of 0.11 in January and a maximum of 0.25 in May. Comparing the thresholds in Albright et al. (2010) to the average P/PET for Fort Collins, no monthly average P/PET exceeded the thresholds of 0.32 for spring / summer or 0.51 for fall / winter, which suggests no storage would be required for the proposed WBC. The same analysis was applied for the wettest year with sufficient data (1997, 3rd wettest since 1889) and the 1997 P/PET versus Albright et al. (2010) thresholds are shown in Fig. 2.3b. The 1997 P/PET did exceed thresholds in April, July, and August; however, progressing through the empirical method for required storage in Albright et al. (2010) indicated that the 1997 analysis also yielded no required storage for the proposed WBC. Based on the calculations and analysis in Fig. 2.3 that indicated no required storage for estimating S_r and subsequently L, Eq. 2.3 was deemed not applicable to LCL. Intuitively, there will be some amount of required storage capacity to store water within the cover and limit percolation into the waste. Thus, thickness of WBC developed for this study were based on CDPHE recommendations (CDPHE 2013).

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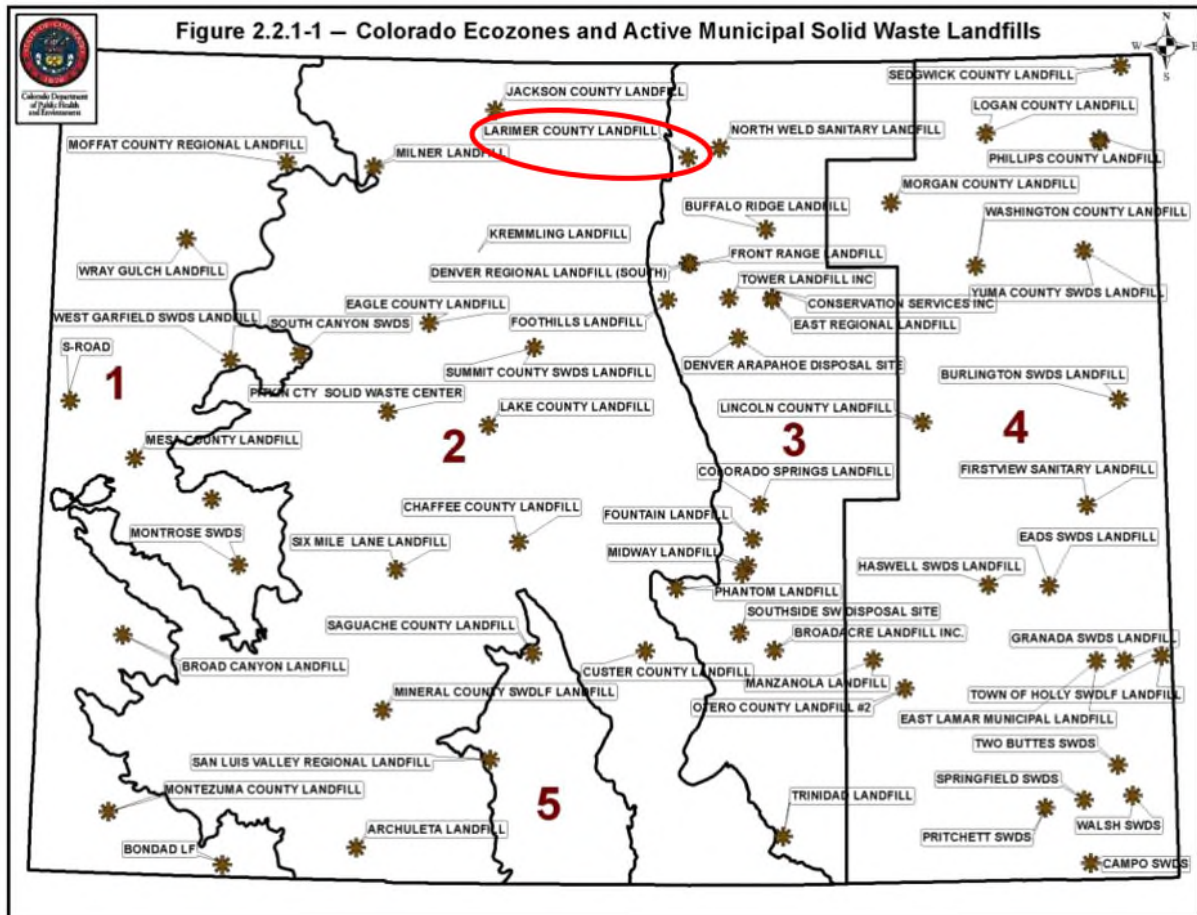
Fig. 2.1 Ecozone delineation from Figure 2.2.1-1 of CDPHE Final Guidance Document on Water Balance Covers in Colorado (CDPHE 2013).

Figure 2.2.1-4
Water Storage Layer Thicknesses for
Ecozone 3
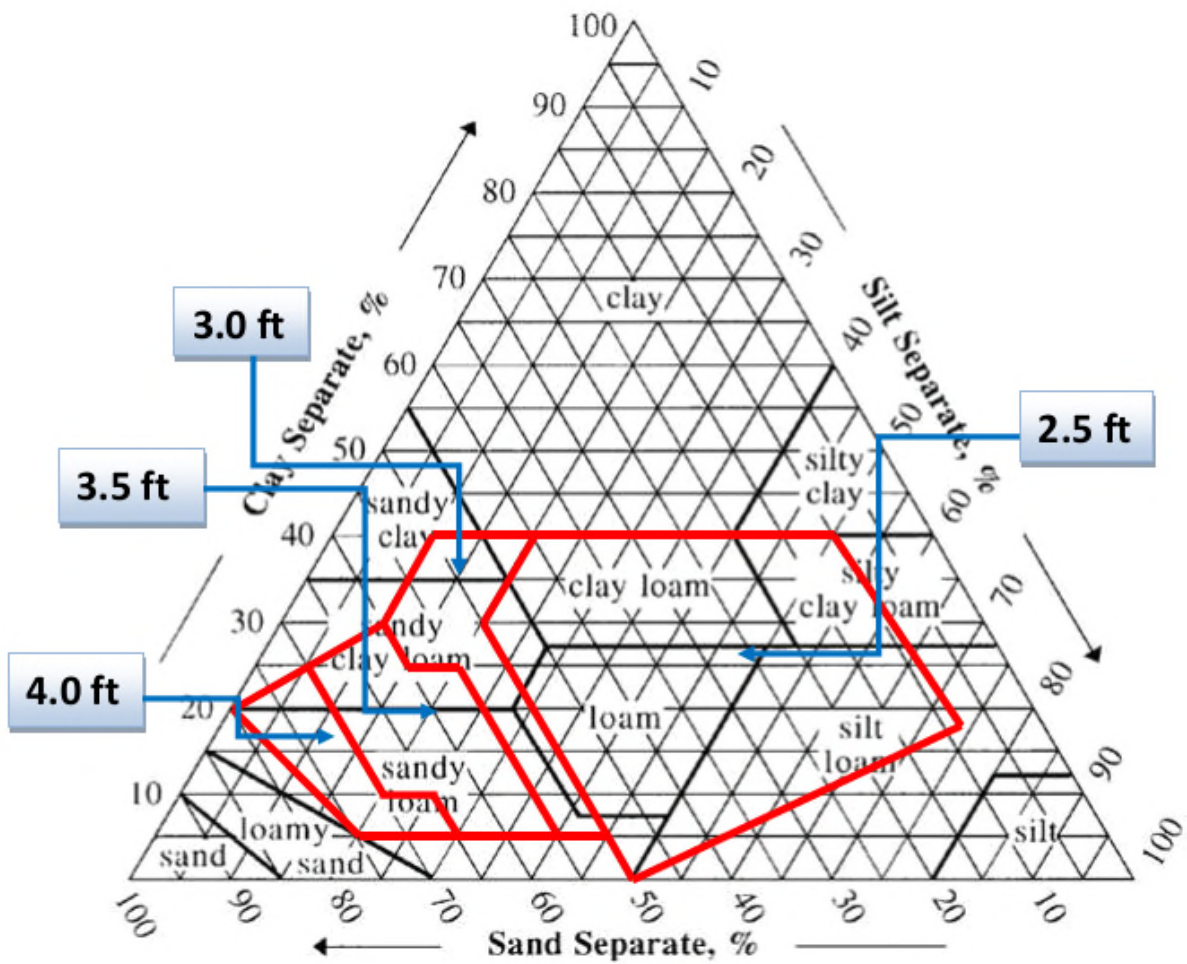
Fig 2.2. Water storage layer thickness for Ecozone 3 from Figure 2.2.1-4 of CDPHE Final Guidance Document on Water Balance Covers in Colorado (CDPHE 2013).
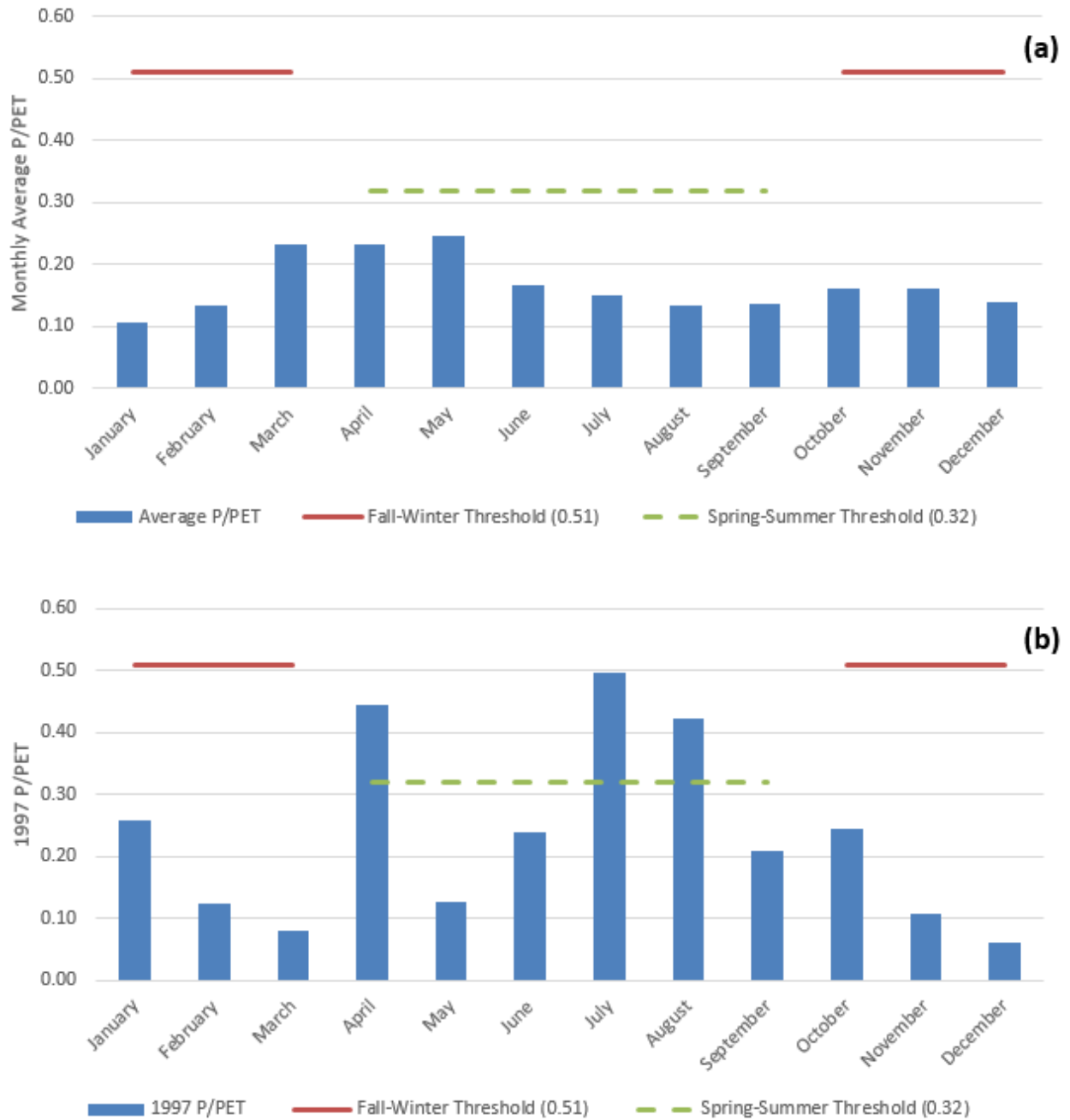
Fig 2.3. Ratio of monthly percolation to potential evapotranspiration (P/PET) for Fort Collins compared to thresholds defined in Alright et al. (2010) for (a) average of 1981 through 2010 and (b) wettest year with sufficient data (1997).

CHAPTER 3: SITE DESCRIPTION

3.1 Physical Setting

The LCL is located in Larimer County, Colorado immediately outside of the city of Fort Collins limits to the southwest of the city. The climate in Fort Collins is classified as semi-arid, receiving, on average, 38.4 cm (15.1 in) of precipitation per year (CSU 2017). The landfill elevation ranges from 1580 to 1600 m (5184 to 5248 ft) above mean sea level (AMSL). The natural slope of the site is from west to east with the lowest elevation on the property at 1554 m (5099 ft) AMSL in a natural drainage on the east perimeter to the south of the landfill footprint. Vegetation in the area is reflective of a semi-arid climate with sparse grass and brush comprising the primary vegetation. The landfill has been in operation since 1963 and in 2016 received waste at rate of approximately 998 Mg/d (1,100 tons/d). An estimated 6.8 million Mg (7.5 million tons) of waste have been deposited in the landfill at the end of 2016. The landfill does not have a bottom liner or a leachate collection system.

3.2 Published Mapping

Soil mapping by the Natural Resources Conservation Service (NRCS 2017) identified the soil types within the waste and borrow area footprint as Fort Collins loam, Kim-Thedalund loams, Kim loam, Heldt clay loam, Minnequa-Laporte complex, Longmont clay, Laporte rock outcrop, and Renohill clay loam (Fig. 3.1a and 3.1b). The United States Department of Agriculture (USDA) texture classifications of these unit names include clay, clay loam, sandy clay loam, silty clay loam, loam, silt loam, and sandy loam. Soil overlays bedrock across most of the site, with exception of some outcrops to the northwest and west of the landfill. The landfill vicinity includes various members of the Colorado Group (Tweto and Ogden 1979), which are sedimentary rock deposits from the Cretaceous period (Fig. 3.2), specifically the Pierre Shale-Lower Unit. More detailed geologic mapping (Braddock et al. 1989) identified units of the

Niobrara Formation (Smoky Hill Shale Member) and Pierre Shale underlying the landfill footprint (Fig. 3.3). The bedrock units have a north-south orientation and dip to the east. No known faulting is present within the landfill footprint.

3.3 Previous Closure Activity

The footprint of the landfill is approximately 72.8 ha (180 ac) of which four closure phases (Phase 1, 2, 3, and 6A) have been completed for a total closure area of 28.3 ha (70 ac) or 39 %. The remaining landfill footprint is anticipated to be closed in the next eight years. The final cover of the previous four phases has been constructed under regulation of the CDPHE. Approval for closure by the CDPHE has either been through a design document approved with a letter dated 25 Sept. 1997 or an Engineering Design and Operations Plan approved on 1 Jul. 2003. The approved final cover design consists of four soil layers (from the surface down): 15.2-cm (6 in) thick topsoil layer, 45.8-cm (18 in) thick rooting/frost protection layer, 45.8-cm (18 in) thick compacted clay infiltration (Infiltration) layer, and a foundation layer above the waste.

The 45.8-cm-thick Infiltration layer is required to have $k_s < 1$ x 10^{-5} cm/s. Construction specifications for the Infiltration layer require the soil to be clay, sandy clay, and/or silty clay having a maximum particle or clod size of 76.2 mm (3 inches), ≥ 50 % fines (particles passing a 0.075-mm sieve), and plasticity index (PI) > 10. The Infiltration layer material must be compacted to ≥ 95 % of ρ_{dmax} at a water content between -2 to +4 % of w_{opt}. A maximum k_s of 1 x 10^{-5} cm/s was to be verified by testing Shelby tube samples from the completed Infiltration layer. Compliance with the k_s requirement immediately following construction of each closure phase is tabulated in Table 3.1. Following earthwork construction, the topsoil layer was seeded with grasses and mulched. Soil used to construct the cover has come from on-site borrow sources to the east (Borrow Area 2) and south (Borrow Areas 3 and 4) as shown in Fig. 3.4.

3.3.1 Phase 1 Closure

Phase 1 of the landfill has an area of approximately 5.67 ha (14 ac) and is located in the northeast corner of the landfill footprint (Fig. 3.4). Phase 1 was closed in 1998 using soil from Borrow Area 2 located immediately to the east and south of Phase 1. In April 1998, eight test pits were excavated approximately 2.4 m (8 ft) below the existing surface for the purpose of obtaining samples for laboratory analysis. Logs detailing the observed subsurface are not available; however, descriptions of the samples and laboratory test results identified the samples as clay and claystone. In-situ moisture content (w) content of the six specimens ranged from 11.9 to 14.1 %. Borrow soils were classified as either low- or high-plasticity clay (CL or CH) according to the Unified Soil Classification System (USCS). These classifications were based on a fines content ranging from 96 to 99 %, liquid limit (LL) ranging from 43 to 52, and PI ranging from 20 to 31.

Standard Proctor testing on six samples indicated ρ_{dmax} ranging from 1.73 to 1.81 megagrams per cubic meter (Mg/m^3) (108.0 to 113.2 pounds per cubic foot [pcf]) and w_{opt} ranging from 16.5 to 19 %. Flexible wall permeability tests yielded k_s ranging from 1.7 x 10^{-7} to 5.8 x 10^{-5} cm/s on specimens remolded to 95 % of γ_{dmax} at w_{opt}.

Construction quality assurance testing consisted of 310 in situ density tests on the Infiltration layer using a nuclear moisture-density gauge and thirteen laboratory permeability tests on Shelby tube samples collected following construction. The in-situ dry density (ρ_d) (ranged from 1.56 to 1.92 Mg/m^3 (97.5 to 120.1 pcf) with an average of 1.78 Mg/m^3 (111.4 pcf). The w ranged from 12.6 to 26.8 % with an average of 17.0 %. The flexible wall permeability test results indicated a range of k_s from 2.2 x 10^{-8} to 1.2 x 10^{-6} cm/s with an average of 1.6 x 10^{-7} cm/s.

3.3.2 Phase 3 Closure

Phase 3 of the landfill was closed in 2004 and has an area of approximately 15.67 ha (4 ac) located in the northwest corner of the landfill footprint. Phase 3 is immediately to the west of Phase 2 and north of Phase 6A (Fig. 3.4). Soil used in construction of the Infiltration layer was from Borrow Area 2. In addition to previous testing during Phase 1 closure in 1998, four additional samples were collected for assessment in fall 2003. Samples were collected using hand-driven samplers and identified as weathered claystone by field personnel.

The ρ_d ranged from 1.72 to 1.86 Mg/m^3 (107.1 to 114.5 pcf) and w ranged from 9.8 to 18.3 %. The fines content ranged from 61 to 76 %. Atterberg limits of the specimens indicated *LL* from 42 to 49 and *PI* from 21 to 29. The fines content and Atterberg limits correspond to a USCS classification of CL.

Standard Proctor testing on the specimen from the "southwest corner" of Borrow Area 2 yielded ρ_{dmax} of 1.69 Mg/m^3 (105.3 pcf) at w_{opt} of 18.9 % whereas ρ_{dmax} of 1.58 Mg/m^3 (98.4 pcf) at w_{opt} of 21.2 % was calculated by testing the specimen from the "northeast corner" of Borrow Area 2. Another sampling event in March 2004 was focused on one "representative sample of native clay materials from the borrow area," which was identified as claystone bedrock. Particle size distributions indicated the fines content was 92.6 % and Atterberg limits indicated an *LL* of 47 and *PI* of 30, yielding a USCS classification of CL. Permeability testing resulted in k_s of 2.51 x 10^{-6}, 1.64 x 10^{-8}, and 5.28 x 10^{-9} cm/s on specimens remolded at respective moisture conditions of 2 % below w_{opt}, at w_{opt}, and 3 % above w_{opt}. All three specimens were compacted to 95 % of standard Proctor effort, which was based on ρ_{dmax} of 1.73 Mg/m^3 (107.8 pcf) and w_{opt} of 17.8 %.

Construction quality assurance testing of the cover soils consisted of 300 in situ density tests using a nuclear moisture-density gauge and sixteen laboratory permeability tests. Samples for permeability testing were collected using a California liner in a hand-drive sampler driven into the constructed cover. The in-situ ρ_d ranged from 1.77 to 1.84 Mg/m^3 (110.6 to 114.6 pcf) and

the in-situ w ranged from 13.8 to 17.2 %. Permeability tests resulted in k_s from 1.5 x 10^{-8} to 4.9 x 10^{-6} cm/s with an average of 4.3 x 10^{-7} cm/s.

3.3.3 Phase 2 Closure

Phase 2 of the landfill encompasses approximately 10.9 ha (27 ac) and was closed in 2008. Phase 2 is located on the north central side of the waste footprint and was closed after Phase 1 to the east and Phase 3 to the west (Fig. 3.4). Borrow Area 2 was the primary source of cover fill and was the same source used in the Phase 1 and Phase 3 closures.

Borrow Area 2 testing data were provided from an investigation in 2003 and another during construction from July to September, 2008 in addition to the investigations described with the Phase 1 and 3 closures. The 2003 investigation included three borings to depths of 7.6 m or 9.1 m (25 or 30 ft) below the existing ground surface. The boring logs show 15.2 cm (6 in) of topsoil above sandy lean clay to a depth of 61 cm (2 ft). Weathered siltstone/claystone extends to 1.2 to 1.8 m (4 to 6 ft) below existing ground surface before comparatively unweathered siltstone/claystone was encountered until the borings were terminated.

Six specimens were selected for particle size distribution and Atterberg limit testing, which yielded fines content between 76 and 99 %, LL from 44 to 53, and PI from 24 to 37. Based on fines content and Atterberg limits, a USCS classification of either CL or CH is applicable. Standard Proctor testing resulted in a ρ_{dmax} ranging from 1.50 to 1.58 Mg/m^3 (93.5 to 98.5 pcf) at w_{opt} from 22.5 to 25.5 %.

The 2008 geotechnical investigation in Borrow Area 2 provided testing results for four specimens taken from either "East or West Excavation Area". The fines content of the specimens ranged from 53 to 86 %, LL ranged from 44 to 47, and PI ranged from 28 to 31. These test results are consistent with a USCS classification of CL. Standard Proctor testing yielded ρ_{dmax} from 1.72 to 1.80 Mg/m^3 (107.5 to 112.5 pcf) and w_{opt} of either 16 or 16.5 %.

An additional geotechnical investigation of an area to the south and west of the landfill footprint identified as "Borrow Area 4" and "Onsite Secondary Borrow Source" was presented in the Phase 2 closure report. Nine geotechnical borings were drilled in August 2002 and another six drilled in February 2006. Soils consisting of sandy lean clay or clayey sand extended to depths of 0 to 7.3 m (0 to 24 ft) with an average depth of 3.47 m (11.4 ft) until a claystone/siltstone/shale was encountered and extended to the termination depth of the borings.

The fines content ranged from 41 to 83 % with an average of 70 % among nine samples collected from the soil stratum. The *LL* ranged from 34 to 47 and *PI* ranged from 19 to 30 based on four specimens. The test results indicated a USCS classification of CL or clayey sand (SC). One sample of the bedrock from B-5 was selected for laboratory testing and the results indicated a fines content of 41 %, *LL* of 32, and *PI* of 14.

Construction quality assurance testing of the constructed cover included 602 in situ density tests with a nuclear moisture-density gauge and sixteen flexible-wall hydraulic conductivity tests conducted on samples collected using Shelby tubes or California samplers driven into the constructed cover. The laboratory k_s ranged from 2.1 x 10^{-9} to 3.0 x 10^{-7} cm/s with an average of 4.5 x 10^{-8} cm/s.

3.3.4 Phase 6A Closure

Phase 6A of the landfill has an area of approximately 6.1 (15 ac) and is located directly south of Phase 3 in the southwest corner of the landfill footprint (Fig. 3.4). Phase 6A was closed in 2011 using Borrow Area 3 as a fill source. A geotechnical investigation of Borrow Area 3 including three soil borings to depths of 10.7 m (35 ft) was conducted in the summer of 2011. The boring logs indicate 1.5 to 7.3 m (5 to 24 ft) of sandy clay with occasional gravels underlain by claystone, which continued until the borings were terminated.

Laboratory testing of the borrow soils yielded fines content between 73 and 83 %, *LL* ranging from 37 to 49, and *PI* ranging from 25 to 36, which correspond to a USCS classification

of CL. Two standard Proctor tests indicated a ρ_{dmax} of 1.75 to 1.83 Mg/m^3 (109 and 114 pcf) both at the same w_{opt} of 16 %. Permeability testing on two specimens resulted in a k_s of 1.6 x 10^{-8} and 2.9 x 10^{-8} cm/s. The condition of the permeability test specimens, either in-situ or remolded, is unclear based on the data available.

A sample identified as "flour" was tested for particle size distribution and Atterberg limits as well. Discussions with Larimer County personnel have revealed the "flour" is a locally found loosely deposited clayey soil. Test results indicated a fines content of 65 %, LL of 45, and PI of 27, that corresponded to a USCS classification of CL.

Testing of two specimens of the claystone resulted in a fines content of 90 and 96 %, LL of 46 and 48, and PI of 29 and 35, indicating a USCS classification of CL. A standard Proctor test on a sample of the claystone indicated a ρ_{dmax} of 1.79 Mg/m^3 (111.5 pcf) at w_{opt} of 16.5 %. A permeability test on a specimen of claystone, undetermined whether in-situ or remolded, resulted in a k_s of 1.7 x 10^{-8} cm/s.

Construction quality assurance testing included seventeen particle-size distributions, fourteen Atterberg limit tests, 141 field-compaction tests, and eight permeability tests on samples of the Infiltration layer. The particle-size distributions indicated fines content between 57 and 89 %. Atterberg limits testing yielded LL ranging from 30 to 47 and PI ranging from 14 to 30. Flexible wall permeability tests had a k_s ranging from 5.1 x 10^{-9} to 1.7 x 10^{-8} cm/s with an average of 1.0 x 10^{-8} cm/s on specimens of the Infiltration layer retrieved using Shelby tubes.

3.4 Previous Borrow Area 3 Investigation

A geotechnical investigation of Borrow Area 3 was completed in 2016 with the intent of gathering data for a future closure phase. The eight geotechnical borings identified clay soils to depths of 2.4 to 7.6 m (8 to 25 ft) where claystone bedrock was encountered or the boring was terminated. Particle-size distributions revealed a fines content between 85 and 97 %. The LL ranged from 41 to 59 and the PI ranged from 20 to 34, indicating a USCS classification of either

CL or CH. The specific gravity (G_s) of the soil ranged from 2.72 to 2.76. A standard Proctor test was conducted on the CH soil and yielded ρ_{dmax} of 1.62 Mg/m^3 (101.1 pcf) at w_{opt} of 20.8 %. A permeability test on a specimen remolded to 95 % compaction and 1.7 % below w_{opt} indicated a k_s of 8.2 x 10^{-8} cm/s.

Two samples of the claystone bedrock were tested for the same parameters. The fines contents were 95 and 82 %, LL = 44 and 38 with PI of 23 and 20, and G_s were 2.73 and 2.72. A standard Proctor test on one of the samples resulted in a ρ_{dmax} of 1.79 Mg/m^3 (111.8 pcf) at w_{opt} of 16.4 %. A permeability test on a specimen remolded to 95 % compaction and 1.5 % below w_{opt} indicated a k_s of 1.8 x 10^{-7} cm/s.

Table 3.1. Construction quality assurance hydraulic conductivity (k_s) test results of samples collected with Shelby tubes (75 mm diameter) immediately after final cover construction at Larimer County Landfill.

Construction Phase (year)	Number of Tests	Average k_s (cm/s)	Maximum k_s (cm/s)	Minimum k_s (cm/s)
Phase 1 (1998)	13	1.6×10^{-7}	1.2×10^{-6}	2.2×10^{-8}
Phase 3 (2004)	16	4.3×10^{-7}	4.9×10^{-6}	1.5×10^{-8}
Phase 2 (2008)	16	4.5×10^{-8}	3.0×10^{-7}	2.1×10^{-9}
Phase 6A (2011)	8	1.0×10^{-8}	1.7×10^{-8}	5.1×10^{-9}
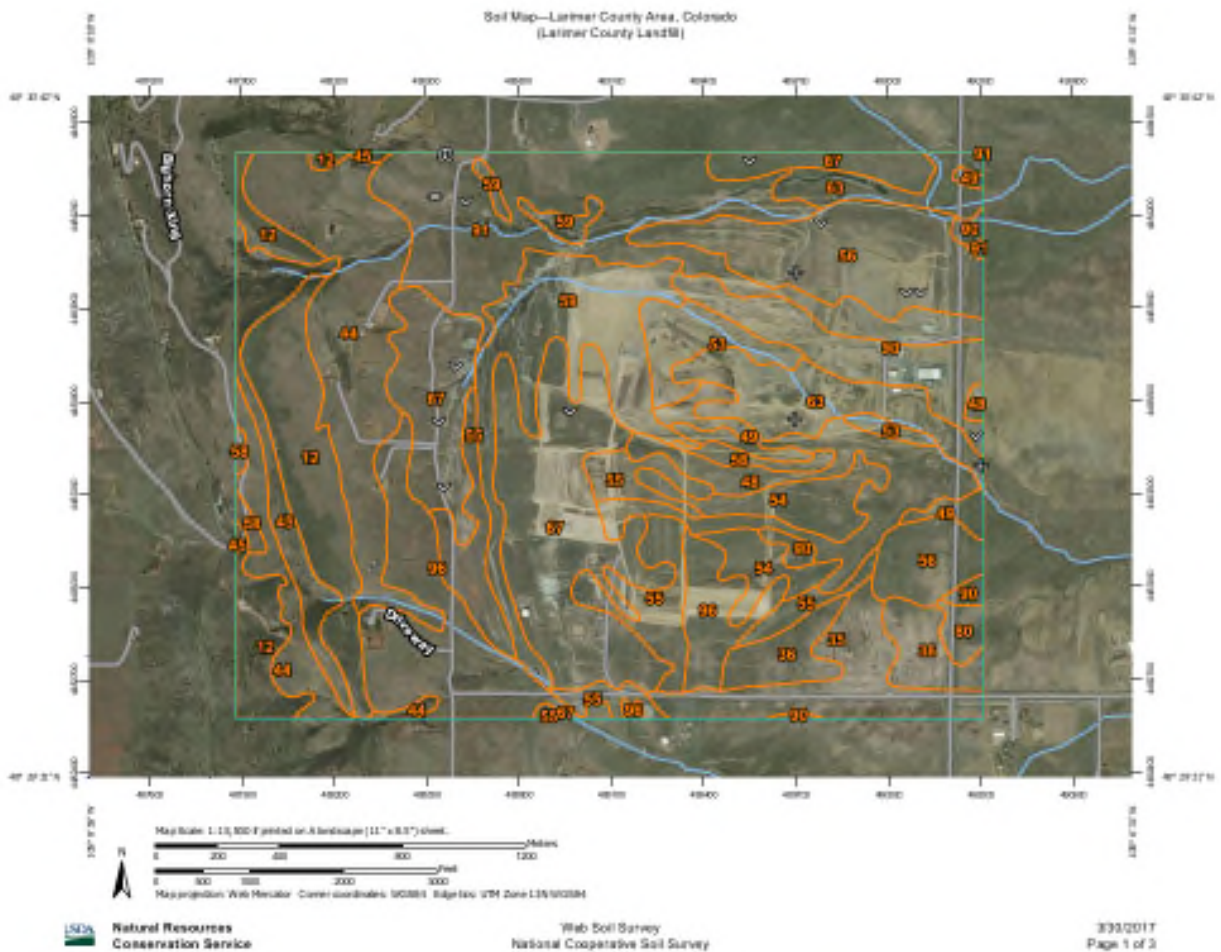
Fig. 3.1a. Soil unit map for the area of Larimer County Landfill developed by NRCS (2017).

Map Unit Legend

Larimer County Area, Colorado (CO644)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
12	Baller-Rock outcrop complex, 15 to 45 percent slopes	80.2	7.3%
35	Fort Collins loam, 0 to 3 percent slopes	40.2	3.6%
36	Fort Collins loam, 3 to 5 percent slopes	30.8	2.8%
44	Haplustolls, hilly	111.0	10.1%
45	Haplustolls-Rock outcrop complex, steep	30.3	2.7%
48	Heldt clay loam, 0 to 3 percent slopes	57.8	5.2%
49	Heldt clay loam, 3 to 6 percent slopes	10.3	0.9%
53	Kim loam, 1 to 3 percent slopes	22.7	2.1%
54	Kim loam, 3 to 5 percent slopes	34.0	3.1%
55	Kim loam, 5 to 9 percent slopes	62.6	5.7%
56	Kim-Thedalund loams, 3 to 15 percent slopes	88.4	8.0%
58	Kirtley-Purner complex, 5 to 20 percent slopes	3.3	0.3%
59	Laporte-Rock outcrop complex, 3 to 30 percent slopes	74.4	6.7%
63	Longmont clay, 0 to 3 percent slopes	55.7	5.0%
67	Minnequa-Laporte complex, 3 to 15 percent slopes	148.0	13.4%
80	Otero-Nelson sandy loams, 3 to 25 percent slopes	5.8	0.5%
90	Renohill clay loam, 3 to 9 percent slopes	44.7	4.1%
91	Renohill-Midway clay loams, 3 to 15 percent slopes	120.2	10.9%
96	Satanta loam, 3 to 5 percent slopes	82.3	7.5%
Totals for Area of Interest		**1,103.0**	**100.0%**

Fig. 3.1b. Soil unit identification from NRCS (2017) maps.
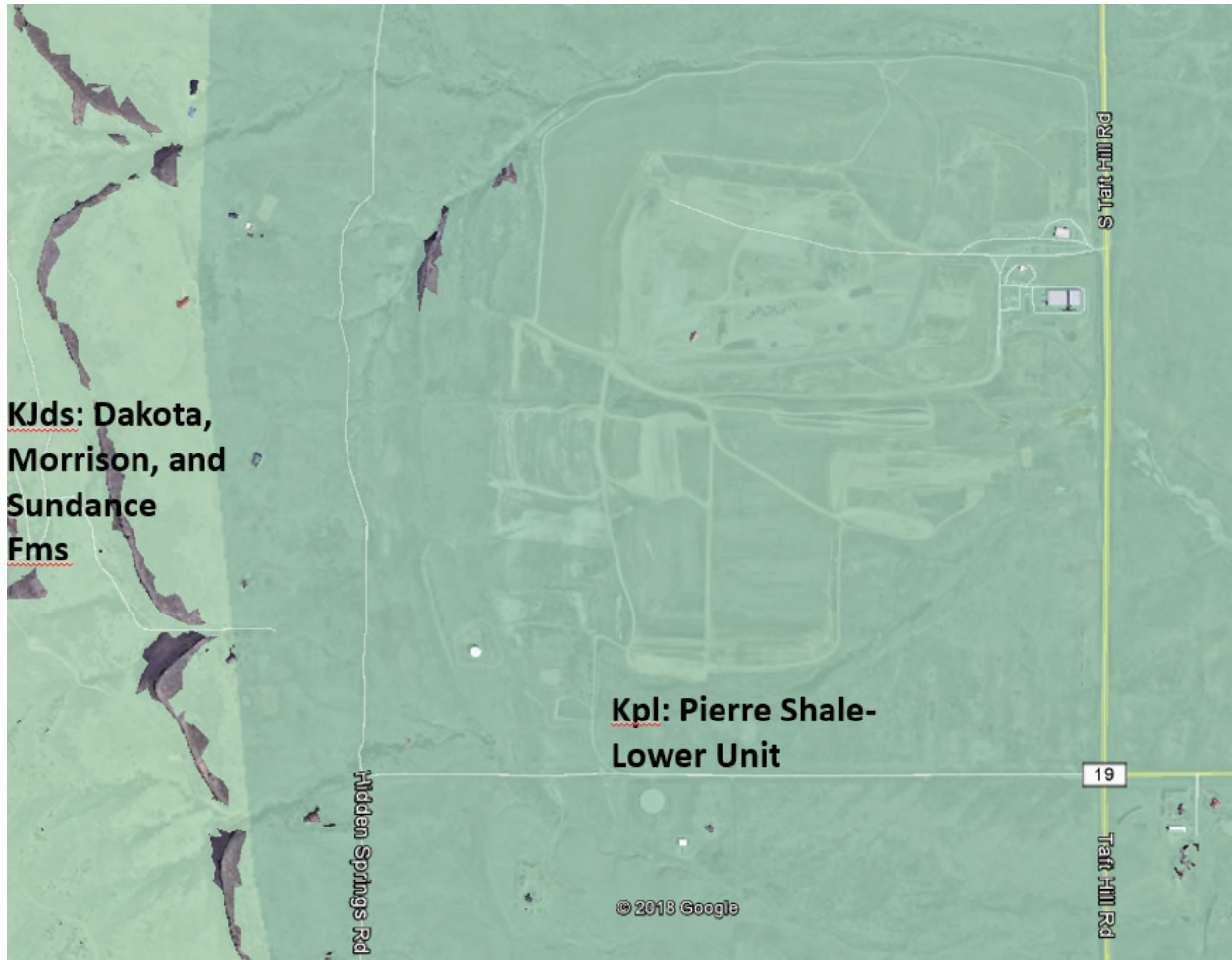
Fig. 3.2. Bedrock geology units identified in Tweto and Ogden (1979) overlain on an aerial photograph of Larimer County Landfill.

Excerpted from: *Geologic Map of the Horsetooth Reservoir Quadrangle, Larimer County, Colorado*
By William A. Braddock, Ronald H. Calvert, Joseph T. O'Connor, and Gordon A. Swann, 1989.
Department of the Interior, U.S. Geological Survey

Pierre Shale

Landfill
Disposal Area
(180 acres)

Niobrara Formation
(Smoky Hill Shale Member)

Carlile Shale

TRUE NORTH

0   1 mile
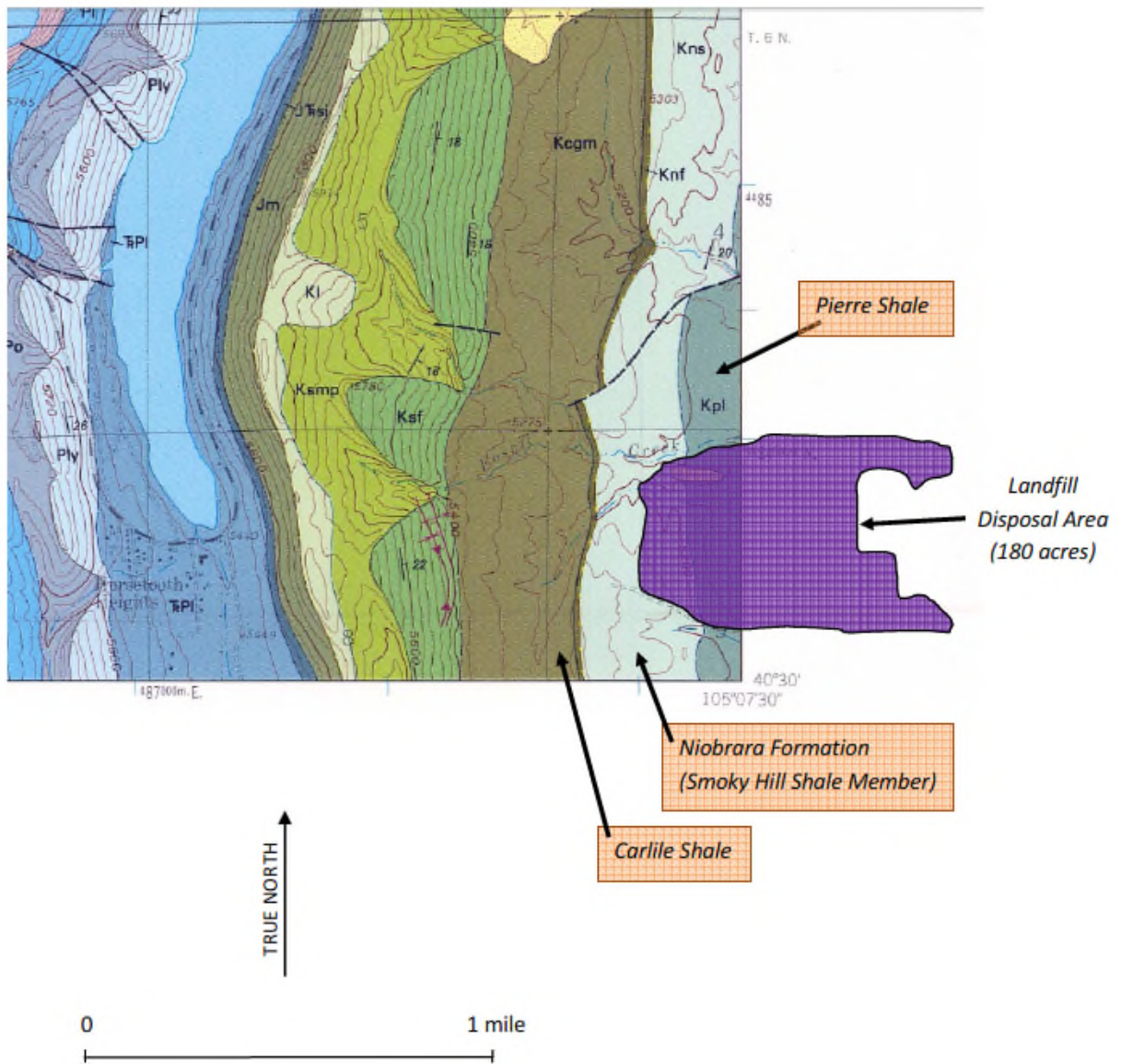
Fig. 3.3. Bedrock geology map by Braddock et al. (1989) provided by Larimer County Landfill.

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Fig. 3.4. Larimer County Landfill closure phases and borrow areas.

CHAPTER 4: METEOROLOGICAL DATA

Hydrologic modeling to assess the water balance of a final cover with VADOSE/W requires daily meteorological (MET) data, including minimum and maximum temperatures, minimum and maximum relative humidity values, precipitation, average wind speed, and solar radiation. A conservative approach to assessing a potential cover design via hydrologic modeling is to use a temporal period representing wetter-than-average conditions (Albright et al. 2010). Annual precipitation recorded at the Fort Collins-Loveland Municipal Airport (Airport) (Weather Underground 2017) is shown in Fig. 4.1. The airport is located 10.5 km (6.5 mi) east of the landfill and the MET data set included measurements dating back to 1889. The wettest 10-yr period was from 1990 through 1999. However, the time period from 1992 through 2001 was selected for this study because this time period represented the 3rd wettest ten-consecutive years on record and had a nearly complete MET data set for each year.

A nearly complete set of temperature and precipitation data from 1992 through the end of 2001 was also available from a weather station at Colorado State University (CSU 2017) located 8.9 km (5.5 mi) north of the landfill. A comparison of the daily temperature data between the Airport and CSU revealed the CSU data was, on average, 95 % of the daily maximum and 98 % of the daily minimum temperatures recorded at the airport. Considering similarities in the data sets, the Airport maximum and minimum daily temperatures were used for modeling to maintain consistency with the rest of the MET data. Precipitation data indicated that CSU received 173 % of the precipitation received at the Airport from 1992-2001. In this case, the CSU station precipitation data were used in the model to favor a conservative estimate of the water balance at LCL.

The final MET data set assembled from 1992 through 2001 had 140 days of the total possible 3,653 days (< 4%) with at least one missing MET data parameter. Meteorological data were estimated for these missing days from 1992 through January 31, 1996, via computing an

average from the day prior and after the missing data point. Missing MET data after February 1,

1996 were obtained from the CSU weather station data.

Annual Precipitation - Fort Collins Weather Station at Colorado State University
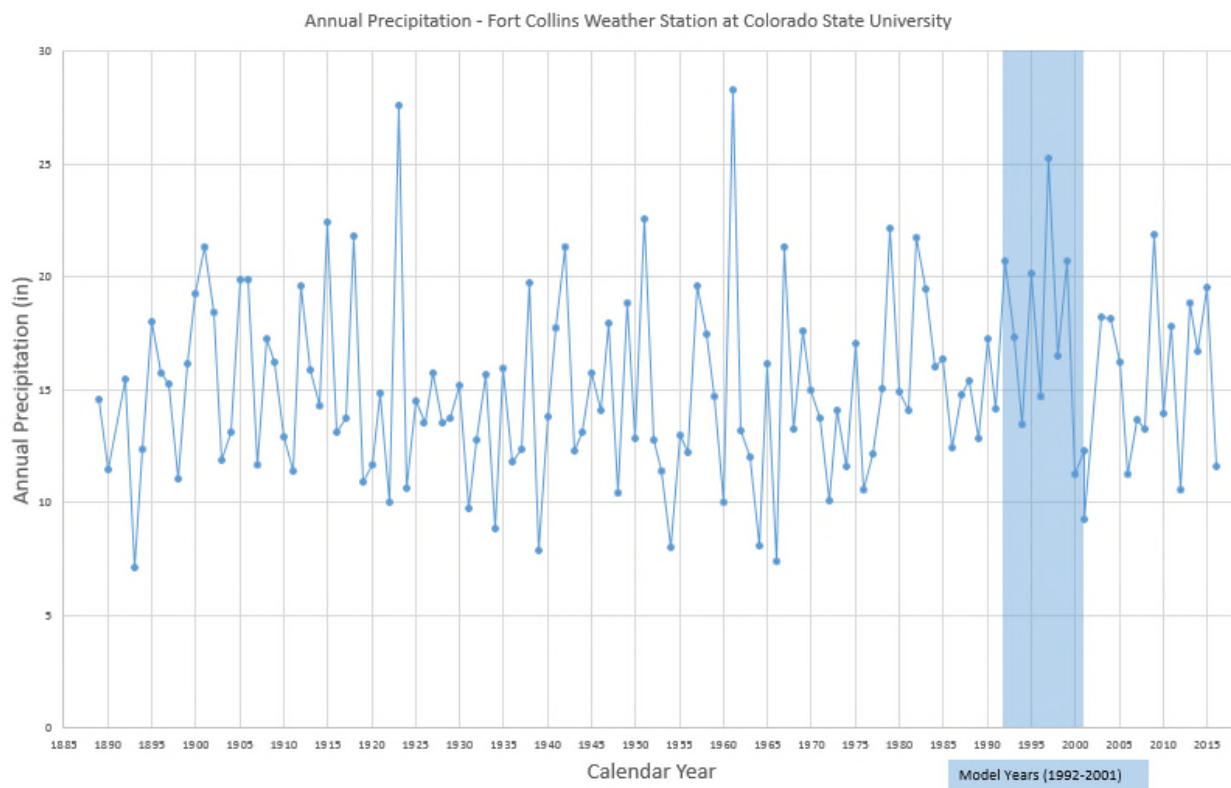
Fig 4.1. Annual precipitation recorded at the Colorado State University Weather Station from 1889 through 2016. The Model Years for water balance modeling used in this study were from the start of 1992 through the end of 2001.
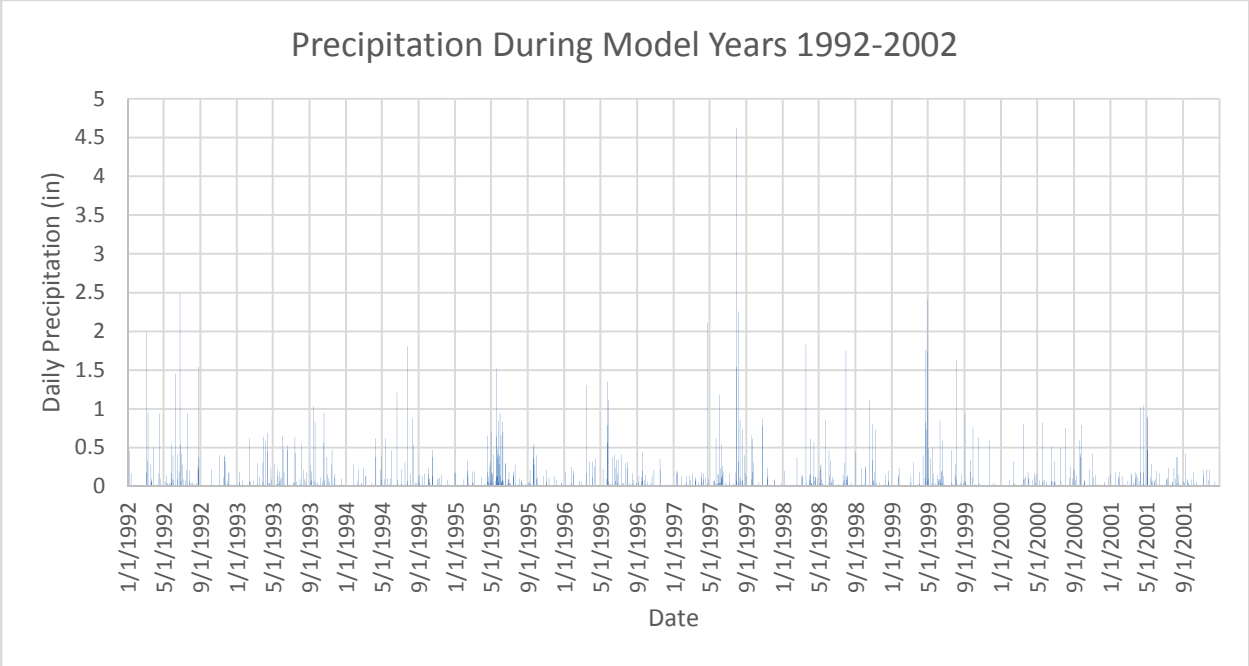
Fig 4.2. Daily precipitation recorded at the Colorado State University Weather Station during the Model Years (1992-2002) used in this study for water balance modeling.

CHAPTER 5: SAMPLING

Soil sampling at LCL occurred on April 6 and June 27, 2017. Samples were collected from Borrow Area 3 and Borrow Area 4 on April 6 and from Phase 1 of the existing final cover on June 27.

5.1 Borrow Area Sampling

The intent of sampling the borrow areas was to obtain soil samples for laboratory testing to represent (i) an undisturbed state that can be expected to represent long-term cover conditions and (ii) re-molded / compacted state to simulate a newly constructed cover. Test pits, approximately 0.9 m (3 ft) deep with a diameter of 1.8 m (6 ft) on the surface and 0.9 m (3 ft) at the bottom, were excavated in Borrow Area 3 and 4. Soil strata in the two borrow areas consisted of approximately 15 cm (6 in) of topsoil with a dense root structure in the upper 7.6 cm (3 in) and some roots penetrating to depths of 45.7 cm (18 in).

The topsoil was low plasticity clay with some gravel, loose, dark brown, moist, and no organic odor. Below the topsoil was a low plasticity clay, stiff, brown to light brown with depth, slightly moist to dry with depth, and mottling present. A list of samples collected from the borrow areas is presented in Table 5.1. During excavation of the topsoil, two grab samples were collected from each location. Excavation continued while keeping an intact column of soil in the center of the excavation to collect a block sample inside a 30.5 cm (12 in) tall by 35.6 cm (14 in) diameter polyvinylchloride (PVC) sampling ring. The PVC ring aided in collecting undisturbed samples, and when the PVC ring fit over a complete specimen, the bottom was sheared off and the sample was wrapped in plastic and secured with wood panels on the top and bottom of the sampling ring. Two block samples were collected in each borrow area, at consecutive 30.5 cm (12 in) depth increments starting at the bottom of the topsoil (final depth of excavation ~ 0.9 m).

Two grab samples were collected to represent both 30.5 cm (12 in) depth increments where block samples were collected.

5.2 Existing Closure Cover Sampling

The Phase 1 closure cover was sampled for laboratory testing of the compacted clay cover 20-yr post-construction and to determine the existing profile for hydrologic modeling. A combination of hand tools and a backhoe were used to excavate a test pit 1.8 m (6 ft) deep with an approximate diameter of 2.7 m (9 ft) on the surface and 1.8 m (6 ft) at the bottom. A 30.5-cm-thick (1 ft) topsoil layer was observed with a less dense root structure than the borrow area samples and the roots were primarily confined to the topsoil layer. The remainder of the excavation was clay fill with fragments of gray claystone, increasing in stiffness and plasticity with depth, brown with some gray, slightly moist to moist with depth, and decreasing desiccation with depth.

A difference in the level of compaction was estimated to occur at a depth of approximately 91.4 cm (3 ft), which corresponded to the interface between the root zone and Infiltration layer that had respective compaction specifications of ≈ 92% and > 95% of the ρ_{dmax} as determined by standard Proctor effort (BE&K/Terranext 1999). Actual layer thicknesses of 30.5 cm (1 ft) topsoil, 61 cm (2 ft) rooting/frost protection layer, and ≥ 91 cm (3 ft) Infiltration layer exceeded the specified thicknesses of 15.2 cm (0.5 ft) topsoil, 45.7 cm (1.5 ft) rooting/frost protection layer, and 45.7 cm (1.5 ft) Infiltration layer from the construction certification report. Contact with the underlying foundation layer, which would indicate the bottom of the Infiltration layer, was not noted in the field. However, the difference may not have been discernable as the foundation layer likely experienced densification during compaction of the final cover and was sourced from the same borrow area (Borrow Area 2).

Grab samples and block samples were collected from the Phase 1 final cover area in a similar manner as the borrow areas. A list of samples collected during the Phase 1 final cover

sampling event is provided in Table 5.1. Block samples were collected from the root/frost protection and Infiltration layers. The excavation was backfilled in lifts using soil from the excavation and supplemental soil from the current borrow area. Each lift was moisture conditioned and compacted with the backhoe bucket and a jumping jack compactor.

Table 5.1. Samples collected from borrow areas and Phase 1 closure cover.

Sample ID	Sample Location	Approximate Sample Depth (cm) [a]	Sample Type [b]
B3-TS	Borrow Area 3	0 to 15 (0.0 to 0.5)	Bulk
B3-BS1	Borrow Area 3	15 to 45 (0.5 to 1.5)	Bulk and Ring
B3-BS2	Borrow Area 3	45 to 76 (1.5 to 2.5)	Bulk and Ring
B4-TS	Borrow Area 4	0 to 15 (0.0 to 0.5)	Bulk
B4-BS1	Borrow Area 4	15 to 45 (0.5 to 1.5)	Bulk and Ring
B4-BS2	Borrow Area 4	45 to 76 (1.5 to 2.5)	Bulk and Ring
LCL-TS	Phase 1	0 to 31 (0.0 to 1.0)	Bulk and Ring
LCL-RZ	Phase 1	38 to 69 (1.25 to 2.25)	Bulk and Ring
LCL-CC1	Phase 1	99 to 130 (3.25 to 4.25)	Bulk and Ring
LCL-CC2	Phase 1	145 to 175 (4.75 to 5.75)	Bulk and Ring

[a] Depths in feet provided in parentheses.
[b] Bulk = grab sample collected from disturbed soil; Ring = block sample collected in 30.5 cm (12 in) tall by 35.6 cm (14 in) diameter polyvinylchloride (PVC) sampling ring

CHAPTER 6: GEOTECHNICAL LABORATORY TESTING

Geotechnical laboratory testing of undisturbed block samples and remolded soil specimens from both borrow areas and Phase 1 was conducted at CSU. Laboratory testing included particle-size distribution (mechanical sieve and hydrometer), Atterberg limits, in situ density, in situ moisture content, specific gravity, standard Proctor, permeability, and soil water retention. American Standards for Testing Materials (ASTM) procedures were followed for the laboratory testing. Results are presented in regards to the location and soil layer of the samples.

6.1 Borrow Area Soil Geotechnical Laboratory Testing

Samples were collected from two borrow areas at depths of approximately 0 to 15 cm (0 to 6 in), 15 to 46 cm (6 to 18 in), and 46 to 76 cm (18 to 30 in). A summary of geotechnical characteristics for borrow area samples is in Table 6.1. The USCS classifications were similar among different layers and between Borrow Area 3 and 4 with all soils yielding low-plasticity clay with sand (CL). The USDA texture of the borrow area samples was a clay loam.

6.1.1 Characterization and Compaction Testing

The 0 to 15 cm (0 to 6 in) soil layer corresponded to topsoil (TS) for Borrow Areas 3 and 4. Particle-size distributions of this TS layer were nearly identical, with 36 % sand, 40-41 % silt, and 23-24 % clay sized particles (Table 6.1). Atterberg limits were also similar between the two TS layers (LL = 35 and 37, and PI = 15). Although the in situ water content for TS from Borrow Area 3 was higher (25 %) compared to Borrow Area 4 (19 %), results from standard Proctor compaction testing were similar between both borrow area TS samples (ρ_{dmax} = 1.58 and 1.64 Mg/m^3 [98.5 to 102.1 pcf] and w_{opt} = 19.5 to 20.0 %, Table 6.1).

The 15 to 46 cm (6 to 18 in) and 46 to 76 cm (18 to 30 in) samples from both borrow areas consisted of native material with lower organic content compared to the TS. These soil

layers were identified as potential borrow material for the closure cover. Particle-size distribution of four samples yielded the following ranges: 32 to 38 % sand, 34 to 40 % silt, and 26 to 34 % clay. Atterberg limits of the same four samples indicated LL ranged from 38 to 46 and PI ranged from 16 to 24 (Table 6.1). The in-situ water content ranged between 9 and 10 %, except for the specimen from 15 to 46 cm in Borrow Area 3 that had an in situ water content of 20 %. The in situ ρ_d measured in block samples from Borrow Areas 3 and 4 were 1.38 and 1.32 Mg/m^3 (86.4 and 82.4 pcf), respectively, corresponding to 85.9 % and 82.2 % compaction. Standard Proctor compaction testing on the four samples from Borrow Areas 3 and 4 yielded comparable results, with ρ_{dmax} ranging between 1.60 and 1.65 Mg/m^3 (100 to 103 pcf) and w_{opt} ranging between 19.3 and 21.1%. Specific gravity of the samples ranged from 2.61 to 2.64.

6.1.2 Permeability Testing

Permeability testing adhering to ASTM D5084 (2016a) standards for flexible wall permeability testing using the falling head-rising tailwater method was used to measure k_s. Permeability testing was performed on block samples and remolded bulk samples. Block samples were extracted from the PVC ring and trimmed to a 305 mm (12 in) diameter with a height ranging from 150 to 220 mm (5.9 to 8.7 in). All remolded specimens were prepared at the target water content and target density in compaction molds with a 102 mm (4 in) inside diameter and 116 mm (4.5 in) height. After preparing the remolded specimens in compaction molds, the specimens were extruded using a hydraulic jack and placed in the permeameters.

All specimens were backpressure saturated to obtain a B-value > 0.95 and consolidated to 15 kPa (313 psf), which is a common effective stress representing soil in a cover application. Benson et al. (2007), Benson and Bareither (2012), Scalia et al. (2017) used effective stress ranging 14 to 19 kPa (292 to 397 psf) for evaluating soil used in a cover. A hydraulic gradient of 5 to 10 was used for WBC materials (i.e., Borrow Area 3 and Borrow Area 4). Each experimental setup consisted of a permeameter, head water (influent), tailwater (effluent), and

cell water. Head water, tailwater, and cell water were connected to pressure panels. The difference between the cell water and the average of the head water and tailwater was maintained at 15 kPa (313 psf).

Tap water (EC = 13 mS/m and pH = 6.9) was used within the permeameters to apply cell pressure as well as in the pressure panel inflow and outflow columns as permeant fluid. Visible air bubbles were flushed from the drainage tubes prior to testing and permeation was conducted upward through the specimen to aid in removing entrapped air bubbles. Filter paper and porous stones were placed on the top and bottom of the specimen. All porous stones were soaked in tap water prior to placement within the permeameter. Specimens were separated from the cell pressure fluid via conventional latex membranes sealed with O-rings.

Permeation of a given hydraulic conductivity specimen was performed until the following termination criteria were achieved for at least four consecutive measurements (ASTM D 5084; Daniel 1994): (i) ratio of effluent volume to influent volume (V_{out} / V_{in}) was between 0.75 and 1.25 and (ii) k_s was within ± 25 % of the geometric mean k_s for k_s ≥ 1 x 10^{-10} m/s. Permeability testing of block samples from Borrow Areas 3 and 4 yielded k_s of 1.1 x 10^{-4} cm/s and 2.4 x 10^{-4} cm/s, respectively. A series of permeability tests were conducted on soil from bulk samples collected from Borrow Areas 3 and 4 that was remolded to different moisture contents and compaction efforts. The target water content and density were selected to simulate possible cover construction scenarios such as if (i) no construction water was added and the compaction effort varied, (ii) water was added to approximate w_{opt} and compaction effort varied, or (iii) the material was compacted to the specifications of a prescriptive cover (Table 6.5).

Hydraulic conductivity measured on the remolded specimens are shown as a function of molding water content and percent relative compaction in Fig. 6.1. Moisture contents of remolded specimens ranged from 5.5 % to 21.3 % and relative compaction ranged from 78 % to 95 % (1.26 to 1.55 Mg/m^3; 78.5 to 96.9 pcf). These permeability tests on remolded specimens yielded k_s ranging from 1.1 x 10^{-6} cm/s to 4.2 x 10^{-4} cm/s. Trends in the data sets indicated that

k_s decreased significantly with increasing water content of the remolded specimen and k_s decreased to a lesser degree with increasing compaction effort for a given moisture content.

6.1.3 Soil Water Retention Testing

Moisture retention tests were conducted in accordance with the drying curve method using a pressure chamber and gravimetric measurements described in ASTM D6836 Method C (ASTM 2016b). The pressure plate chamber was used to apply air pressures from 5 kPa to 1500 kPa (104 to 31,330 psf) that were converted to soil suction (Ψ) by axis translation. Relatively undisturbed specimens trimmed from block samples were prepared in oedometer rings with inside diameter = 150 mm (5.9 in) and height = 76.2 mm (3 in). Samples of in-situ or remolded soil specimens were prepared in oedometer rings with inside diameter = 63.5 mm (2.5 in) and height = 25.4 mm (1 in). Weight loss at each testing stage (i.e., each Ψ) was measured and then converted to a change in volumetric water content.

Soil water retention testing yielded relationships between volumetric water content (θ) and soil suction (Ψ) (i.e., soil water characteristic curves, SWCCs) that were fit with the van Genuchten equation (1980):

$$\theta = \theta_r + \left(\theta_s - \theta_r\right)\left\{\frac{1}{1+(\alpha \cdot \psi)^n}\right\}^m \qquad (6.1)$$

where θ_r is residual volumetric water content, θ_s is saturated volumetric water content (i.e., porosity), and α, *m*, and *n* are fitting parameters. Eq. 6.1 was fit to Ψ-θ data to develop a soil water characteristic curve using a non-linear least squares optimization that allowed α and *n* to vary with the constraint that $m = 1 - n^{-1}$. The θ_s was computed by weight-volume relationships and fixed during fitting of Eq. 6.1. The θ_r was held constant based on values presented in Rawls et al. (1982) organized by USDA soil texture or from the Rosetta Model (USDA, 2008) developed by the USDA for estimating unsaturated hydraulic functions. The Rosetta Model uses the density and percentages of sand, silt, and clay to predict van Genuchten parameters.

Unsaturated hydraulic properties obtained from soil water retention tests and van Genuchten equation fits are presented in Table 6.2. Relationships of θ versus Ψ along with fitted soil water characteristic curves based on the van Genuchten equation are shown in Fig. 6.2. van Genuchten parameters for the Borrow Area 3 block sample were α = 0.348 kPa^{-1} (0.017 psf^{-1}) and n = 1.261 with θ_s = 0.481 and θ_r = 0.04. The same procedure on the Borrow Area 4 block samples resulted in α = 0.061 kPa^{-1} (0.003 psf^{-1}) and n = 1.633 with θ_s = 0.495 and θ_r = 0.04.

6.2 Existing Closure Cover Phase 1 Geotechnical Laboratory Testing

Samples collected from the Phase 1 closure cover were separated by presumed construction layers (topsoil, rooting/frost protection, Infiltration layer) associated with the sample depth and excavation observations. Geotechnical characteristics of four samples from the three layers (two samples from Infiltration layer) sampled from the Phase 1 closure cover are in Table 6.3. The topsoil layer and rooting-zone layer were similar and classified as CL, whereas the two samples collected from the Infiltration layer classified as CH (high-plasticity clay). This difference in classification was anticipated since LCL had used select soil for the Infiltration layer that had higher plasticity and lower hydraulic conductivity (described subsequently). All three layers of the Phase 1 cover had a USDA soil texture of a silty clay.

6.2.1 Characterization Testing

The topsoil consisted of 3 % sand, 51 % silt, and 45 % clay, with LL = 45 and PI = 23. The in situ w was measured as 9.4 %. Standard Proctor compaction testing indicated ρ_{dmax} = 1.58 Mg/m^3 (98.7 pcf) and w_{opt} = 20.7 %. The rooting-zone layer was 57 % silt and 43 % clay, and exhibited LL = 46 and PI = 24. The in situ moisture content of the rooting-zone specimen was 13.8 %.

The two samples from the Infiltration layer were collected from depths of approximately 107 to 137 cm (3½ to 4½ feet) and 137 to 168 cm (4½ to 5½ feet). Both samples were 100 % fine-grained particles, contained 44 to 45 % clay-sized particles, had LL = 53 to 55, and PI = 30 to 32 (Table 6.3). The in situ w and ρ_d were 16.0 % and 1.79 Mg/m^3 (111.9 pcf) for the upper sample and 14.7 % and 1.91 Mg/m^3 (119.3 pcf) for the lower sample. Standard Proctor compaction testing yielded ρ_{dmax} = 1.74 Mg/m^3 (108.7 pcf) and w_{opt} = 17.7 % for the upper sample and ρ_{dmax} = 1.75 Mg/m^3 (109 pcf) and w_{opt} = 18.4 % for the lower sample. Test results indicate a relative compaction of 103 and 109 % for the upper and lower Infiltration layer samples.

6.2.2 Permeability and Soil Water Retention Testing

Permeability and soil water retention tests results are summarized in Table 6.4. These experiments were carried-out following similar procedures as described previously with the exception of using a hydraulic gradient of 20 to 30 for existing Phase 1 cover material because this soil had a lower permeability than the WBC soils. Permeability testing of the Infiltration layer block samples resulted in k_s = 1.2 x 10^{-7} cm/s for the upper sample and 8.9 x 10^{-8} cm/s for the lower sample. The k_s was measured as 6.5 x 10^{-8} cm/s and 7.3 x 10^{-8} cm/s when the upper and lower bulk samples were remolded to approximately 95 % compaction at 2 % wet of w_{opt} determined by standard Proctor. Relationships of θ versus Ψ along with fitted SWCCs based on the van Genuchten equation are shown in Fig. 6.3 and the fitting parameters are presented in Table 6.4. van Genuchten parameters for the upper Infiltration layer block sample were α = 0.028 kPa^{-1} (0.0013 psf^{-1}) and n = 1.737 with θ$_s$ = 0.264 and θ$_r$ = 0.078. The van Genuchten parameters for the lower Infiltration layer block sample resulted in α = 0.026 kPa^{-1} (0.0012 psf^{-1}) and n = 1.319 with θ$_s$ = 0.290 and θ$_r$ = 0.078.

6.3 Phase 1 Comparison: Laboratory Results and Construction Certification Reports

Geotechnical characterization of samples collected from the Phase 1 final cover as part of this study were compared to available data from Borrow Area 2 that was used to construct the Phase 1 final cover in 1998. The soil classification test results from this study and the 1998 construction are presented in Fig. 6.4. The 2017 samples had fines content of 100 % for all four samples. The *LL* ranged from 45 to 55 and *PI* ranged from 23 to 33. These test results yielded USCS classifications of CH or CL. The 1998 Borrow Area 2 investigation test results also yielded a USCS classification of CH or CL based on a fines content ranging from 96 to 99, *LL* ranging from 43 to 52, and *PI* ranging from 20 to 31. The two data sets show a strong correlation between laboratory test results from the constructed Phase 1 cover and the Borrow Area 2 investigation before construction of the final cover.

A moisture content of 13.8 % was measured on a sample collected from the rooting/frost protection layer of the Phase 1 cover, which compared favorably to construction documentation indicating the rooting/frost protection layer was placed at *w* between 12.0 and 17.3 % with an average *w* = 14.4 % based on 20 nuclear moisture-density test results. The ρ_d of the sample of the rooting/frost protection layer was 1.74 Mg/m^3 (108.8 pcf) versus a range of 1.67 to 1.86 Mg/m^3 (104.2 to 116.2 pcf) with an average ρ_d = 1.78 Mg/m^3 (111.1 pcf) from 20 nuclear moisture-density test results. Comparison of exhumed and construction quality assurance test results indicate the sample tested was near the average and within the range recorded during construction quality assurance testing conducted in 1998.

The Infiltration layer in situ *w* and ρ_d from the 1998 and 2017 investigations are shown in Fig 6.5. The laboratory measured *w* of the exhumed upper and lower Infiltration layer specimens in 2017 were 16.0 % and 14.7 % respectively. Quality assurance testing of the Infiltration layer using a nuclear moisture-density gauge for 310 tests from Phase 1 construction indicated *w* at the time of placement ranged from 12.6 to 26.8 %, with an average *w* = 17.0 %. The laboratory measured ρ_d from the exhumed samples was 1.79 and 1.91 Mg/m^3 (111.9 and 119.3 pcf)

compared to construction quality assurance testing results of a ρ_d ranging from 1.56 to 1.92 Mg/m^3 (97.5 to 120.1 pcf) with an average of 1.79 Mg/m^3 (111.4 pcf). The test results indicate that the in situ w and ρ_d of the exhumed Phase 1 samples were within the ranges of the construction quality assurance testing from 1998.

Permeability test results of samples from Phase 1 cover construction are compared to permeability test results from samples collected as part of this study in Fig. 6.6. Thirteen Shelby tube samples were collected as part of Phase 1 construction in 1998 and permeability testing yielded k_s ranging from 2.2 x 10^{-8} to 1.2 x 10^{-6} cm/s, with an average of 1.6 x 10^{-7} cm/s. The block samples of the Infiltration layer from this study yielded k_s = 1.2 x 10^{-7} cm/s for the upper sample and k_s = 8.9 x 10^{-8} cm/s for the lower sample. Comparing the test results from post-construction in 1988 versus the exhumed 2017 block samples indicates the k_s is still within the range of the 1998 samples and is within 45 % of the average of the previous test results.

Permeability testing was also conducted on exhumed Phase 1 bulk samples that were remolded to 95 % compaction and 2 % wet of w_{opt} as determined by standard Proctor. The remolded permeability test results were k_s = 6.5 x 10^{-8} cm/s for the upper sample and k_s = 7.3 x 10^{-8} cm/s for the lower sample, which indicates the in-situ k_s of the block samples has increased 82 % and 22 %, respectively, since construction if originally compacted under the same conditions.

6.4 Comparison of Laboratory Test Results versus Literature

6.4.1 Effect of Pedogenesis on Hydraulic Properties

Benson et al. (2007) monitored ten WBC over a four-year period to assess changes in soil hydraulic properties. The relationship between post-construction k_s and as-built k_s from Benson et al. (2007) is shown in Fig. 6.7. Their results indicated that post-construction k_s of cover soils at all ten sites increased by a factor ranging from 10 to 10,000 compared to the as-built k_s. The change was more pronounced in soils with lower as-constructed k_s, such that post-

construction k_s at nearly all sites ranged between 10^{-3} and 10^{-5} cm/s after four years, termed the "In-Service Condition". The main explanation for the increase in k_s from as-built to post-construction was pedogenesis, which is a natural soil formation process that leads to formation of a macropore structure due to processes such as freeze-thaw, wet-dry cycling, root growth and decay, and burrowing animals (Buol et al. 1997; Othman and Benson,1994; Albrecht and Benson 2001).

The k_s measured on block samples collected from exhumed Phase 1 samples in this study are plotted in Fig. 6.7 with respect to the average k_s measured on Shelby tube samples from Phase 1 that represent the as-built condition. Comparing the as-built k_s of the Phase 1 Infiltration layer to the 2017 exhumed samples indicates the post-construction k_s decreased 35 %, which is contrary to observations in Benson et al. (2007). A likely explanation for this contrast is that block samples of the Infiltration layer were collected from 107 to 168 cm (3 ½ to 4 ½ ft) deep, which appears to have been sufficiently deep to avoid macropore formation due to pedogenesis. The processes contributing to pedogenesis likely did not penetrate the upper 107 cm (3½ feet) of topsoil and rooting zone to impact the Infiltration layer at LCL. Another explanation could be the limited post-construction samples (i.e., two) or the difference between the as-built sampling method (75-mm diameter Shelby tube) versus the post-construction sampling method (300-mm-diameter block samples). A study by Benson et al. (1999a) indicated that 14 of 17 samples had higher k_s in the laboratory when sampled using a 305-mm-diameter (12 in) block samples versus a 75-mm-diameter (3 in) Shelby tube samples.

The k_s measured on block samples from Borrow Areas 3 and 4 are plotted along with k_s measured on remolded specimens in Fig. 6.7. The block samples yielded k_s of 1.1 x 10^{-4} cm/s and 2.4 x 10^{-4} cm/s, which is near the middle of the "In-Service Condition" reported by Benson et al. (2007). Although specimens from the borrow areas were never placed as a constructed cover, they were collected from the upper 76 cm (2 ½ ft) where pedogenesis processes are more influential. Comparing k_s of the in situ samples versus the k_s of the bulk samples remolded

under different compaction scenarios resulted in k_s ranging from 0.25 to 53 times greater (average of 20 times greater) k_s in the in situ samples versus remolded samples, which is in agreement with observations by Benson et al. (2007).

Benson et al. (2007) also studied changes in the van Genuchten parameters θ_s, α, and n with time. They observed that θ_s increased up to a factor of two over four years and the change was more prevalent in soils that started with θ_s lower than 0.35 such as calculated at LCL. The increase in θ_s was attributed to pedogenesis decreasing the soil density, which has an inverse relationship with θ_s. The 2017 measured ρ_d of 1.79 and 1.91 Mg/m^3 (111.9 and 119.3 pcf) are equal to or higher than the average value of 1.79 Mg/m^3 (111.4 pcf) from the 1998 construction quality assurance test results correlating to an equal or lower θ_s with time, which is contrary to the Benson et al. (2007) conclusion. Comparing ρ_d of the remolded borrow area samples versus in situ ρ_d indicates a 14 % (Borrow Area 3) and 18 % (Borrow Area 4) difference in ρ_d, which would demonstrate an increase in θ_s if the in situ borrow soils had been placed as compacted fill.

Comparison of α and n values from 1998 and 2017 cannot be performed because moisture retention testing was not completed in 1998. Benson et al. (2007) indicated that α increased with time and that all values ended up within a range from 0.002 to 0.2 kPa^{-1} (0.042 to 4.17 psf^{-1}) regardless of the initial α. Both Phase 1 Infiltration layer samples tested for soil water retention as part of this study were within the range from Benson et al. (2007) as was the sample from Borrow Area 4. The exception was the sample from Borrow Area 3 with α = 0.348 kPa^{-1} (0.017 psf^{-1}), which was higher and corresponds to a coarser-grained soil. The n parameter decreased with time in the observations by Benson et al. (2007) and they state that 1 < n < 2 for fine-textured soils (Tinjum et al. 1997; Gurdal et al. 2003), which was true for n values from all four samples evaluated from the Phase 1 and borrow areas that were fine-grained soils (> 50 % passing #200 sieve).

6.4.2 Effect of Compaction Moisture Content and Effort on k_s

The series of permeability testing on six Borrow Area 3 and six Borrow Area 4 samples at varying moisture contents and compaction efforts was compared to observations by Benson et al. (1999a) who sampled and tested compacted clay liners from 85 sites. Benson et al concluded that k_s was more sensitive to moisture content at the time of compaction than the compaction effort applied. Permeability testing of the remolded borrow area samples indicated that an increase in w at the time of remolding generally resulted in a decrease in k_s (Fig. 6.1a). Less of a correlation was observed when comparing the percent compaction to k_s (Fig. 6.1b). Fig. 6.1b illustrates correlations of k_s to both w and percent compaction and again demonstrates that the remolded moisture content was the most sensitive parameter. Observations from this study are consistent with conclusions by Benson et al. (1999a).

Table 6.1. Laboratory characterization and engineering property test results for soil samples collected from the borrow areas at Larimer County Landfill.

Sample Location	Units	Borrow Area 3			Borrow Area 4		
ID	N/A	TS	BS1	BS2	TS	BS1	BS2
LL	(%)	37.4	40.7	45.7	35.3	39.9	38.3
PL	(%)	22.3	21.6	21.4	19.9	20.2	22.6
PI	(%)	15.1	19.1	24.3	15.3	19.6	15.7
USCS	N/A	CL	CL	CL	CL	CL	CL
Sand Content	(%)	36	38.1	31.6	35.7	34.3	36.5
Fines Content	(%)	64	61.9	68.4	64.3	65.7	63.5
Silt Content	(%)	41.3	36.2	34.2	40	38.9	4.6
Clay Content	(%)	22.6	25.7	34.3	24.3	26.9	25.9
In-Situ Moisture Content	(%)	25	20	9	19	10	10
In-Situ Dry Density	(Mg/m^3 - lb/ft^3)	NM	1.38 - 86.4	NM	NM	1.32 - 82.4	NM
w_{opt}	(%)	20	21.1	19.6	19.5	20.1	19.3
γ_{dmax}	(Mg/m^3 - lb/ft^3)	1.58 - 98.5	1.61 - 100.6	1.60 - 100.0	1.64 - 102.1	1.61 - 100.2	1.65 - 103.0
G_s	N/A	2.46	NM	2.61	2.51	2.64	2.64

Note*:* N/A: Not applicable, TS: topsoil, BS1: Block Sample 1, 15 – 45 cm (0.5 – 1.5 ft), BS2: Block Sample 2, 45 – 76 cm (1.5 – 2.5 ft). LL = liquid limit; PL = plastic limit; PI = plasticity index; USCS = Unified Soil Classification System; w_{opt} = optimum moisture content; γ_{dmax} = maximum dry density; G_s = specific gravity; NM = Not measured

Table 6.2. Saturated hydraulic conductivity (k_s) and unsaturated hydraulic properties of soil samples collected from the borrow areas at Larimer County Landfill.

Sample Location	ID	k_s (cm/s)	α (kPa^{-1}) [a]	n	θ_s	θ_r
Borrow Area 3	BS1	1.06 x 10^{-04}	0.348 (0.017)	1.261	0.481	0.04
Borrow Area 4	BS1	2.43 x 10^{-04}	0.061 (0.003)	1.633	0.495	0.04

Note: α and n = van Genuchten equation parameters, θ_s = saturated water content, θ_r = residual water content
[a] Units of psf^{-1} included in parentheses.

Table 6.3. Laboratory characterization and engineering property test results for soil samples collected from the Phase 1 existing closure cover at Larimer County Landfill.

Presumed Construction Layer		Topsoil	Rooting Zone	Infiltration (upper sample)	Infiltration (lower sample)
ID	N/A	TS	RZ	CC1	CC2
LL	(%)	44.5	45.7	54.5	52.6
PL	(%)	22.1	22.2	22.1	22.8
PI	(%)	22.5	23.5	32.4	29.8
USCS	N/A	CL	CL	CH	CH
Sand Content	(%)	3.33	0	0	0
Fines Content	(%)	96.7	100	100	100
Silt Content	(%)	51.3	57.5	56.2	54.6
Clay Content	(%)	45.4	42.5	43.8	45.4
In-Situ Moisture Content	(%)	9.4	13.8	16	14.7
In-Situ Dry Density	(Mg/m^3) [a]	NM	NM	1.79 (111.9)	1.91 (119.3)
w_{opt}	(%)	20.7	19.4	17.7	18.4
γ_{d-max}	(Mg/m^3) [a]	1.58 (98.7)	1.74 (108.8)	1.74 (108.7)	1.75 (109)
G$_s$	N/A	NM	NM	NM	NM

Note*: N/A = Not applicable; LL = liquid limit; PL = plastic limit; PI = plasticity index; USCS = Unified Soil Classification System; w_{opt} = optimum moisture content; γ_{dmax} = maximum dry density; G_s = specific gravity; NM = Not measured
 [a] Units of lb/ft^3 included in parentheses.

Table 6.4. Saturated hydraulic conductivity (k_s) and unsaturated hydraulic properties of Phase 1 existing closure cover Infiltration Layer.

Presumed Construction Layer	ID	k_s (cm/s)	α (kPa^{-1}) [a]	n	θ_s	θ_r
Infiltration (upper sample)	CC1	1.18 x 10^{-7}	0.028 (0.0013)	1.737	0.264	0.078
Infiltration (lower sample)	CC2	8.87 x 10^{-8}	0.026 (0.0012)	1.319	0.290	0.078

Note: α and n = van Genuchten equation parameters, θ_s = saturated water content, θ_r = residual water content
[a] Units of psf^{-1} included in parentheses.

Table 6.5. Saturated hydraulic conductivity (k_s) of borrow area soils remolded to varying moisture contents and percent compaction in order from highest k_s to lowest k_s within soil samples collected from the borrow areas at Larimer County Landfill.

Borrow Area	Sample ID	Moisture Content Relative to Optimum (%)	Moisture Content (%)	Dry Density (Mg/m^3) [a]	Compaction (%)	k_s (cm/s)
3	BS2	-11.6	8.0	1.26 (78.5)	78.5	4.2 x 10^{-4}
3	BS2	-12.6	7.0 (In-situ)	1.33 (83.2)	83.2	1.3 x 10^{-4}
3	BS2	+0.5	20.1	1.32 (82.7)	82.7	5.7 x 10^{-6}
3	BS1	-1.3	19.8 (In-situ)	1.45 (90.6)	90.0	3.8 x 10^{-6}
3	BS1	-1.1	20.0 (In-situ)	1.45 (90.5)	90.0	3.8 x 10^{-6}
3	BS1	0.0	21.1 (In-situ)	1.52 (95.2)	94.6	2.0 x 10^{-6}
4	BS2	-13.8	5.5	1.39 (87.0)	84.5	8.0 x 10^{-5}
4	BS1	-10.1	10.0 (In-situ)	1.51 (94.5)	94.3	3.0 x 10^{-5}
4	BS2	-9.3	10.0 (In-situ)	1.38 (86.2)	83.7	2.5 x 10^{-5}
4	BS2	-9.3	10.0 (In-situ)	1.52 (94.8)	92.0	2.5 x 10^{-5}
4	BS2	+2.0	21.3	1.31 (81.9)	79.5	8.4 x 10^{-6}
4	TS	-0.1	19.2 (In-situ)	1.45 (90.3)	91.7	4.6 x 10^{-6}
4	BS2	+2.0	21.3	1.55 (96.9)	94.1	1.1 x 10^{-6}

Notes: TS: topsoil, BS1: Block Sample 1, 15 – 45 cm (0.5 – 1.5 ft), BS2: Block Sample 2, 45 – 76 cm (1.5 – 2.5 ft), In-situ: remolded moisture content similar to in-situ moisture content of block sample
 [a] Units of lb/ft^3 included in parentheses.
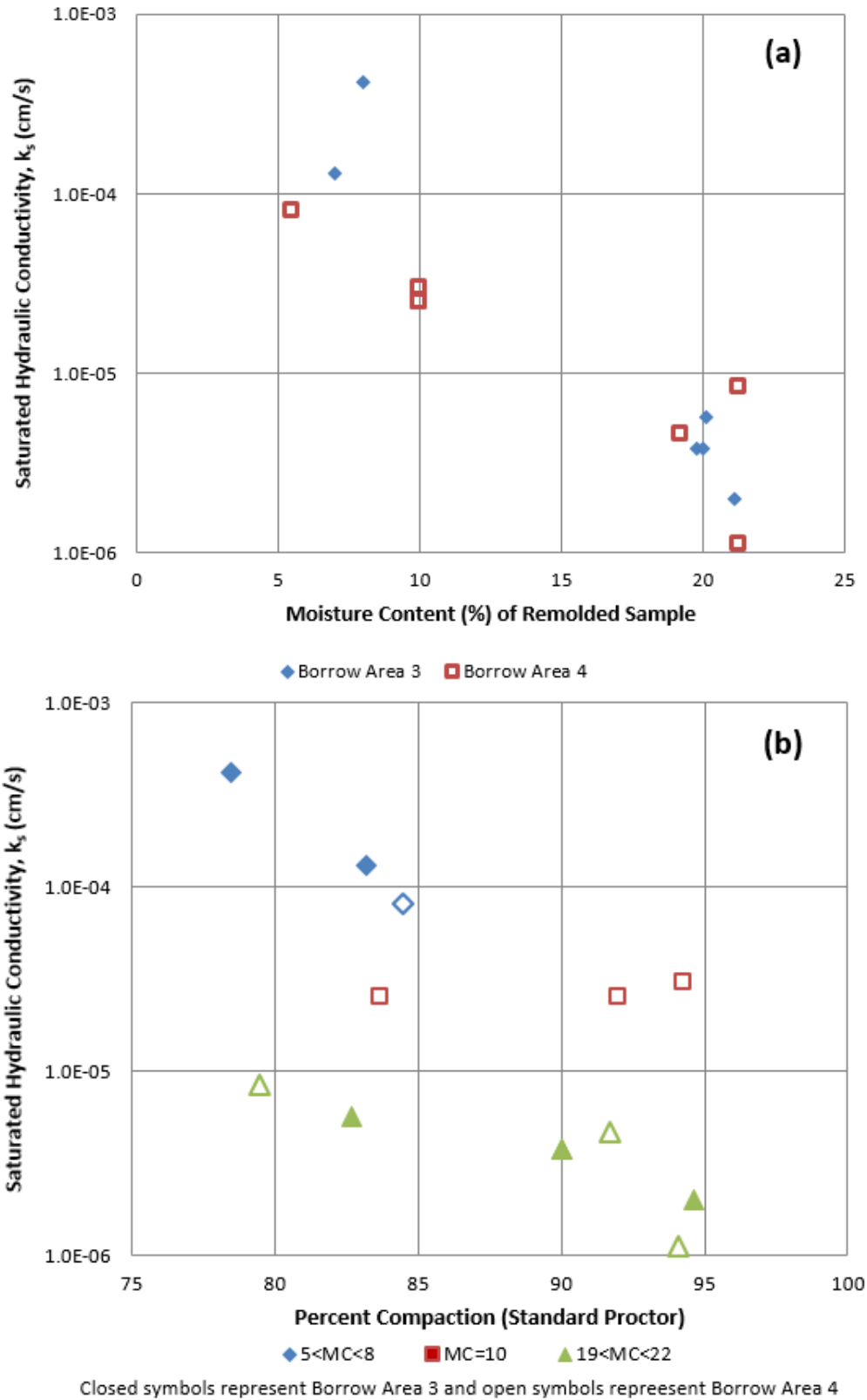
Fig. 6.1. Saturated hydraulic conductivity of remolded borrow area soils versus (a) remolded moisture content and (b) remolded percent compaction and moisture content.
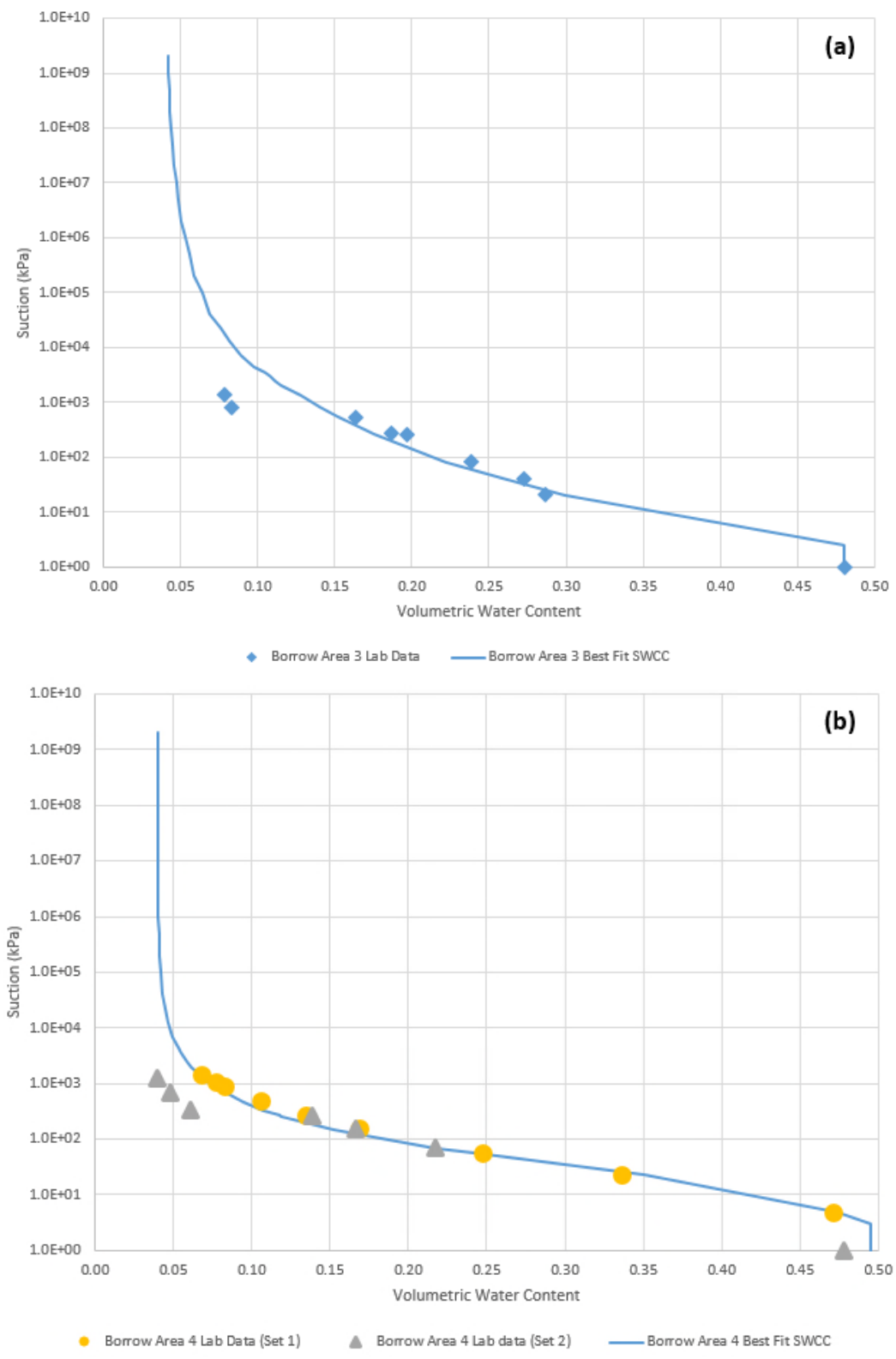
Fig. 6.2. Soil water characteristic curve and unsaturated flow laboratory test results from (a) Borrow Area 3 and (b) Borrow Area 4.
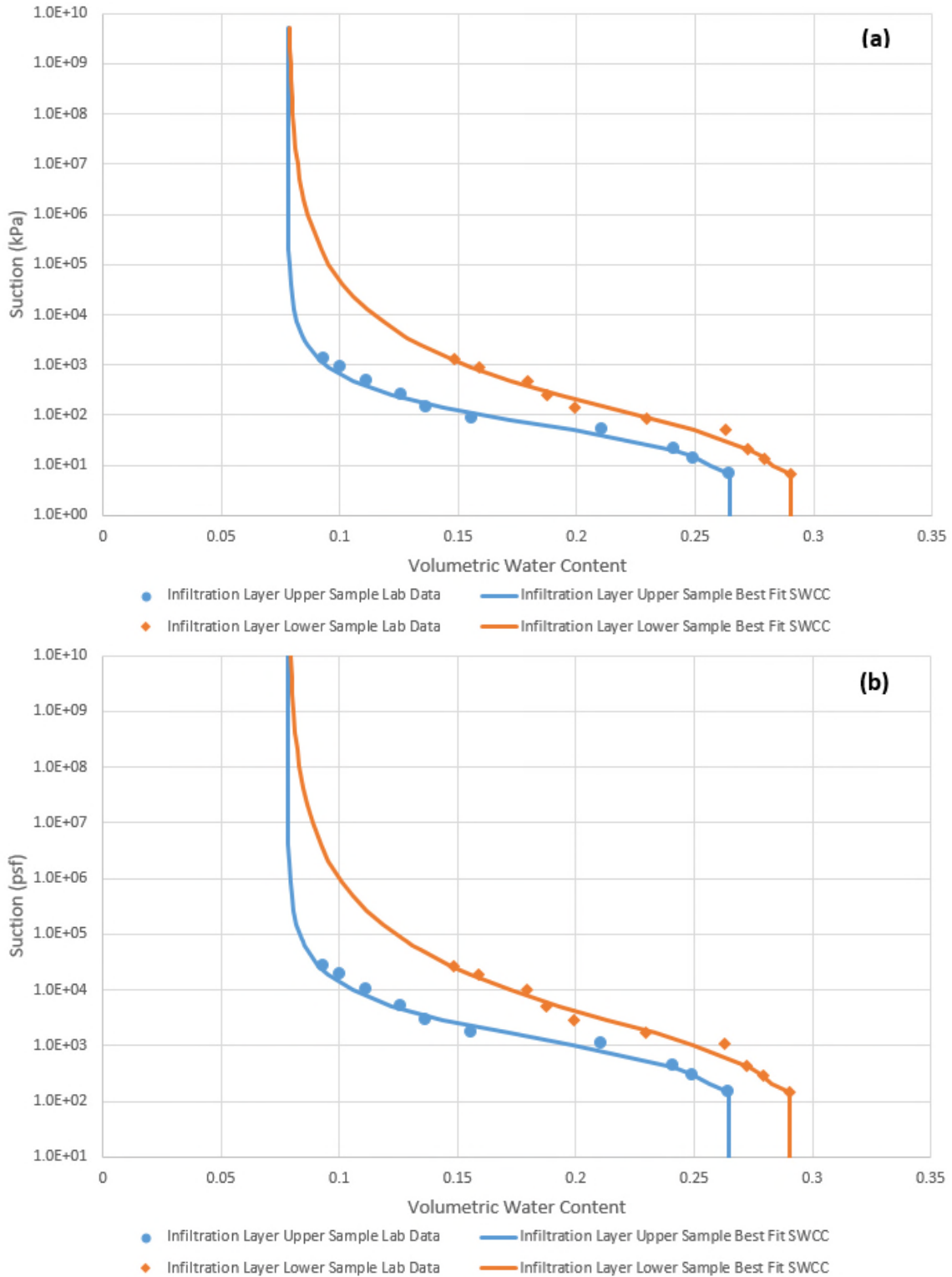
Fig. 6.3. Soil water characteristic curves for Phase 1 Infiltration Layer in (a) metric units and (b) English units.
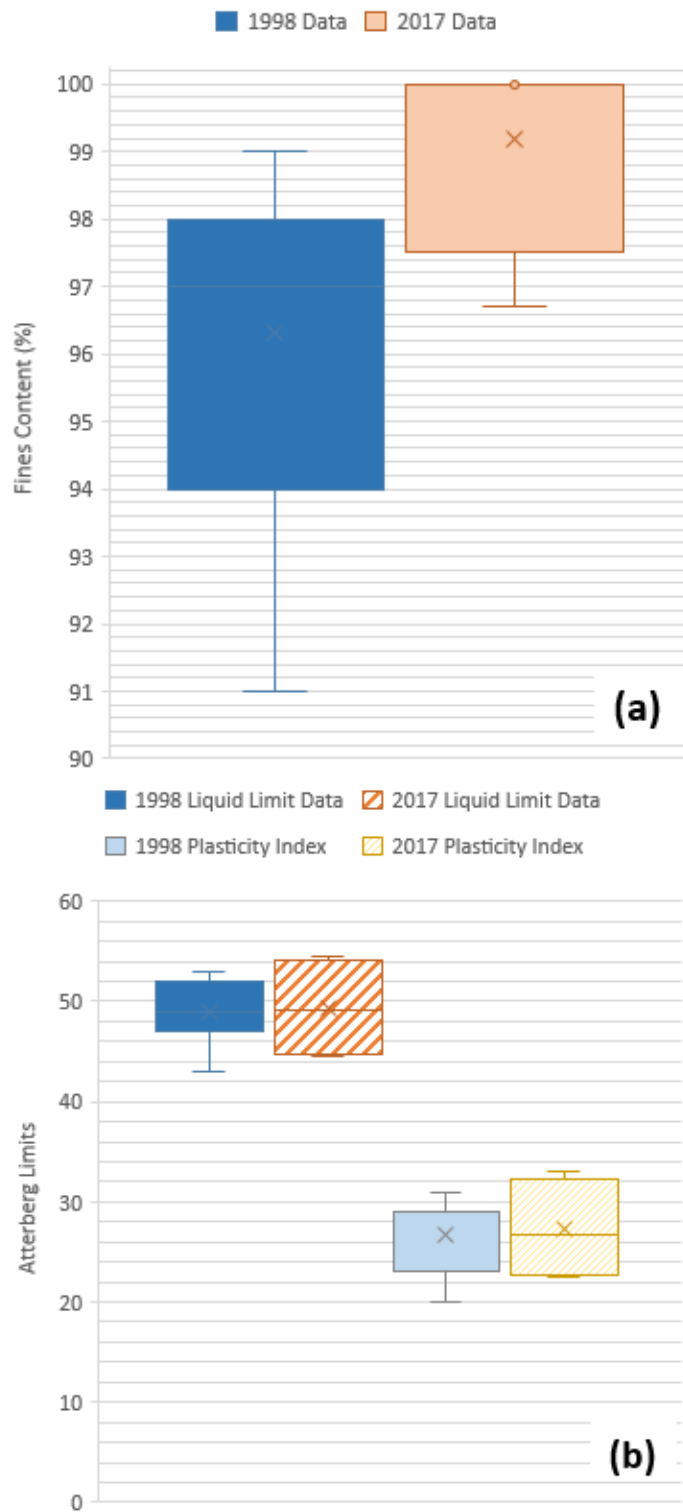
Fig. 6.4. Comparison of (a) fines content and (b) Atterberg limits determined from soil investigations conducted in 1998 and 2017 (this study).
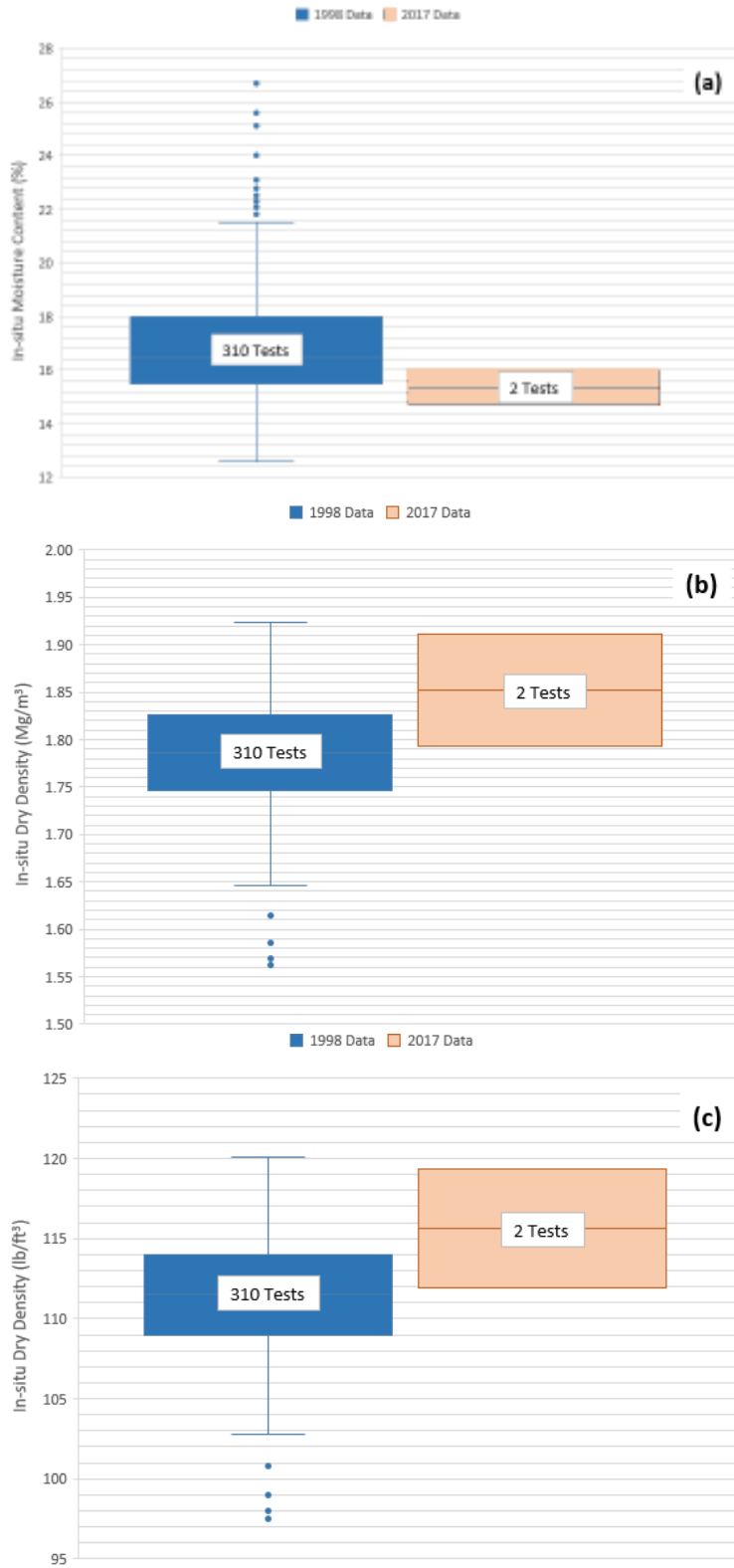
Fig. 6.5 Test results from 1998 and 2017 laboratory investigations of the Infiltration Layer for (a) in-situ moisture content, (b) dry density (metric units), and (c) dry density (English units).
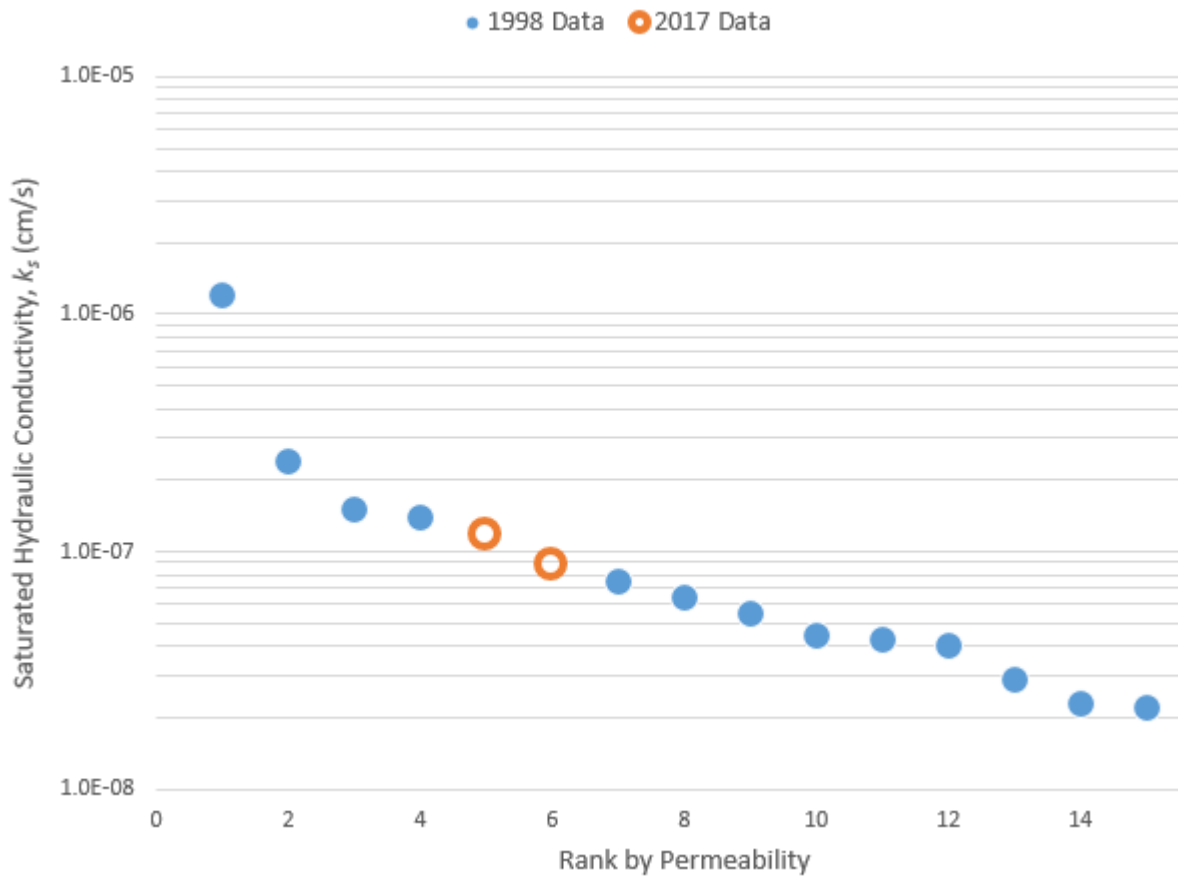
Fig. 6.6 In-situ dry density of the Infiltration Layer from the 1998 and 2017 investigations.
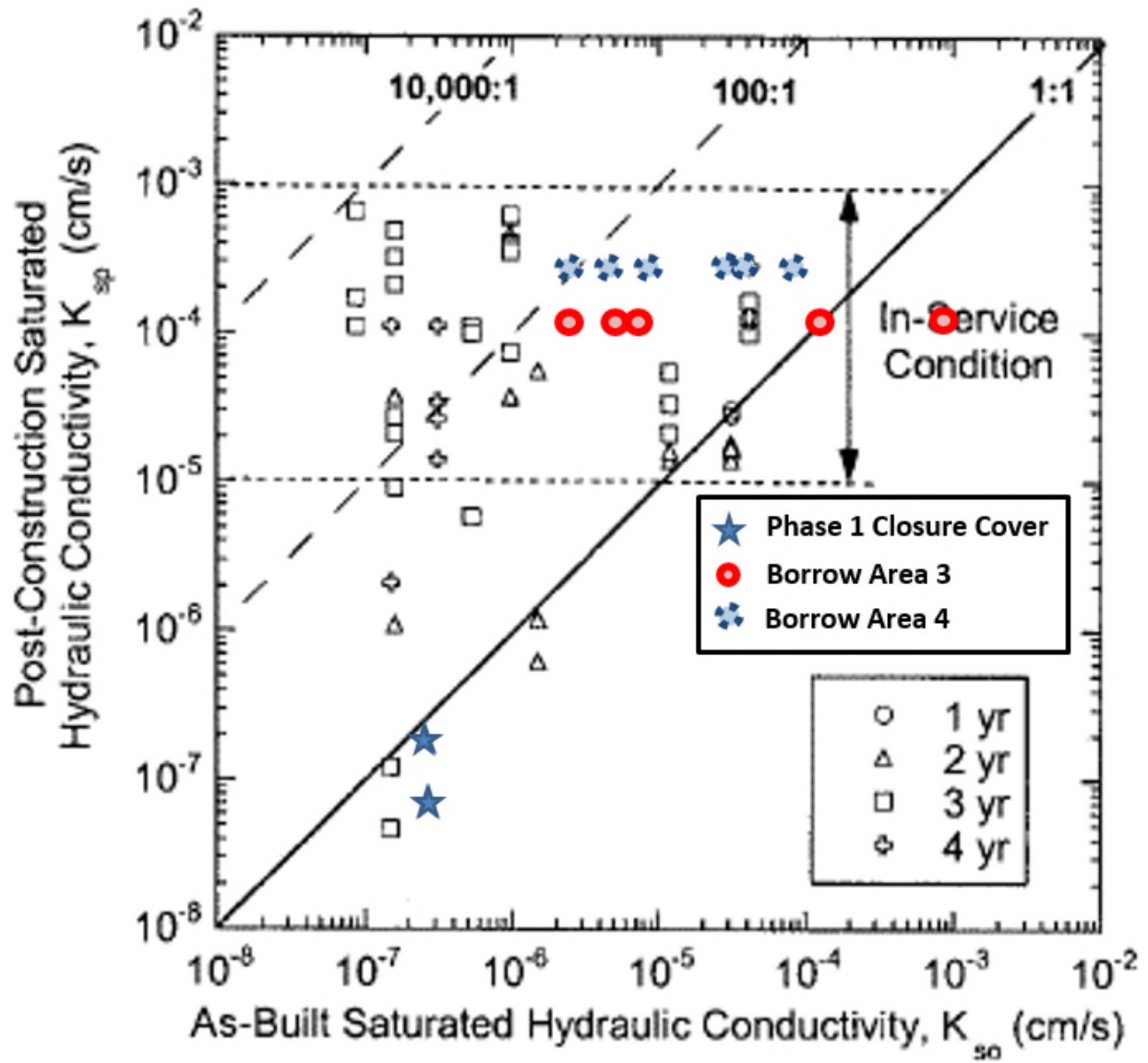
Fig. 6.7 Reproduced figure from Benson et al. (2007) supplemented with saturated hydraulic conductivity results from this study.

CHAPTER 7. VEGETATION

Vegetation on a final cover removes water through transpiration and reduces erosion. A mixture of grass, shrub, and forb species was planted on the final cover at LCL as part of each closure phase. The Fromme Prairie seed mixture that was used for the final cover in Phase 1 of LCL is tabulated in Table 7.1. This mixture was applied at the rate of 8.03 kg (17.7 lb) of pure live seed per 0.40 ha (1 acre) using the drill seeding method. A qualitative survey of vegetation on the Phase 1 cover indicated that many of the species from the original seed mix were non-existent and new species were present. Particularly predominant was the invasion of smooth brome grass and alfalfa that were speculated to have originated from the neighboring prairie and hay mulch, respectively. No shrubs were presently growing on the final cover at LCL at the time of this study.

A qualitative vegetation survey of the remaining borrow areas was also conducted. The borrow areas represent a more natural habitat than the final cover; however, select areas have been disturbed in the past for wheat farming and local recreation. Vegetation in the borrow areas is more diverse, with small trees, shrubs, and grasses. Vegetation in the borrow area is less dense, but the species have a deeper and denser root system than vegetation on the final cover.

Table 7.1. Larimer County Landfill Phase 1 final cover seed mixture.

Species	Purity (%)	Germination (%)
Buffalograss	31.66	86
Western Wheatgrass	12.60	86
Sideoats Grama	11.24	78
Bluebunch Wheatgrass	9.18	86
Indian Ricegrass	6.85	96
Needle and Thread	4.62	95
Big Bluestem	3.57	86
Purple Prairie Clover	2.61	86
Lewis Flax	2.06	85
Little Bluestem	1.52	88
Blue Grama	1.44	93
Upright Prairie Coneflower	0.97	97
Rubber Rabbitbrush	0.55	80
Fringed Sage	0.52	85
Yarrow	0.49	95

Note: Additional contribution of 9.62 % inert, 0.27 % weeds, and 0.22 % crop within the seed mixture.

CHAPTER 8. DESCRIPTION OF MODEL AND MODEL PARAMETERS

Hydrologic modeling was conducted with the finite element program VADOSE/W in GeoStudio to assess the water balance of the final cover in Phase 1 and potential WBC at LCL. VADOSE/W is capable of simulating flow of water, heat, and vapor in saturated and unsaturated soils (GEO-SLOPE 2014). Variably saturated flow is simulated via the Richards equation and vapor flow is simulated via mathematical expressions in Wilson (1990) and Milly (1982). Actual evaporation of the soil layer is computed via the Penman-Wilson (1990) equation, and actual transpiration is determined by vegetative uptake combined with surface energy based on canopy cover (Tratch 1996). Root uptake of water within the soil layer depends on root depth and density, and water stress (i.e., soil suction). A three-stage modeling approach was implemented for all model simulations, whereby Stages 1 and 2 conditioned the model to create an end-state hydrologic profile within a cover system that simulated long-term conditions and Stage 3 included the unique 10-yr, daily MET data from 1992 to 2002. Stage 3 model simulations were the simulations used to compare hydrologic performance of the final covers considered at LCL.

8.1 Model Geometry

The model geometry was one-dimensional (1-D) with cover thickness varying between 61 and 106.7 cm (2 and 3.5 ft) depending on the scenario simulated. A 1-D model was used in this study to provide conservative water balance estimate and decrease computation time. The runoff component of the water balance equation is removed in VADOSE/W when using a 1-D simulation, which allows more available water to enter the cover; thus, yielding a conservative assessment of the water balance.

The model geometry with element mesh and boundary conditions is illustrated in Fig. 8.1. Surface layers were assigned within the model geometry to discretize the mesh and create

a quadrilateral element mesh parallel to the primary gradient direction and perpendicular to the ground surface. The vertical element spacing varied between 9.5 and 76 mm (0.37 and 3 in) among the models, and a finer mesh was used near the surface where climate and vegetation interaction with the soil was more prevalent. Preliminary model simulations started with larger mesh spacing, which resulted in shorter computation times but larger water balance errors. If the water balance error exceeded 1% of the precipitation, results were considered inaccurate and the mesh size was reduced and the model was re-run until an acceptable water balance error was achieved.

8.2 Boundary Conditions

Boundary conditions were specified on the top and bottom boundaries of the 1-D simulations to drive hydraulic and heat flow and simulate evapotranspirative interactions between the cover soil and climate. VADOSE/W requires a steady state analysis to initially develop pore pressures (and corresponding volumetric water content) and temperature within the cover, which is used as a parent analysis to the transient analyses that simulates actual MET data over a modeled time period. Different boundary conditions were applied to the steady state model for Stage 1 than were used in the transient models for Stages 2 and 3 (Fig. 8.1).

The upper boundary condition in Stage 1 included assigned pore pressures and temperatures to approximate initial conditions. The model was run with a unit gradient as the bottom boundary condition to generate an initial distribution of pore pressure and temperature throughout the model domain. Final steady-state pore pressure and temperature profiles from Stage 1 were used as initial conditions for the model domain in Stage 2.

Transient analysis conducted in Stage 2 and 3 models included a climate boundary condition at the top boundary and unit gradient at the bottom. The climate boundary condition consisted of four components identified in VADOSE/W: (i) MET data set, (ii) leaf area index (LAI) function, (iii) rooting depth (RD) function, and (iv) plant moisture limiting (PML) function.

The MET data set consisted of daily maximum and minimum temperature, maximum and minimum relative humidity, average wind speed, and precipitation. Radiation energy was estimated by VADOSE/W based on the specified site latitude (i.e., 40.5° N). The other three components for the climate boundary condition deal with vegetation parameters (discussed subsequently).

The time period of MET data evaluated in this study was 1992 to 2002. Input MET data for VADOSE/W included 15 years of data: Years 1-5 were used for model conditioning (Stage 2) and Years 6-15 pertained to calendar years 1992-2002 (Stage 3). Stage 2 included data from 1996 cycled five times consecutively. The year 1996 was selected because this year received slightly above average precipitation based on precipitation data from 1889 to 2016. Thus, the goal of Stage 2 was to generate a realistic soil moisture and temperature profile to be used as initial conditions for the Stage 3 simulation that included the years 1992 through 2002. A unit gradient boundary condition was assigned to the bottom of the model to allow pore water to freely flow through the bottom of the cover at a rate matching the hydraulic conductivity.

8.3 Vegetation Properties

Leaf area index (LAI) is an approximation of the plant canopy used by VADOSE/W to calculate actual evaporation by quantifying the amount of net radiation available at the soil surface. Temporal trends of two LAI functions that were used in the water balance modeling are shown in Fig. 8.2. One LAI function simulated a revegetated cover based on plant species present in the Phase 1 construction seed mix and observed on site. The other LAI function simulated a natural cover that represented vegetation observed in the borrow areas. The LAI function of the revegetated cover started May 1, peaked at an LAI = 3 from June 19 through July 11, and then reduced to zero by October 28 when vegetation was assumed dormant. The peak LAI = 3 was based on the mean LAI computed from Scurlock et al. (2001) for "Grassland"

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and the U.S. EPA Hydrologic Evaluation of Landfill Performance (HELP) Model manual (Schroeder et al. 1994) for "a good stand of grass".

The natural cover was assumed to be a more diverse biome with shrubs, forbs, and grasses. The more diverse vegetation competes amongst itself for sunlight and grows vertically and laterally resulting in relatively dense cover in some areas but also bare locations as observed in the borrow areas. The diversity and native origin of species in the natural cover results in a longer growing season compared to the revegetated cover. The LAI function for the natural cover began on April 1, peaked at an LAI = 2 from June 20 through August 10, and then reduced to zero by November 16 when vegetation was assumed dormant. The peak LAI = 2 was based on Scurlock et al. (2001) for "Shrubs" in combination with qualitative observations from the borrow area.

The Rooting Depth (RD) function specifies the density of root growth with depth during the time vegetation is assumed active (i.e., LAI > 0). A triangular distribution of roots was selected with a maximum root depth of 30.5 cm (1 ft) and 46 cm (1.5 ft) for the revegetated and natural covers, respectively. These rooting depths were determined based on observations during sampling, and inherit differences between the revegetated grassland and more diverse plant species that represented the natural cover.

The Plant Moisture Limiting (PML) function was used to simulate the amount of available water in the soil matrix that vegetation can remove with respect to matric suction. The PML function (Fig. 8.3) begins at 1.0 as suction increases to 100 kPa at which point the PML function decreases linearly until a value of 0.0 at a suction of 1,500 kPa. The 1,500 kPa soil suction corresponds to the wilting point, whereupon most plants can no longer remove water from the soil matrix. The same PML function was used in the revegetated and natural cover.

8.4 Material Properties

Material properties for the soil layers simulated in the water balance models were determined for Borrow Area 3, Borrow Area 4, and all three layers of the Phase 1 cover (i.e., topsoil, rooting/frost protection, and Infiltration layers). The rooting/frost protection and Infiltration layers were modeled as the same layer based on similarities between their particle size distribution, as-built compaction parameters, and observations during sampling. Laboratory test results for density, specific gravity, soil water retention, and k_s were the basis of the hydraulic functions assigned for each material in GeoStudio. Soil water characteristic curves developed using the least means squared method presented in Chapter 6 were used for the water content functions (Fig. 8.4) of each layer except topsoil.

The topsoil water content function was calculated using van Genuchten parameters derived from the Rosetta Model (USDA, 2008) based on soil composition (percent sand, silt, and clay) and bulk density determined in the laboratory. Parameters from the Rosetta model for topsoil included θ_s = 0.496, θ_r = 0.099, α = 0.0124, and n = 1.386, and the SWCC based on these parameters is shown in Fig. 8.4b.

The hydraulic conductivity function for each material was estimated using a method developed by Fredlund et al (1994). The method integrates along the volumetric water content function starting at k_s until a maximum suction is reached (Fig. 8.5). The laboratory measured k_s was used for each material except for topsoil where the Rosetta Model output of 1.2×10^{-4} cm/s was the basis for k_s.
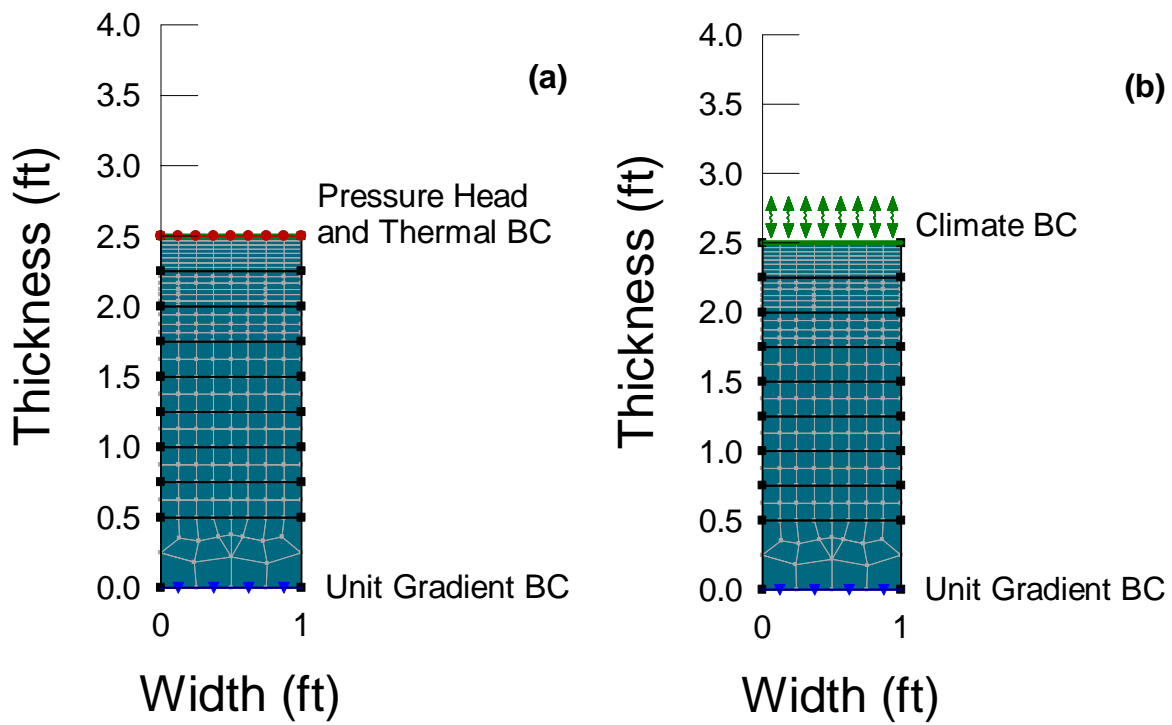
Fig. 8.1. Model geometry and boundary conditions for a 76.2-cm-thick (2.5 ft) cover simulation: (a) Stage 1 steady-state model and (b) Stages 2 and 3 transient models.
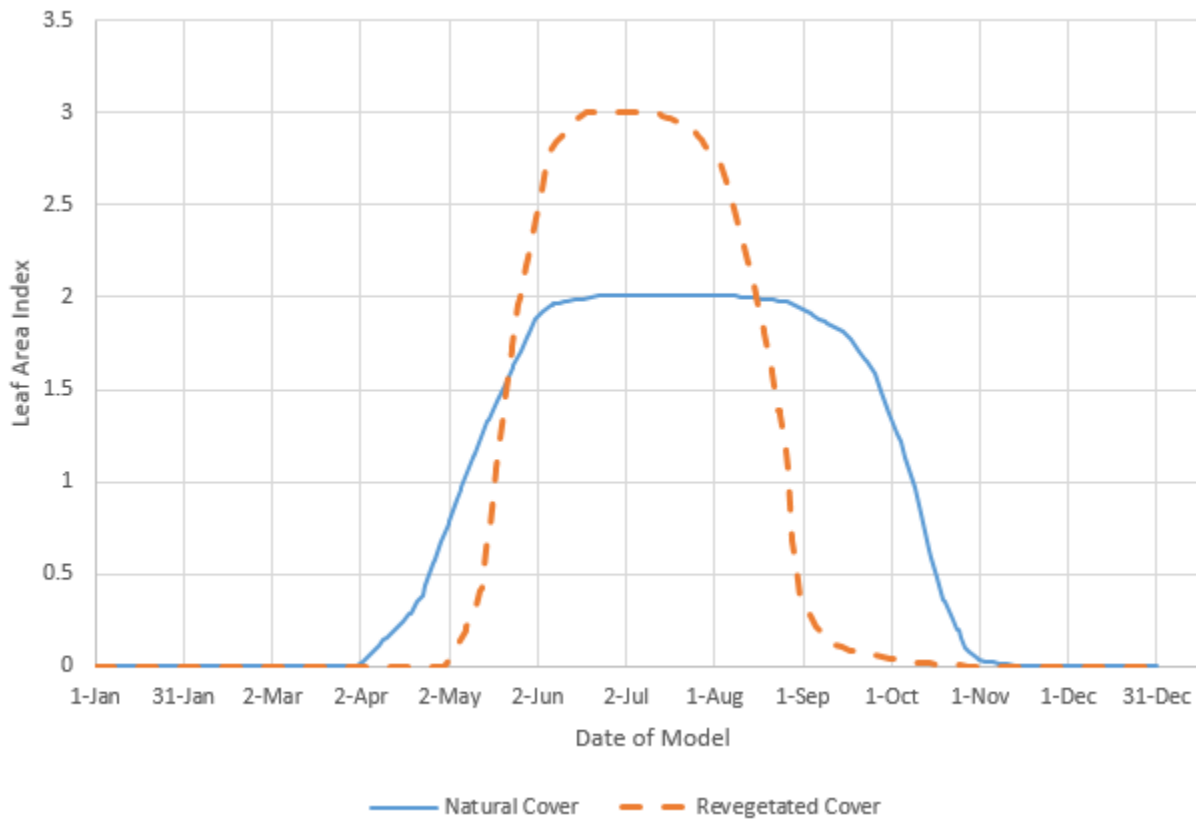
Fig. 8.2 Leaf area index functions.
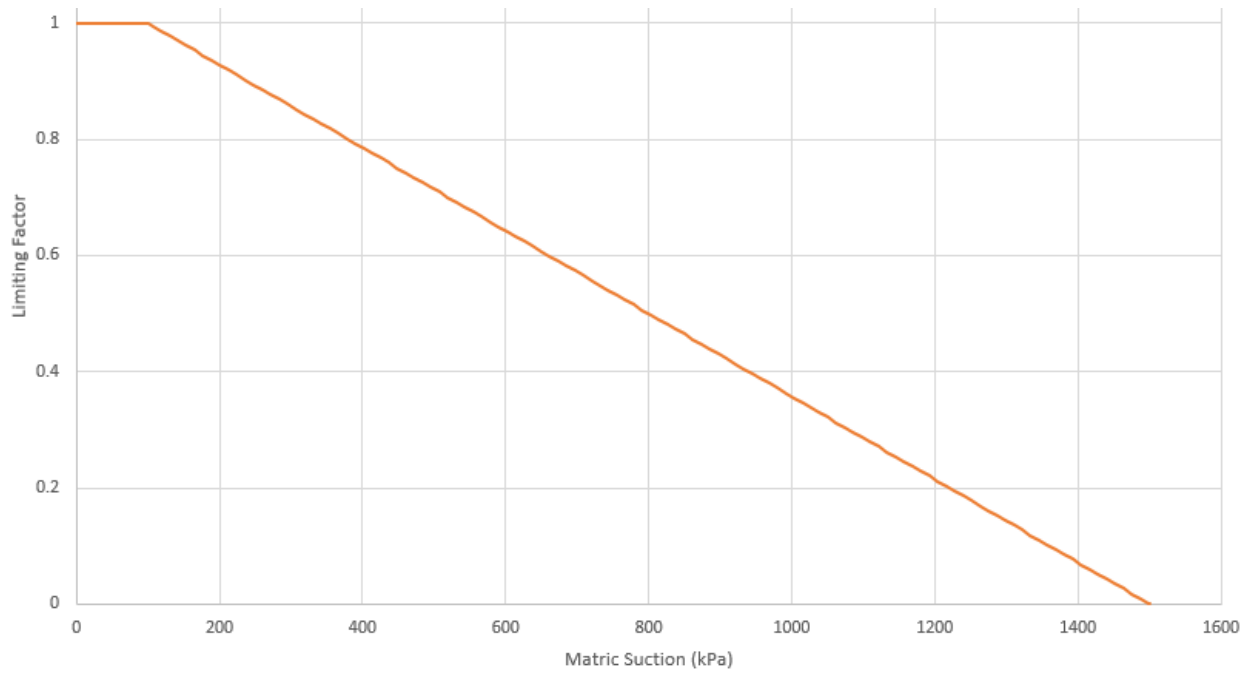
Fig. 8.3 Plant moisture limiting function.
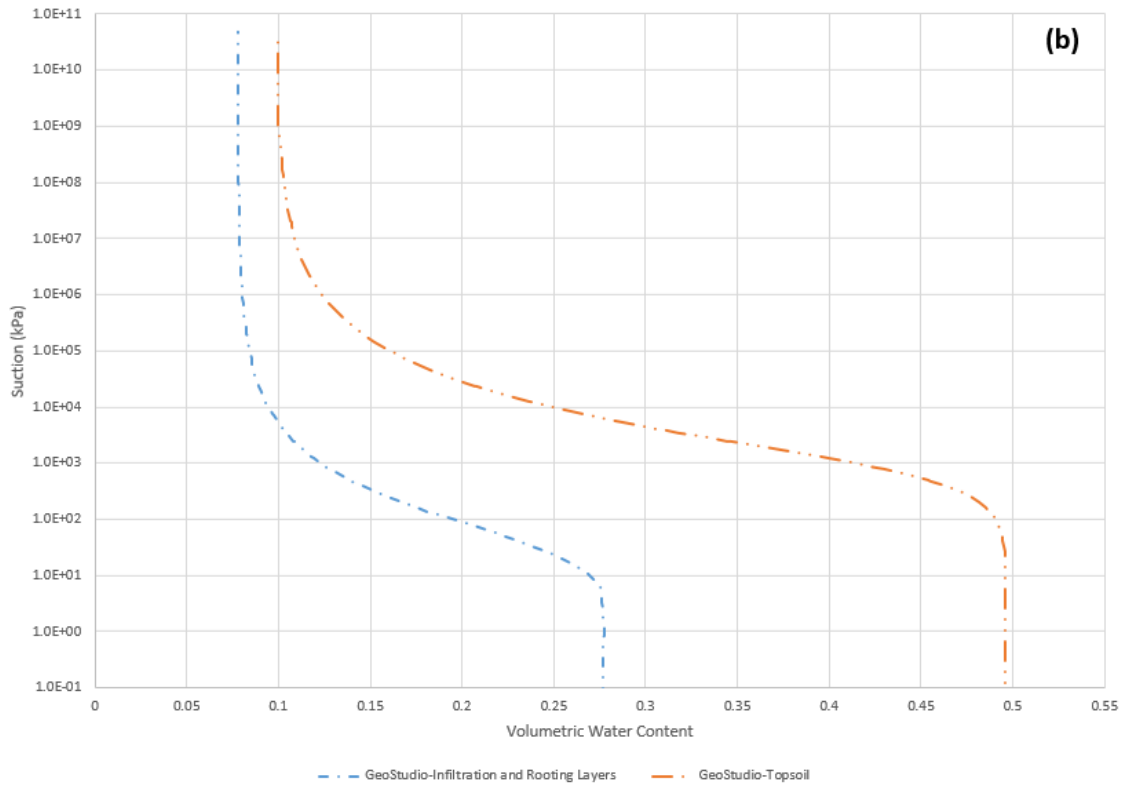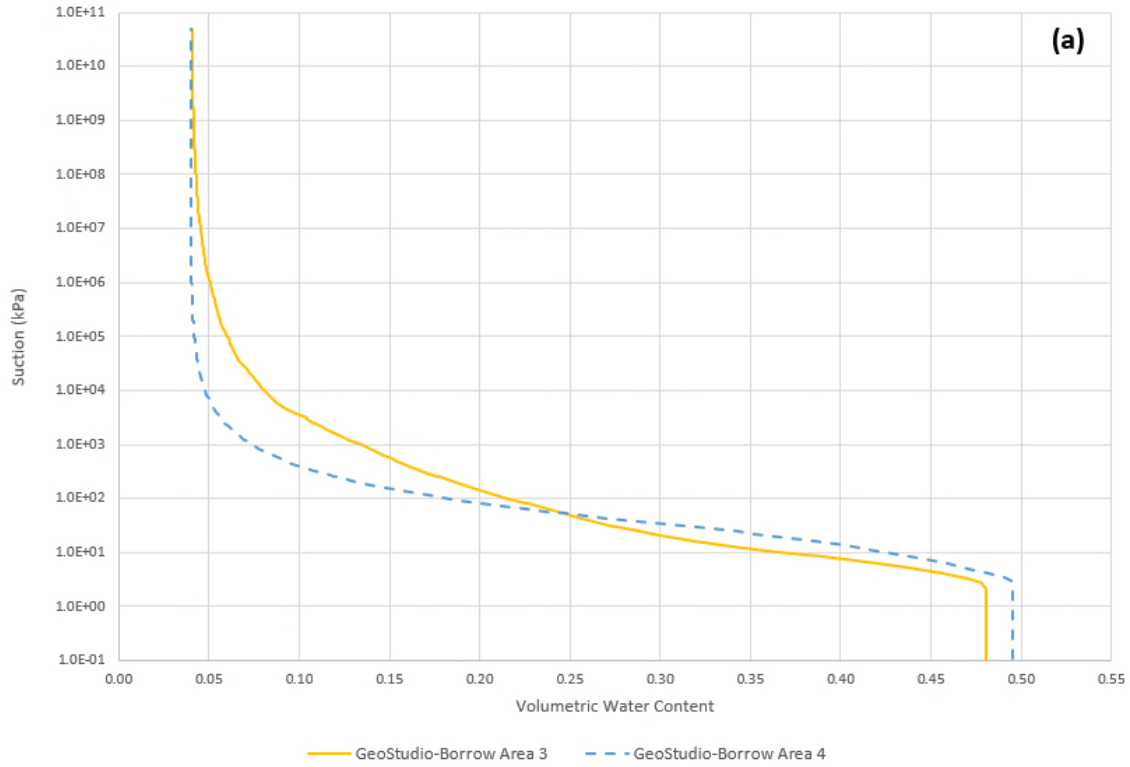
Fig. 8.4 Modeled soil water characteristic curves for (a) water balance cover and (b) Phase 1 final cover soils.
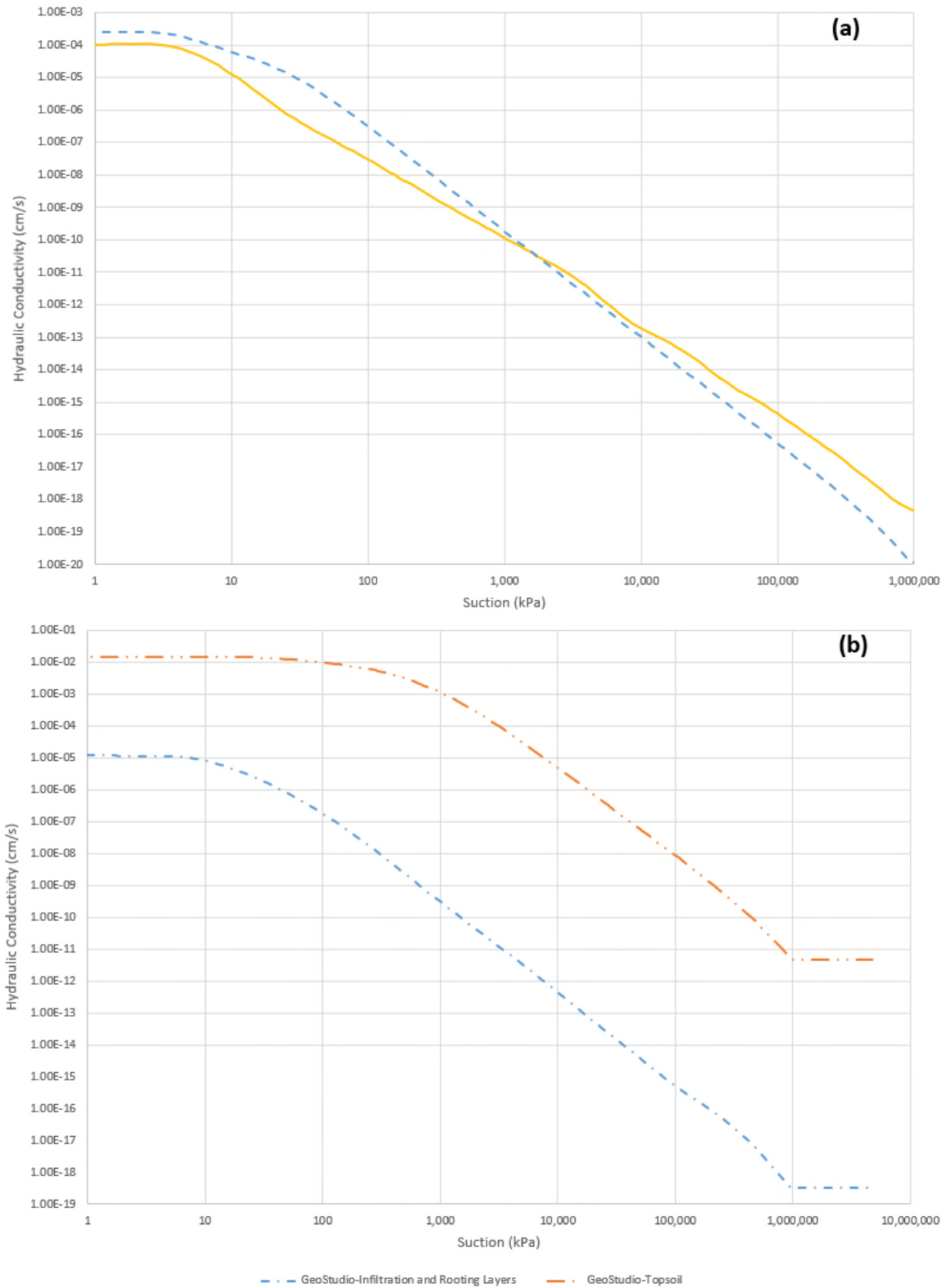
Fig. 8.5 Modeled hydraulic conductivity functions for (a) water balance cover and (b) Phase 1 final cover soils.

CHAPTER 9. MODEL RESULTS

Variably saturated flow modeling using VADOSE/W (GeoStudio, 2016) was performed to compare the hydraulic performance of prescriptive and water balance covers. Schematics of the covers evaluated in this study are shown in Fig. 9.1. A sensitivity analysis was conducted for the prescriptive covers that incorporated two k_s (1.0 x 10^{-5} cm/s or 1.2 x 10^{-7} cm/s). Similarly, sensitivity analysis was conducted for the WBC models to compare cover thickness, soil from Borrow Area 3 versus Borrow Area 4, and revegetated versus natural vegetation. Components of the water balance equation (Eq. 2.1) were analyzed to compare the different covers simulated (Fig. 9.1) and assess the effects of model variables on water balance in the sensitivity analysis.

9.1 Model Scenarios

9.1.1. Prescriptive

The prescriptive cover model was based on thicknesses from CCR 1007-2, 40 CFR 258.60, and the CDPHE approved LCL design for the Phase 1 closure. The approved prescriptive cover design included from the surface down (i) ≥ 15 cm (0.5 ft) erosion layer capable of sustaining native plant growth (topsoil), (ii) ≥ 45.7 cm (1.5 ft) rooting layer, and (iii) ≥ 45.7 cm (1.5 ft) Infiltration layer with k_s ≤ 1 x 10^{-5} cm/s or k_s ≤ of any bottom liner, whichever is lower (Fig. 9.1). Although the Phase 1 cover at LCL was based on the aforementioned cover profile, the test pit excavated in Phase 1 revealed a thicker profile: (i) topsoil ≈ 30.5 cm (1 ft); (ii) rooting layer ≈ 61 cm (2 ft); and (iii) Infiltration layer > 91 cm (3 ft). The thicker "as-built" Phase 1 prescriptive cover was not modeled since the thicker cover profile was not considered representative of state or federal regulated prescriptive covers and may not be present across all LCL closure phases.

The average k_s was 1.6 x 10^{-7} cm/s among 13 construction quality assurance tests from the 1998 construction. The two samples collected from the Infiltration layer from this investigation had k_s = 1.2 x 10^{-7} cm/s for the upper sample and 8.9 x 10^{-8} cm/s for the lower sample. Modeling of the Phase 1 prescriptive cover was performed using the highest measured k_s from this study (k_s = 1.2 x 10^{-7} cm/s) and the regulatory acceptable k_s of 1 x 10^{-5} cm/s.

9.1.2. Water Balance Covers

A 76.2-cm-thick (2.5 ft) WBC meets CDPHE requirements (2013) based on LCL being located in Ecozone 3 (Fig 2.1) and a USDA soil texture of clay loam identified for the borrow area soil (Fig. 2.2). Additional WBC models using a 76.2-cm-thick cover were completed to assess differences in soil properties between Borrow Area 3 and Borrow Area 4 and revegetated versus natural vegetation parameters. These models were completed to determine model sensitivity to soil and vegetation conditions and ultimately arrive at a recommended WBC design. In addition to the 76.2-cm-thick WBC, covers with thicknesses of 61 cm (2 ft) and 91.4 cm (3 ft) were modeled to quantify the effect of WBC thickness on percolation. For the models with varying cover thickness, Borrow Area 3 soil and revegetated conditions were used.

9.2 CDPHE Accepted Covers Model Results

Guidance and regulations from the state of Colorado indicate a prescriptive cover with a combined thickness of 106.7 cm (3.5 ft) or a WBC with a thickness of 76.2 cm (2.5 ft) would be acceptable for construction based on soil characteristics determined from investigations in Phase 1 and the borrow areas. Annual percolation and evapotranspiration (*ET*) rates based on model simulations for the prescriptive cover and WBC for LCL are summarized in Table 9.1. The model results indicate an annual percolation rate < 0.1 mm/yr for the prescriptive cover using k_s measured in this study (1.2 x 10^{-7} cm/s) and a percolation rate 2.2 mm/yr for the prescriptive cover with the regulatory k_s = 1 x 10^{-5} cm/s. The most effective WBC had an annual

percolation rate of 6.3 mm/yr. The most effective WBC in terms of achieving low percolation rates were simulated with soil from either Borrow Area 3 or Borrow Area 4 and natural vegetation (Table 9.1). The maximum annual percolation of 11.3 mm/yr resulted from a WBC simulated with Borrow Area 3 soil and vegetation simulating a revegetated cover.

Temporal trends of percolation and precipitation during the model simulation period for the CDPHE acceptable prescriptive and water balance covers are shown in Fig. 9.3. Cumulative percolation through the prescriptive cover with $k_s = 1.2 \times 10^{-7}$ cm/s was less than 1 mm, which forced the percolation data to plot along the x-axis in Fig. 9.3. Percolation through the prescriptive cover with $k_s = 1.0 \times 10^{-5}$ cm/s and percolation through the WBC models reflect surges of percolation in response to precipitation events. This surge behavior is typical of simulated WBC and represents periods of high precipitation that coincided with high levels of soil saturation (Bareither et al. 2016). During these precipitation events, insufficient storage is available within the cover, which allows percolation to occur. In this study, these isolated, high percolation events represented the majority of percolation that was simulated.

CDPHE or federal regulations do not define an allowable percolation threshold for the bottom of a cover profile. Instead, percolation thresholds are defined from either (i) preconstruction or immediate post construction soil properties and layer thicknesses, or (ii) an equivalency demonstration in the case of a WBC (as described in Chapter 1). Interpretation of the model results presented in the WBC guidance document from CDPHE (2013) shown in Fig. 9.2 and the CDPHE acceptable thickness criteria (Fig. 2.2) indicate that a percolation rate ranging from 11.2 to 22.4 mm/yr was used to determine acceptable cover thicknesses in the CDPHE WBC guidance document. Equivalency is not quantified in the regulations; thus, the acceptable difference in percolation between a prescriptive and water balance cover cannot be determined. However, all WBC simulations completed on acceptable CDPHE covers yielded percolation rates that were lower than the minimum CDPHE value of 11.2 mm/yr except for the

scenario of Borrow Area 3 soils and revegetated conditions which resulted in a percolation rate of 11.3 mm/yr.

Model output for percolation, *ET*, soil water storage (storage), and runoff was evaluated to assess the water balance in response to the simulated climatic conditions (Table 9.1). Percolation was low in all models, and calculated to be approximately 0.0 % to 0.5 % of the prescriptive cover water balance, and between 0.3 % and 0.8 % of the WBC water balance. Evapotranspiration was the dominant mechanism that removed water from the system, and in all model simulations *ET* removed between 94 % and 102 % of the precipitation during the modeled period. The similarity in magnitude of *ET* and precipitation indicates the two were favorably balanced during the years simulated. Storage was the next most significant water balance component relative to *ET*, consisting of a gain of 2.4% or a cumulative loss of 0.3 % in the prescriptive cover models and a loss of 2.2 % to 3.4 % in the WBC models. A gain in storage indicates the model geometry is accumulating water throughout the modeled period and a loss in storage indicates the model is losing water throughout the modeled period. Runoff was negligible in all models, which was expected for the 1-D simulations.

Annual average precipitation, evaporation, and transpiration for the water balance simulations are shown graphically on Fig. 9.4. The data in Fig. 9.4 demonstrate that in the prescriptive cover the dominant water balance component was evaporation, which removed 62 % and 67 % of the precipitation. In contrast, transpiration was the dominant water balance component that removed precipitation from the WBC profiles, accounting for 58 % to 73 % of the cumulative precipitation. These data indicate that the lower permeability of the prescriptive cover soil stored precipitation closer to the surface where evaporation was most influential. In contrast, the higher permeability WBC allowed for deeper infiltration of the precipitation where transpiration was more influential.

9.3 Borrow Area 3 WBC Sensitivity Analysis Model Results

Additional Borrow Area 3 WBC scenarios with varying thickness were modeled to quantify the effect of cover thickness on percolation and further assess equivalency relative to the prescriptive cover. Borrow Area 3 soils were selected for the sensitivity analysis because the 76.2-cm-thick (2.5 ft) CDPHE acceptable WBC had higher percolation than the Borrow Area 4 WBC with the same thickness and vegetation type. Model simulations were completed such that the cover thicknesses varied ± 15.2 cm (0.5 ft) from the acceptable thickness of 76.2 cm (2.5 ft).

Water balance modeling results for the Borrow Area 3 WBC with varying cover thickness are summarized in Table 9.2. Modeling results indicate a trend of decreasing percolation with increasing cover thickness. The maximum percolation of 13.2 mm/yr was simulated for the 61-cm-thick (2 ft) WBC with a revegetated cover, whereas a minimum percolation of 4.9 mm/yr was simulated for the 91.4 cm-thick (3 ft) WBC with a natural cover. Analysis of the water balance in Table 9.2 indicates that transpiration was the dominant component for the Borrow Area 3 WBC. Evaporation was also a relatively large contribution to the water balance when compared to the other components. Combined, *ET* contributed 92 % to 95 % of precipitation removed under revegetated conditions and 97 to 100 % of precipitation removed under natural vegetation conditions. The similar magnitude of *ET* and precipitation again demonstrates the balance between *ET* and precipitation that was apparent in the CDPHE acceptable cover models. Annual storage showed a slight decrease in the rate of storage loss with an increase in the WBC thickness indicating the thinner covers lost slightly more water during the simulation.

9.4 Further Detail of Model Results

Volumetric water content (θ) of the modeled WBC constructed of Borrow Area 3 soils and revegetated cover characteristics were analyzed to further evaluate percolation. The WBC modeled with Borrow Area 3 soils and revegetated parameters was selected because this model scenario presented the highest percolation rate among the models.

Temporal trends of θ at the bottom of the WBC and percolation during the 10-year simulation are shown in Figure 9.5 for the following time periods: (a) 1992-2002, (b) 1997 (wettest year on record), and (c) during the Spring Creek Floods of 1997. A 30-hr precipitation of 16.1 cm was measured at the CSU weather station during the Spring Creek Floods, which was a historically significant event to the city of Fort Collins. The shorter time periods in Fig. 9.5b through 9.5d were reviewed to analyze θ in response to higher-than-normal precipitation. Over the majority of the simulation, θ was lower for the thinner WBC; however, when precipitation events occurred, the thinner WBC had higher θ and a corresponding larger increase in percolation. This change in θ identified as a spike in response to precipitation events is referred to as amplitude. The larger amplitude of the thinner cover was attributed to lower available storage capacity in the thinner cover.

The lower available storage capacity of the thinner cover ultimately led to more percolation during high precipitation events due to the thinner cover having insufficient storage capacity to retain infiltrated water. As well as having a larger amplitude, the thinner WBC had a shorter duration of increased θ following precipitation events than the thicker WBC. This behavior was attributed to the transpiration component of the WBC. Transpiration removes a greater percentage of water from the thinner WBC compared to the thicker WBC because the revegetated rooting depth function of 30.5 cm (1 ft) consists of a greater percentage of total cover thickness in the thinner WBC. The average θ at the bottom of the cover from 1992-2002 with respect to depth is shown on Fig. 9.6. Despite allowing more percolation, the average θ of the thinner cover is less than the thicker cover and the difference increases with depth of the profile. As the thicker cover extends further beyond the limits of the revegetated rooting depth function, soil near the base of the thicker covers retained more water and had higher θ.

Temporal trends of θ at 30.5 cm (1 ft) below the WBC surface and percolation from 1992 to 2001 are shown in Fig. 9.7. The θ in Fig. 9.7 shows a larger amplitude when compared to Fig. 9.5.a, which indicates that soil located closer to the surface was more sensitive to climatic

conditions. Additionally, the difference in θ among the three cover thicknesses was less near the surface (Fig. 9.6) when compared to the difference in θ at the bottom of the covers (Fig. 9.5.a). This was attributed to climate and vegetation conditions being relatively the same at 30.5 cm below the surface and independent of the WBC thickness.

9.5 Practical Implications of Research Results

Results of this research indicate that on-site borrow soils at LCL meet regulatory requirements for either prescriptive or water balance final closure covers if regulatory design standards for layer thickness and/or k_s are implemented. Regulatory compliance has been previously achieved through four closure phases with prescriptive covers at LCL, starting with Phase 1 in 1998. Variably saturated flow modeling of the prescriptive cover indicated an annual percolation rate of < 0.1 to 2.2 mm/yr, dependent on k_s (1.2 x 10^{-7} cm/s or 1.0 x 10^{-5} cm/s).

The WBC design was varied in regards to thickness, soil properties, and vegetation to assess the impact on percolation. Water balance models yielded percolation rates ranging between 6.3 and 11.3 mm/yr. The lowest percolation rates were independent of Borrow Area 3 or Borrow Area 4 soils, but corresponded to vegetation conditions represented by natural vegetation observed in the borrow areas during this study. Interpretation of model results from the CDPHE Water Balance Guidance (CDPHE 2013) indicated a percolation rate of 11.2 to 22.4 mm/yr was used to assign acceptable layer thicknesses for covers composed of soils similar to those identified in Borrow Areas 3 and 4. However, Federal or Colorado regulations do not define equivalency or quantify allowable percolation through a WBC for comparison purposes to a prescriptive cover. Thus, percolation cannot be used solely to determine acceptance of a WBC at LCL. Instead, soil properties from the borrow areas and constructed layer thickness will be used to design a WBC that meets CDPHE regulations. When selecting between a prescriptive or WBC, Larimer County should consider the effects of pedogenesis on soil properties, stability of the cover system, constructability, and cost.

The Engineering Design of Operations Plan (EDOP) must be revised for CDPHE approval prior to design of a WBC at LCL in the event the final cover design is changed from a prescriptive cover to a WBC. Soil particle size distribution, layer thickness, quality assurance testing, and seed mix of the cover must be updated in the EDOP. Larimer County Landfill has already sampled and characterized Borrow Area 3 and Borrow Area 4, which can be used to develop the WBC design. No discernible difference was observed in the soil characterized from material in the upper horizon of the borrow areas (topsoil) compared to the lower horizon; however, the upper material should be preserved and used as the topsoil layer during WBC construction to promote vegetation growth.

Construction quality controls such as surveys or staking rods should be used to verify layer thickness during construction. A construction quality assurance plan must meet the requirements of the CDPHE Water Balance Guidance (CDPHE 2013) that specifies types of tests and testing frequency. A seed mix with more diverse species that are native to the area should be used to represent the natural vegetation, which will be more effective at decreasing percolation via increasing transpiration. Requirements from the CDPHE Water Balance Guidance, as well as the effects of vegetation on erosion control, aesthetics, and long-term succession, should also be considered when selecting a revegetation seed mix.

Table 9.1 Water balance metrics for prescriptive and water balance covers that met CDPHE regulations.

| Cover Type	Cover Soil Location	Vegetation	Thickness cm (ft)	Avg. Annual Percolation (mm/yr)	Avg. Annual ET (mm/yr)	Avg. Annual Evaporation (mm/yr)	Avg. Annual Transpiration (mm/yr)	Avg. Annual Storage (mm/yr)
Prescriptive	Phase 1, Measured k_s	Revegetated	106.7 (3.5)	< 0.1	425	277	148	-2.9
Prescriptive	Phase 1, k_s=1. x 10^{-5} cm/s	Revegetated	106.7 (3.5)	2.2	398	259	138	10.2
WBC	Borrow Area 3	Revegetated	76.2 (2.5)	11.3	389	141	248	-18.7
WBC	Borrow Area 3	Natural	76.2 (2.5)	6.3	411	114	296	-19.9
WBC	Borrow Area 4	Revegetated	76.2 (2.5)	9.6	397	156	241	-18.8
WBC	Borrow Area 4	Natural	76.2 (2.5)	6.3	420	127	293	-29.2

Note: 415 mm/yr average annual precipitation over model years (1992-2002); Average annual runoff < 0.1 mm/yr for all models

Table 9.2 Water balance metrics for water balance covers simulated with Borrow Area 3 soil parameters but with varying vegetation parameters (revegetated versus natural) and cover thickness.

Cover Type	Vegetation	Thickness cm (ft)	Avg. Annual Percolation (mm/yr)	Avg. Annual Evaporation (mm/yr)	Avg. Annual Transpiration (mm/yr)	Avg. Annual Storage (mm/yr)	Avg. Annual Runoff (mm/yr)
WBC, BA3	Revegetated	61 (2)	13.2	141	241	-18.9	<0.1
WBC, BA3	Revegetated	76.2 (2.5)	11.3	141	248	-18.7	<0.1
WBC, BA3	Revegetated	91.4 (3)	10.1	142	252	-18.5	<0.1
WBC, BA3	Natural	61 (2)	8.1	115	288	-20.4	<0.1
WBC, BA3	Natural	76.2 (2.5)	6.3	114	296	-19.9	<0.1
WBC, BA3	Natural	91.4 (3)	4.9	115	301	-19.7	<0.1

Note: 415 mm/yr average annual precipitation over model years (1992-2002)
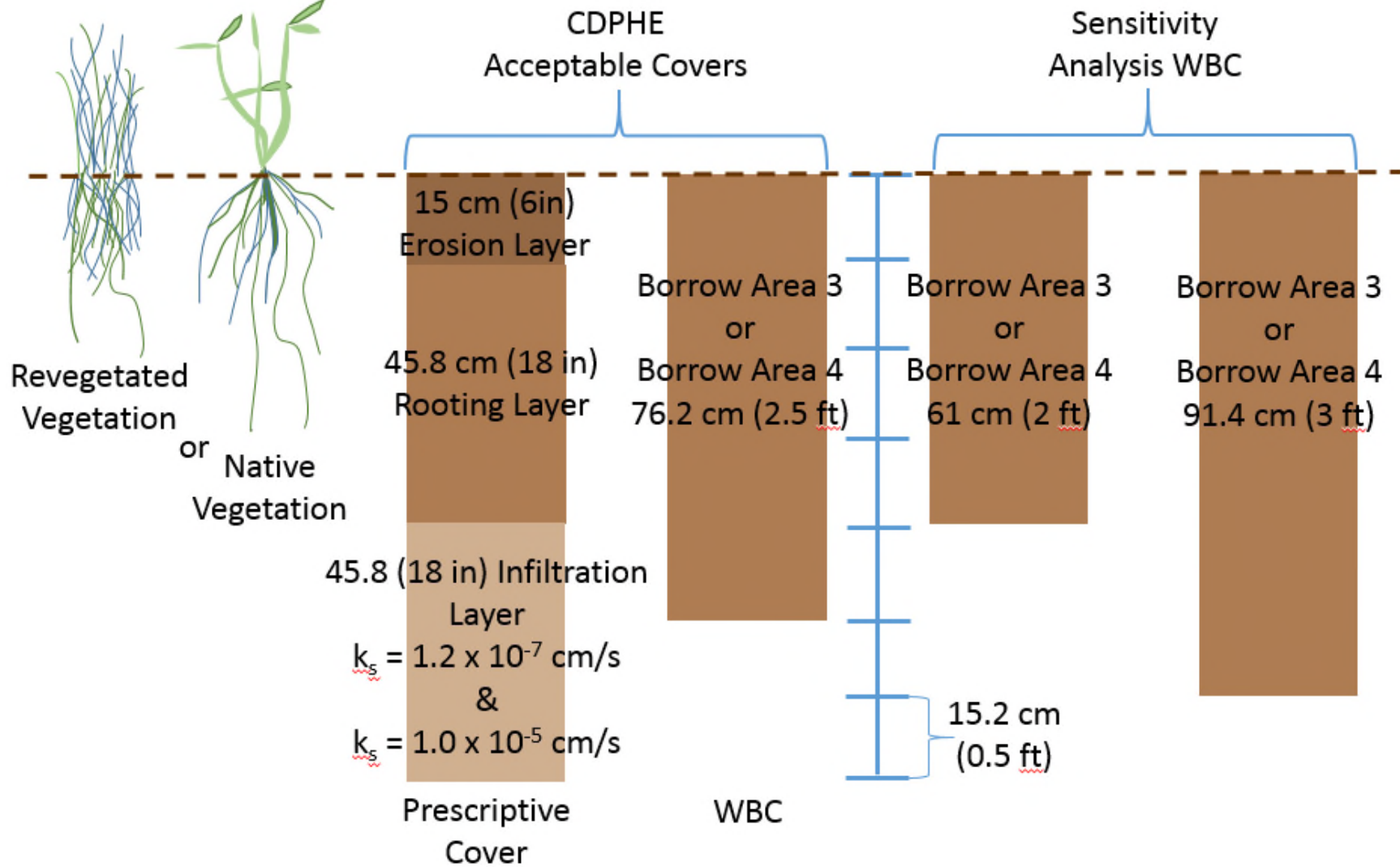
Fig. 9.1. Schematics of the prescriptive and water balance cover model scenarios analyzed for this study.
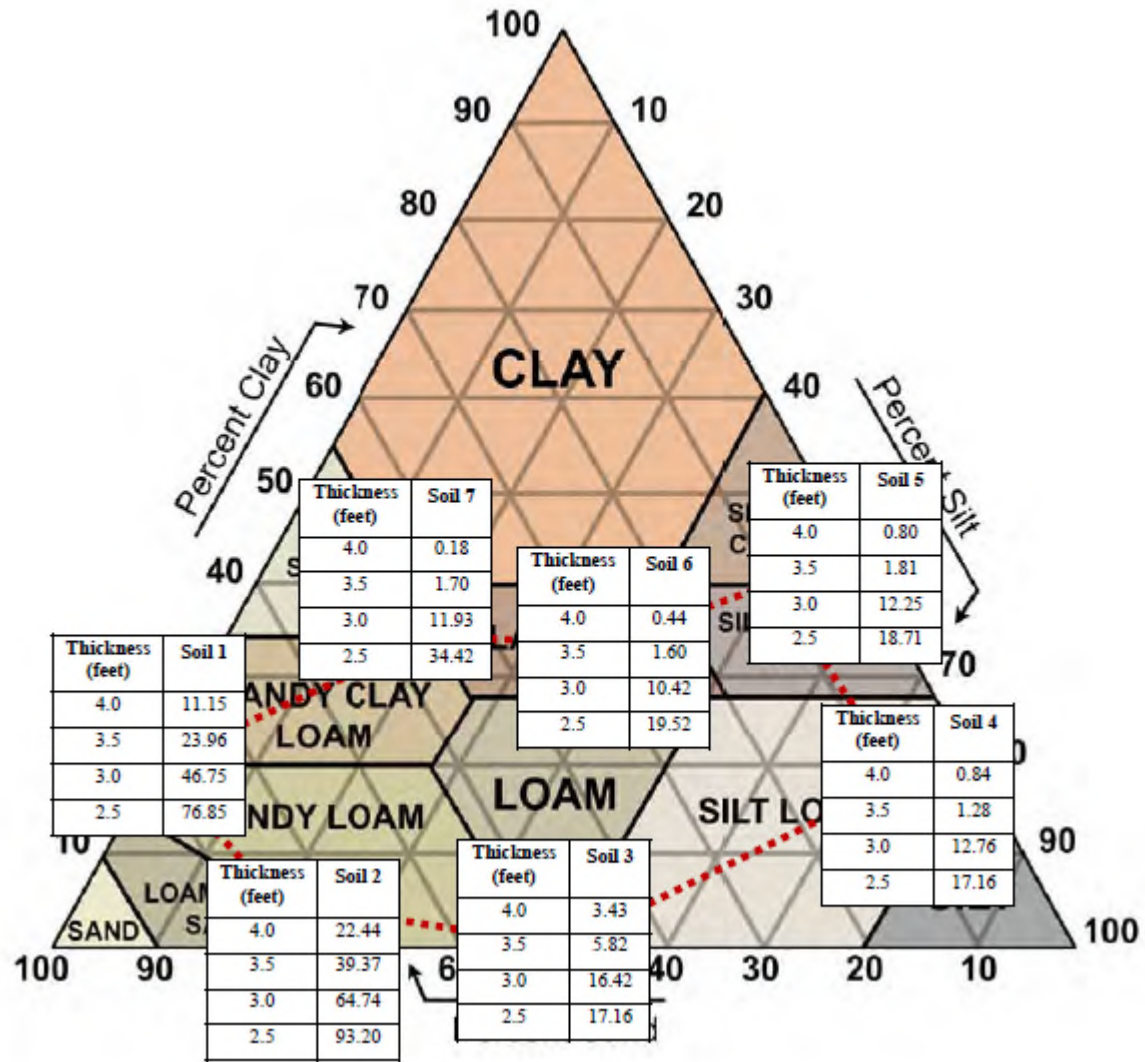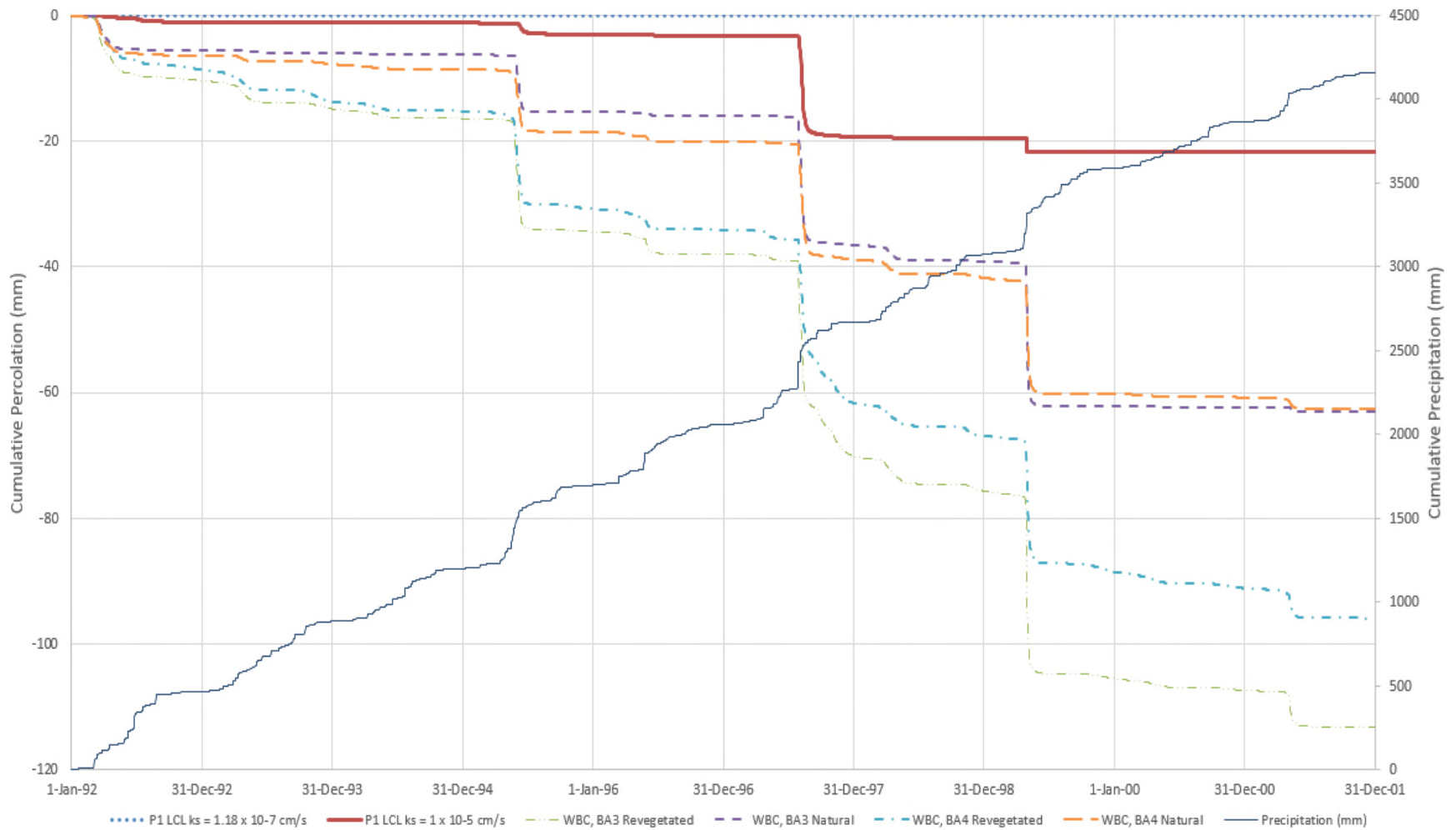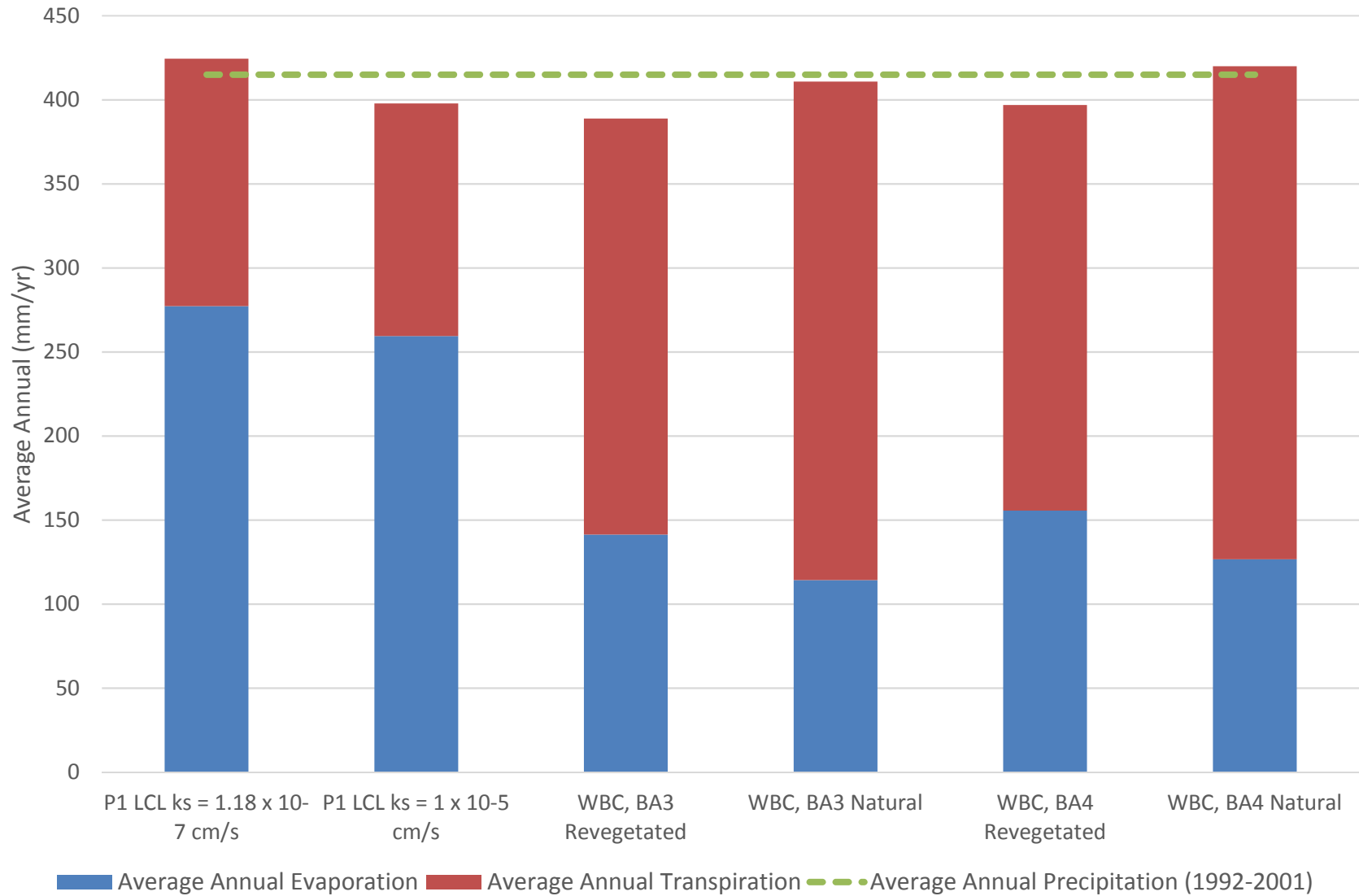
Fig 9.2. Model results for Ecozone 3 from Figure 19 of CDPHE Water Balance Guidance (2013).

Fig 9.3. Temporal trends from 1992-2002 of cumulative precipitation and percolation from the prescriptive and water balance cover model simulations completed for the covers that met CDPHE regulations.

Fig 9.4. Average annual evaporation, transpiration, and precipitation the prescriptive and water balance cover model simulations completed for the covers that met CDPHE regulations.
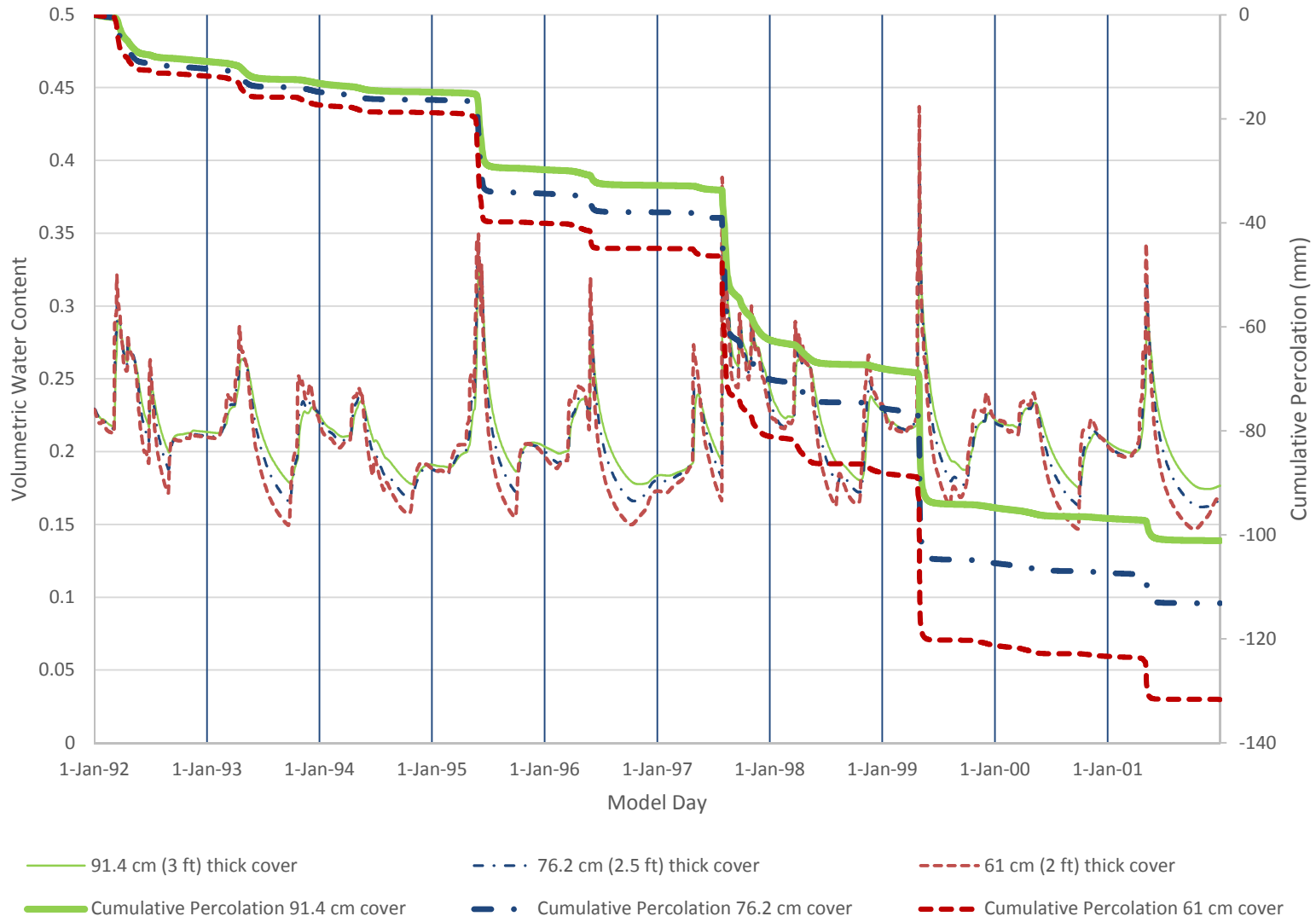
Fig. 9.5.(a) Percolation and volumetric water content from 1992-2002 at the bottom of the cover profile for water balance covers simulated with Borrow Area 3 soil, revegetated vegetation parameters, and varying thicknesses.
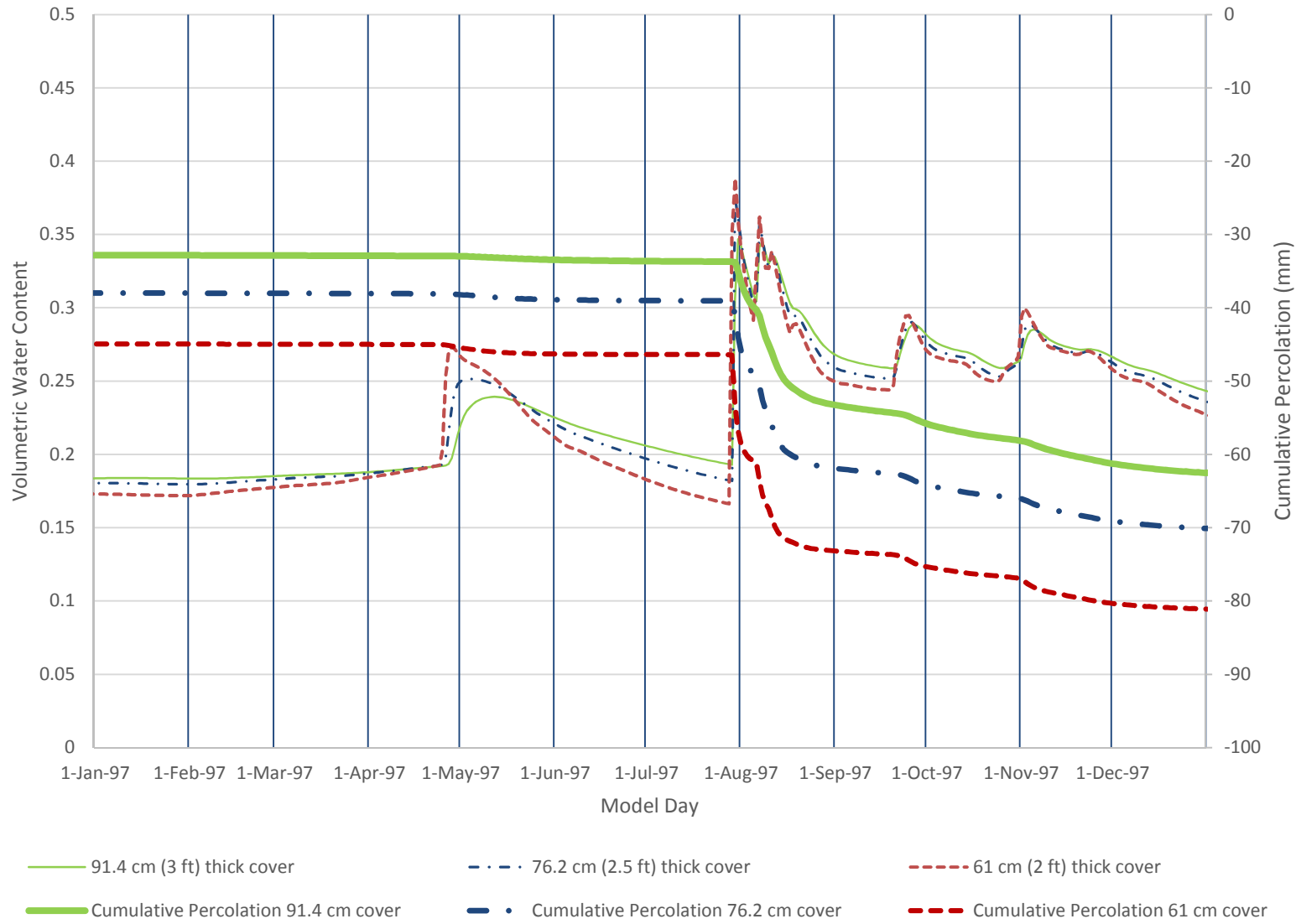
Fig. 9.5.(b) Percolation and volumetric water content during 1997 (wettest year modeled) at the bottom of the cover profile for water balance covers simulated with Borrow Area 3 soil, revegetated vegetation parameters, and varying thicknesses.
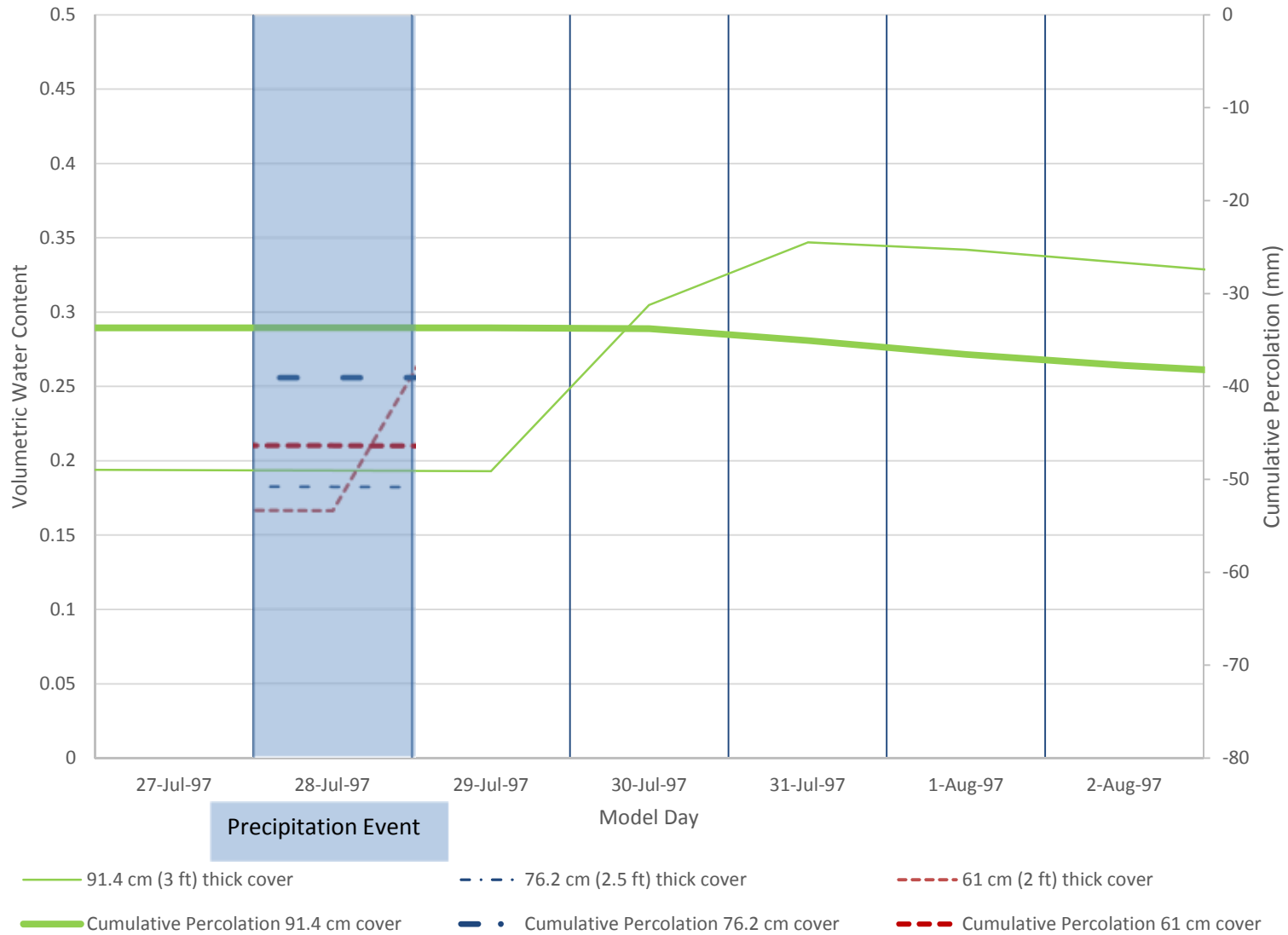
Fig. 9.5.(c) Percolation and volumetric water content during Spring Creek Floods of 1997 at the bottom of the cover profile for water balance covers simulated with Borrow Area 3 soil, revegetated vegetation parameters, and varying thicknesses.

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Fig. 9.5.(d) Volumetric water content and incremental percolation during Spring Creek Floods of 1997 at the bottom of the cover profile for water balance covers simulated with Borrow Area 3 soil, revegetated vegetation parameters, and varying thicknesses.

Fig. 9.6 Relationships of average volumetric water content versus (a) percent of cover thickness and (b) depth below the surface for three water balance covers with varying thickness simulated with Borrow Area 3 soil and revegeted vegetation parameters.
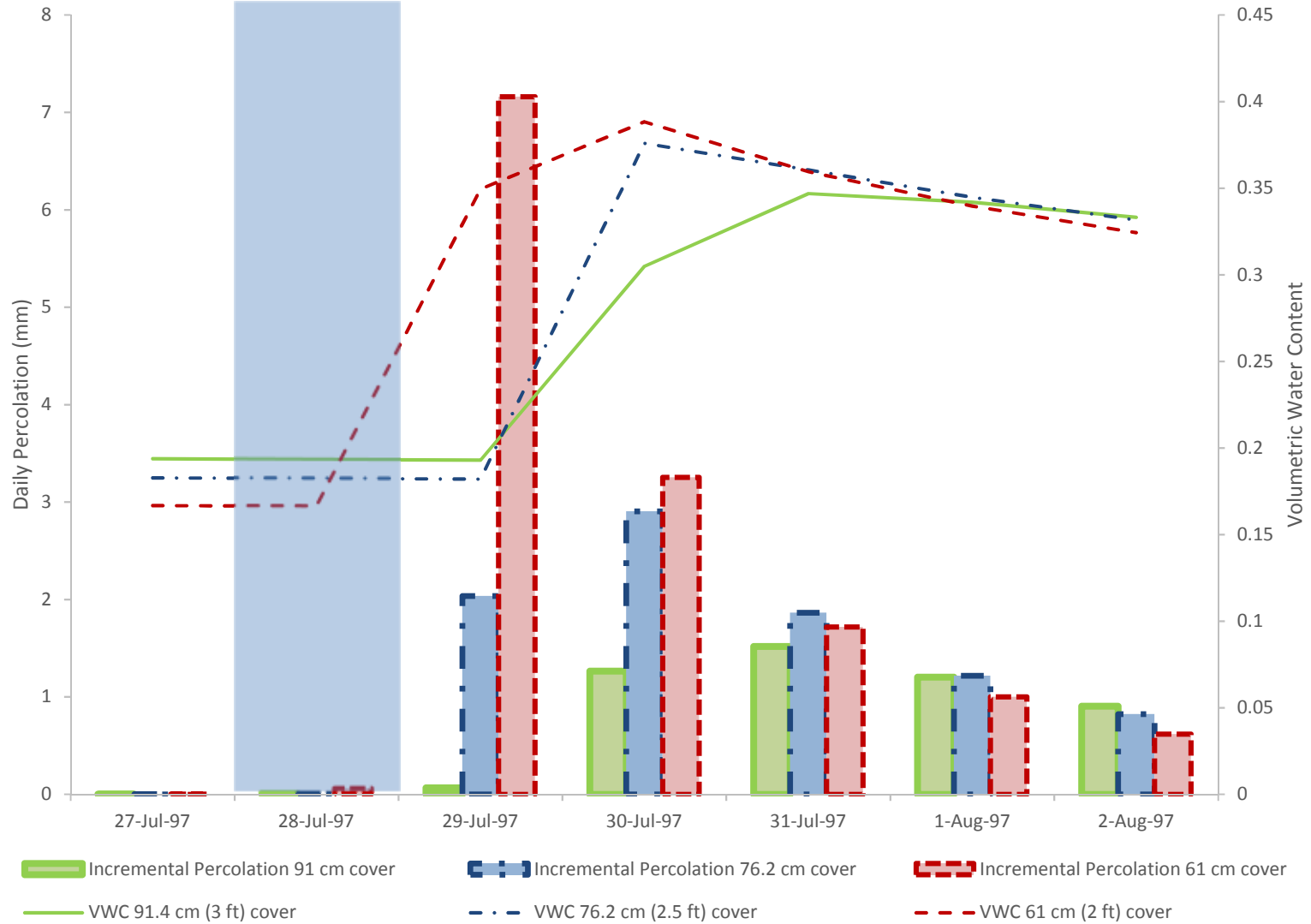
Fig. 9.7 Percolation and volumetric water content from 1992-2002 at 30.5 cm below the ground surface for water balance covers simulated with Borrow Area 3 soil, revegetated vegetation parameters, and varying thicknesses.
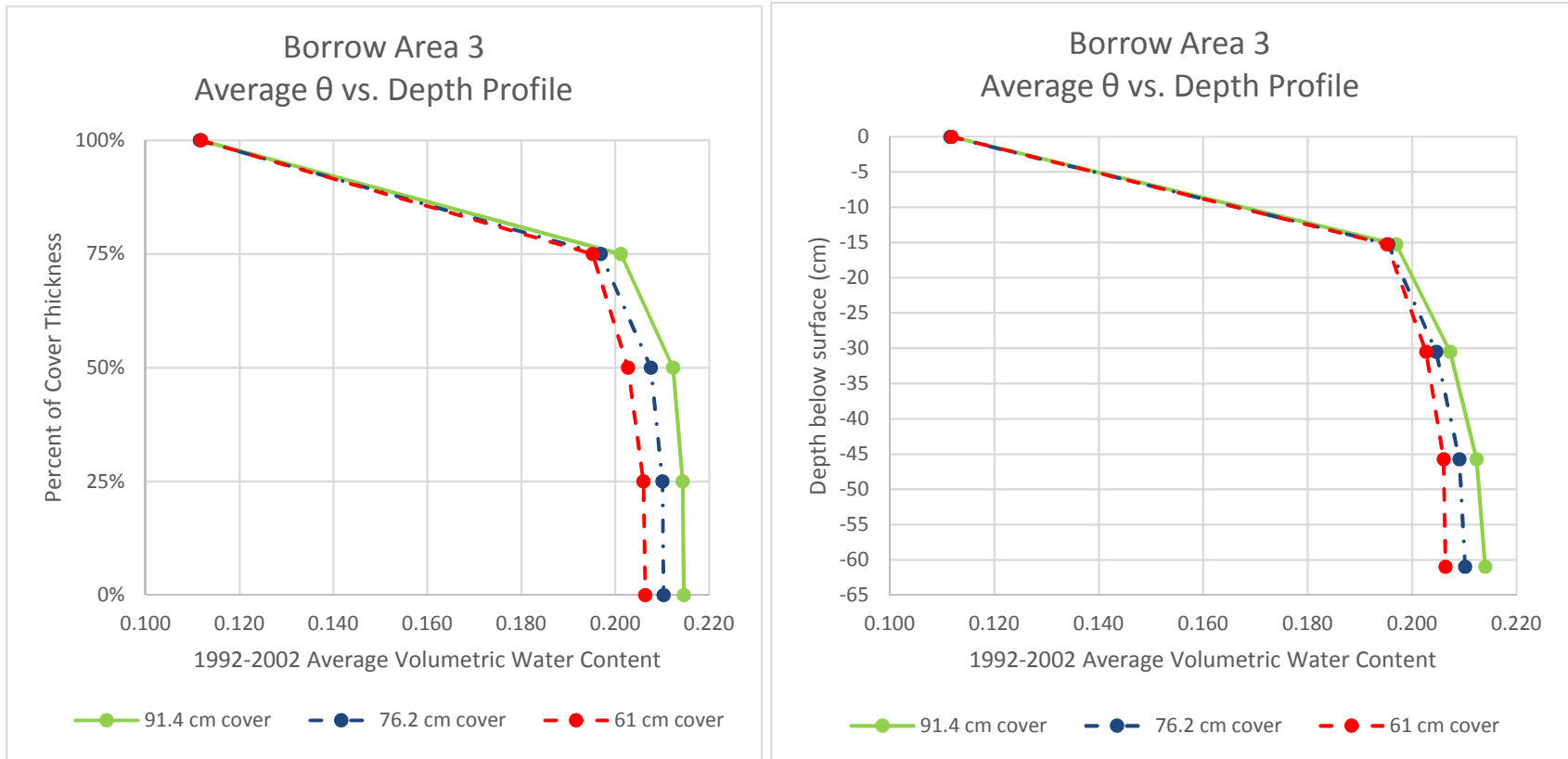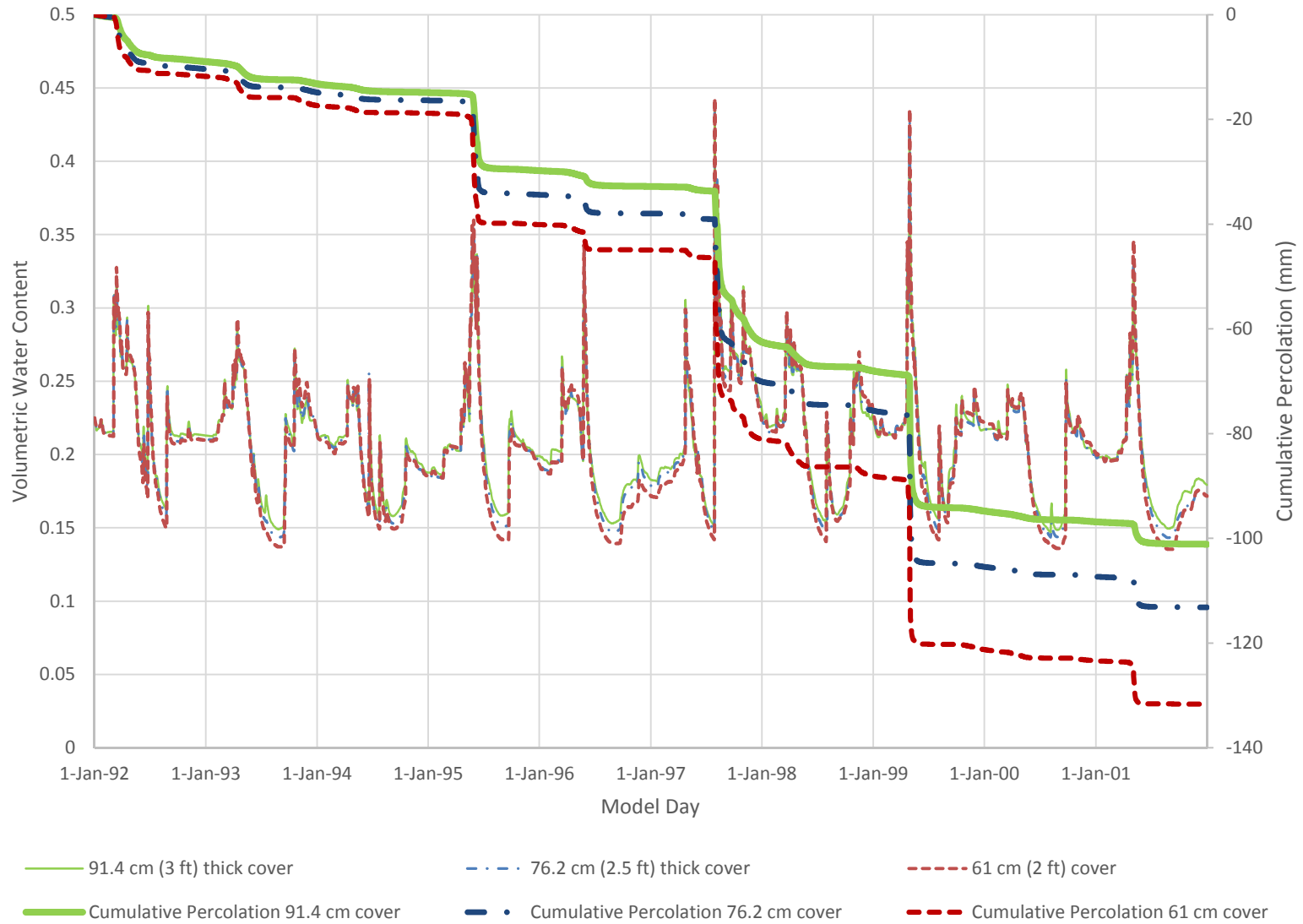
CHAPTER 10. SUMMARY, CONCLUSIONS, AND FUTURE WORK

10.1 Summary and Conclusions

The hydrologic performance of a prescriptive cover and WBC at LCL were evaluated in this study using variably-saturated flow modeling with parameters based on regulatory standards, field observations, laboratory testing data, MET data, and vegetation characteristics. Regulations for LCL specify a prescriptive cover must include a low-permeability layer (i.e., Infiltration layer) with a maximum k_s of 1.0 x 10^{-5} cm/s. Regulations for LCL allow for alternative closure covers (e.g., water balance cover) considering that equivalency is demonstrated relative to a prescriptive cover. Water balance cover designs for Colorado are recommended by the CDPHE based on the particle-size distribution of soil to be used for the cover and geographical location of the landfill.

Larimer County Landfill has constructed four phases of prescriptive closure covers since 1998, starting with the Phase 1 closure area. Excavation, sampling, and testing of the Phase 1 cover for this study indicated layer thicknesses exceeding the minimum required thicknesses and k_s approximately two orders of magnitude lower than required. Soil characterization and engineering properties determined for soils from Phase 1 were similar to those measured during Phase 1 construction quality assurance testing. Sampling was also conducted in Borrow Areas 3 and 4 to evaluate suitability of the borrow area soils for use in a WBC. Based on the particle-size distribution and LCL located in Ecozone 3 (CDPHE 2013), the recommended WBC design was a 76.2-cm-thick (2.5 ft) cover.

Finite element modeling using VADOSE/W was performed to predict the percolation rate through the prescriptive and water balance covers. The wettest ten consecutive years on record for Fort Collins that had a sufficiently complete MET data set (1992-2002) were selected for the analysis. Vegetation parameters were assigned to represent either the revegetated state observed over the existing closure phases or the natural conditions observed in the borrow

areas. Predicted percolation through a prescriptive cover was < 0.1 to 2.2 mm/yr corresponding to an Infiltration layer with k_s of 1.2 x 10^{-7} or 1.0 x 10^{-5} cm/s. Evaporation was the primary component for removing water from the prescriptive cover models with a contribution of 62 or 67 % of the water balance. WBC models predicted a percolation rate from 6.3 to 11.3 mm/yr depending on the borrow area and vegetation parameters. Water balance covers that yielded the lowest percolation were simulated with either Borrow Area 3 or Borrow Area 4 soil and natural vegetation characteristics. Transpiration was the primary component for removing water from the WBC models with a contribution of 58 to 73 % of the water balance. Within all of the CDPHE acceptable cover models, *ET* removed 94 to 102% of the precipitation received during the ten-year model simulations.

Results of this study indicate that either a prescriptive cover with a total thickness of 106.7 cm (3.5 ft) or a water balance cover with a thickness of 76.2 cm (2.5 ft) would meet CDPHE criteria for closure cover design at LCL. Water balance modeling predicted less percolation through the prescriptive cover relative to the WBC based on soil and vegetation parameters determined in this study. Regulations for final covers in Colorado do not include an acceptable amount of percolation or define what would be considered equivalent performance.

Pedogenesis was anticipated to increase k_s of the compacted clay in the prescriptive cover after nearly 20 yr of operation, but this phenomenon was not observed. Saturated hydraulic conductivities of 1.2 x 10^{-7} and 8.9 x 10^{-8} cm/s were measured on samples from Phase 1, whereas the average k_s from 1998 construction quality assurance testing was 1.6 x 10^{-7} cm/s. The similarity in k_s from 1998 to 2017 was attributed to a lack of pedogenesis due to the thicker prescriptive cover that constructed in Phase 1 versus the design thickness. The as-constructed cover extended to greater depths, whereby the Infiltration layer (i.e., low k_s layer) was sufficiently deep below the ground surface where pedogenesis has less influence. An increase in k_s as a result of pedogenesis would have increased k_s to a similar magnitude observed in the

borrow area samples (1.06 x 10^{-4} and 2.43 x 10^{-4} cm/s). Higher k_s would have resulted in higher percolation rates that were closer to those predicted by the WBC models.

10.2 Future Work

Further development of this study can proceed by constructing a field-scale lysimeter based on a recommended WBC design to monitor field performance and compare to the existing prescriptive cover and water balance simulations. An alternative to a single field-scale lysimeter would be multiple small-scale lysimeters constructed in the field to further assess variables such as soil source, vegetation, compaction effort, and moisture content during compaction on actual water balance performance. Assessing these variabilities would further help to understand the effects of each variable on WBC performance and yield valuable information for other sites considering closure cover design options. Measured percolation rates in the field lysimeters could be compared to predicted model results to evaluate accuracy of models and refine modeling procedures for future studies. Finally, monitoring lysimeters for several years would provide the ability to assess the effect of pedogenesis on soil covers.

Additional soil water retention (ASTM D6836) and permeability (ASTM D5084) laboratory testing on samples recovered from this study would provide a better understanding of the effect of particle size distribution, compaction effort, and moisture content during compaction on hydraulic parameters. Infiltration testing (ASTM D5093) on the existing closure cover phases would provide another data set of permeability to assess the effect of pedogenesis with time. Varying the depth of the field test within the covers would introduce another variable since pedogenesis is more prevalent on the surface than with depth where the upper soils provide less protection from climate and vegetation interaction.

Multiple finite element software programs are available to model variably saturated flow. VADOSE/W was used for variably saturated flow modeling of the covers as part of this study.

Parameters used for modeling in this study could be used in other modeling programs to compare the water balance results, particularly with regards to percolation.

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