

Closure Plan

**Public Service Company of Colorado, an
Xcel Energy Company**



**Hayden Station Ash Disposal Facility
Project No. 98286**

December 2018

Closure Plan

prepared for

**Public Service Company of Colorado,
an Xcel Energy Company
Hayden Station Ash Disposal Facility
Hayden, Colorado**

Project No. 98286

December 2018

prepared by

**Burns & McDonnell Engineering Company, Inc.
Denver, Colorado**

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INDEX AND CERTIFICATION

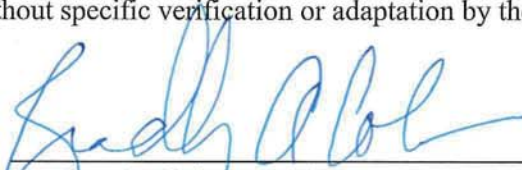
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Qualified Professional Engineer Certification

In accordance with 40 CFR Section 257.102(b)(4) and 257.102(d)(3)(iii), I hereby certify, as a Professional Engineer in the State of Colorado, that the information in this document was assembled under my direct personal charge and that the information presented herein is accurate to the best of my knowledge. This report is not intended or represented to be suitable for reuse by Public Service Company of Colorado, an Xcel Energy Company or others without specific verification or adaptation by the Engineer.



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Date: 12/20/18



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LIST OF ABBREVIATIONS

<u>Abbreviation</u>	<u>Term/Phrase/Name</u>
CCR landfill	Ash Disposal Facility
CCR	Coal combustion residual
CDPHE	Colorado Department of Public Health and Environment
CFR	Code of Federal Regulations
cm/sec	Centimeters per second
EDOP	Engineering, Design, and Operations Plan
EOC	End-of-construction
FS	Factor of safety
LTSS	Long-term steady state
PSCo	Public Service Company of Colorado, an Xcel Energy Company
RCRA	Resource Conservation and Recovery Act
USEPA	United States Environmental Protection Agency
WBC	Water Balance Cover

1.0 GENERAL AND OPERATIONAL DATA

This Closure Plan has been prepared for the coal combustion residuals (CCR) landfill located at the Public Service Company of Colorado (PSCo), an Xcel Energy Company, Hayden Station. Hayden Station is a 446-megawatt coal-fired, steam turbine power plant owned and operated by PSCo. The station is located at 13125 U.S. Highway 40, Hayden, Colorado 81639. The CCR landfill location is shown on Figure 1-1.

This plan was prepared to comply with the requirements of the U.S. Environmental Protection Agency's (USEPA's) CCR Rule for disposal of CCR under Subtitle D of the Resource Conservation and Recovery Act (RCRA). The final rule was published in the Federal Register, Volume 80 Number 74 on April 17, 2015, and became effective on October 19, 2015.

1.1 Facility Description

The CCR landfill is located on Routt County Road 27 approximately one mile south of Colorado Highway 40 in Routt County, Colorado. A facility site plan is included as Figure 1-2. The CCR landfill is in an unincorporated portion of Routt County. The location is approximately 5 miles east of Hayden, Colorado and 20 miles west of Steamboat Springs, Colorado. The CCR landfill is generally located in the west half of Section 16 and the east half of Section 17, Township 6 North, Range 87 West of the 6th Principal Meridian, Routt County, Colorado. The service area for the CCR landfill is limited to the Hayden Station power plant. Wastes are not accepted from any other source.

The CCR landfill is an unlined ash monofill. The wastes accepted at the CCR landfill consist of coal ash, air emission control byproducts, water intake silt, excavation soils and coal impurities. The area inside the permitted boundary of the CCR landfill consists of approximately 154 acres of which approximately 136 acres is used for ash disposal and approximately 18 acres for storm water control structures, access roads, and borrow area.

1.2 Regulatory Requirements

This report has been prepared to fulfill the requirements of 40 Code of Federal Regulation (CFR) Section 257.102.b and 257.102.d. Section 257.102.b requires a written closure plan that describes the steps necessary to close the CCR landfill at any point during the active life of the landfill. The Hayden CCR landfill will be closed by leaving CCR in place. Thus, Section 257.102.d requires that the unit is closed in a manner that will

- Control, minimize or eliminate, to the maximum extent feasible, post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated run-off to the ground or surface waters or to the atmosphere;
- Preclude the probability of future impoundment of water, sediment, or slurry;
- Include measures that provide for major slope stability to prevent the sloughing or movement of the final cover system during the closure and post-closure care period;
- Minimize the need for further maintenance of the CCR unit; and
- Be completed in the shortest amount of time consistent with recognized and generally accepted good engineering practices.

Lastly, an alternative final cover system design has been selected. Thus, this closure plan addresses the following requirements of Section 257.102.d.3.ii:

- The design of the final cover system must include an infiltration layer that achieves an equivalent reduction in infiltration as an 18-inch thick infiltration layer with a permeability no greater than 1×10^{-5} centimeters per second (cm/sec).
- The design of the final cover system must include an erosion layer that provides equivalent protection from erosion as a minimum six inches of earthen material that is capable of sustaining native plant growth.
- The disruption of the integrity of the final cover system must be minimized through a design that accommodates settling and subsidence.

The above requirements are addressed in the remainder of this closure plan

.

2.0 NARRATIVE CLOSURE DESCRIPTION

The Hayden CCR landfill is an active, unlined, CCR disposal unit that began construction and operation in 1983 and has remained in continuous operation since that time. The CCR landfill is operated under an Engineering Design and Operations Plan (EDOP) (Burns & McDonnell, 2018) approved by the Colorado Department of Public Health and Environment (CDPHE) pursuant to Colorado Regulations Pertaining to Solid Waste Sites and Facilities, 6 CCR 1007-2 Part 1. The CCR landfill has an estimated remaining 20-year life expectancy and will provide CCR disposal capacity through approximately 2038, assuming current ash production rates.

Closure of the CCR landfill is implemented in phases as outer soil berms are constructed for each lift. This results in ongoing closure construction activities occurring at the CCR landfill. According to PSCo, as of 2018, approximately 18 acres are considered closed.

According to 40 CFR 257.102(d)(3)(ii), an alternative final cover system is required to be designed to achieve an equivalent reduction in infiltration as a standard cover system would, with a permeability less than or equal to that of the soil or bedrock underlying the CCR material and an infiltration layer that is a minimum of 18-inches of earthen material. This closure plan includes an alternative final cover system design, a water balance cover (WBC) that will utilize evapotranspiration to allow equivalent or less infiltration than an 18-inch infiltration soil layer with an overall permeability no greater than that of the underlying Lewis Shale layer. Based on packer test data in the EDOP, the Lewis Shale has a permeability in the range of 5×10^{-8} cm/sec. The alternative cover's 2.5-foot thick infiltration layer will be covered by a 6-inch erosion layer capable of sustaining native vegetation. The alternative cover performance is described in Section 3.6

An on-site soil borrow area will be mined for soil to be used for the 2.5-foot infiltration soil layer. The soil borrow area is located along the east boundary of the CCR landfill. The on-site borrow soil is fine grained clayey sands and sandy clays.

As it is encountered, existing on-site topsoil material will be stripped and stockpiled for future use. The existing topsoil will be reinstalled above the infiltration layer soils as the 6-inch final topsoil layer. After topsoil is installed it will be tracked and seeded. The vegetative cover will provide long-term stabilization of the slopes, limit erosion due to stormwater run-off, and reduce the potential for wind-blown nuisance dust.

If closure occurs prior to reaching final waste placement grades, the CCR surface and/or clean soil will be graded to provide a free-draining surface. The final cover will then be constructed over the shaped surface.

Upon completion of closure activities, a notification of completion of closure will be completed, per 40 CFR 257.102(h) and 257.105(i)(8). The notification will document that all requirements and conditions of the Closure Plan were achieved. The report will be signed and sealed by a Colorado registered Professional Engineer.

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3.0 ALTERNATIVE FINAL COVER

The CCR landfill final cover system was designed in accordance with Section 257.102(d)(1) and Section 257.102(d)(3)(ii) as an alternative final cover system when leaving CCR in place. The final cover system was designed utilizing the Final Guidance Document, Water Balance Covers in Colorado (CDPHE 2013), included as Appendix A. The use of water balance covers in Colorado is strongly encouraged by CDPHE in lieu of low permeability earthen covers, and the final WBC design has been approved by CDPHE for use at the Hayden CCR landfill.

The CDPHE Final WBC Guidance Document identifies regions of Colorado by climate data and establishes Ecozones for each unique climate type. In cooperation with USEPA's Office of Research and Development Engineering Technical Support Center, modeling was performed for each of these Ecozones using a variety of soil types, to establish the basis for WBC design specifications within each Ecozone. Climate data calculations (see Appendix C) show that the Hayden CCR landfill is located near the boundary of Ecozone 1 and Ecozone 2, but more closely resembles Ecozone 1; therefore, the Ecozone 1 requirements were followed to determine the minimum WBC layer thickness.

3.1 Perimeter Berms

Prior to starting each lift of ash, side slope perimeter berms will be constructed using compacted WBC material to create a final soil cover greater than three-feet thick and a minimum of 25-feet wide. The perimeter berms will be compacted WBC for stability. Perimeter berms will be constructed with an outside slope of approximately three horizontal to one vertical (3:1). Approximately every 20 vertical feet a bench is constructed for slope stabilization and water runoff control. This results in an overall side slope no steeper than approximately 4:1. The CCR landfill Design Drawings in Appendix B illustrate the final cover grading, configuration, and details. Perimeter berms have a top width of approximately 20 feet and a typical initial height of five feet. Storm water is directed off the CCR landfill along the benches and down the slopes via downslope channels.

3.2 Top of CCR landfill

The top of the CCR landfill will be closed to meet the final design grades once ash disposal operations are complete. The top of CCR landfill final cover WBC layer will be placed in a single loose lift to function as a standard water balance cover. The minimum three-foot thick top cover will have a slope of approximately five percent and be free draining to direct storm water toward the side slopes of the CCR landfill and consist of 2.5 feet of WBC material overlain by a 6-inch erosion layer. The CCR landfill Design Drawings in Appendix B illustrate top of CCR landfill final cover grading, configuration and

details. If the CCR landfill is closed prior to meeting design grades, appropriate grading will be performed to maintain minimum slope requirements and promote free-draining off the final cover.

3.3 Performance

The WBC was designed to eliminate post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated runoff to the ground or surface waters or to the atmosphere as required by Section 257.104(d)(1)(i). The modeling completed in the Final Guidance Document indicates that the WBC will eliminate or nearly eliminate any infiltration into the waste as indicated in Table 12 of Appendix A. WBCs function by storing infiltration within the cover layer during wet times which then is released to the atmosphere during dryer times via evaporation and vegetative transpiration. Based on Table 12 of Appendix A, the resulting reduction in infiltration of this type of cover will be less than or equal to that allowed by the natural Lewis Shale layer located immediately beneath the CCR material.

The vegetative cover is an important part of the WBC as it acts to remove moisture from the cover soil via transpiration, and provides long-term stabilization of the slopes, limits erosion due to stormwater run-off, and reduces the potential for wind blown nuisance dust.

The WBC is a natural cover that can account for any settling or subsidence without affecting the performance of the WBC. Overall and differential settlement of the CCR landfill is anticipated to be minimal due to the CCR being an overall homogeneous material and that it was/is placed and compacted in thin horizontal lifts.

A detailed global stability analysis was performed to analyze the potential for sloughing or movement of the final cover system and the underlying CCR material. The results indicate that the CCR landfill is stable under both static and seismic conditions. This analysis is included in the EDOP.

3.4 Storm Water Diversion and Control

The combination of drainage benches, downslope channels and storm water detention ponds will minimize site erosion, provide slope stability to prevent sloughing of the final cover system and maintain water quality of runoff from the site while reducing the need for future maintenance in accordance with Section 257.102(d)(1)(iii) and (iv). Downslope channels and benches will be lined with grass or erosion control mat as appropriate. Riprap, or similar, will be placed to dissipate energy of flow within the downslope channels as necessary to protect against erosion. A perimeter channel will be constructed around the CCR landfill. Storm water channels will be directed toward one of four detention ponds located adjacent to the CCR landfill. Permanent storm water controls are designed to control run-off from a 100-year, 24-hour storm event. See Appendix B for design details.

3.5 Contact Water Pond Closure

Once ash placement is complete, the contact water pond will be closed prior to placement of the final cover. The pond liner will be cut into pieces and removed along with the sump and sump structure. The liner and sump materials will be transported to an authorized off-site landfill. The southern end of the pond will be regraded to allow the area to be free draining, with runoff directed to a stormwater drainage channel. The final cover will then be constructed over the former contact water pond area as shown on Drawing C002 of Appendix B.

4.0 INVENTORY ESTIMATE

In accordance with 257.102(b)(1)(iv) an estimate of the maximum inventory of CCR ever on-site over the active life of the CCR landfill must be provided.

The CCR landfill accepts approximately 230,000 cubic yards of CCR annually, with approximately 25 percent being bottom ash and 75 percent being fly ash. Additionally, approximately 500 cubic yards of approved non-CCR waste is disposed at the CCR landfill annually. Construction excavation soils are occasionally disposed of or used for cover material at the CCR landfill on a project-by-project basis.

Assuming the above quantities have remained consistent since the CCR landfill opened in 1983, the estimated total CCR currently deposited within the CCR landfill is approximately 8,000,000 cubic yards.

When the CCR landfill reaches final capacity in 2037, the estimated final volume of CCR will be approximately 12,500,000 cubic yards.

5.0 AREA REQUIRING FINAL COVER

In accordance with 257.102(b)(1)(v) an estimate of the largest area of the CCR unit ever requiring a final cover must be provided.

The largest area requiring final cover and closure at the CCR landfill at any given time will be approximately 50 acres. The CCR landfill closure will be completed in phases to minimize the area requiring closure at the end of the CCR landfill life.

6.0 SCHEDULE OF CLOSURE ACTIVITIES

In accordance with Section 257.102(b)(vi), phased closure milestones dates are included in the timeline below.

Closure of the CCR landfill is implemented in phases as outer soil berms are constructed for each lift. This results in periodic construction of the final cover on the outer slopes of the landfill throughout the active life of the facility. The final top deck cover will be constructed upon reaching final grades in the permitted disposal capacity, currently anticipated in 2038, and is expected to take approximately six to ten months to complete. Final closure is expected to be complete by 2039. Post closure care will follow the procedures set forth in the Post Closure Care Plan, and will continue for a minimum of 30 years, or until 2070.

7.0 REFERENCES

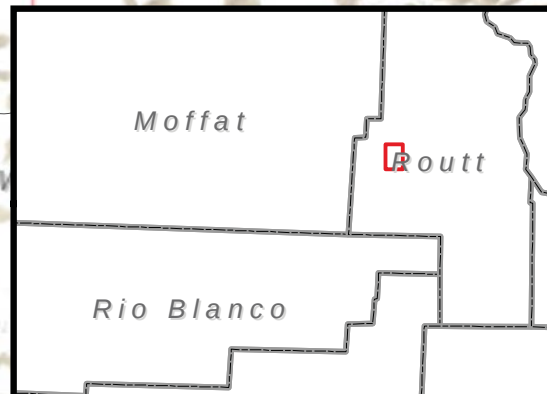
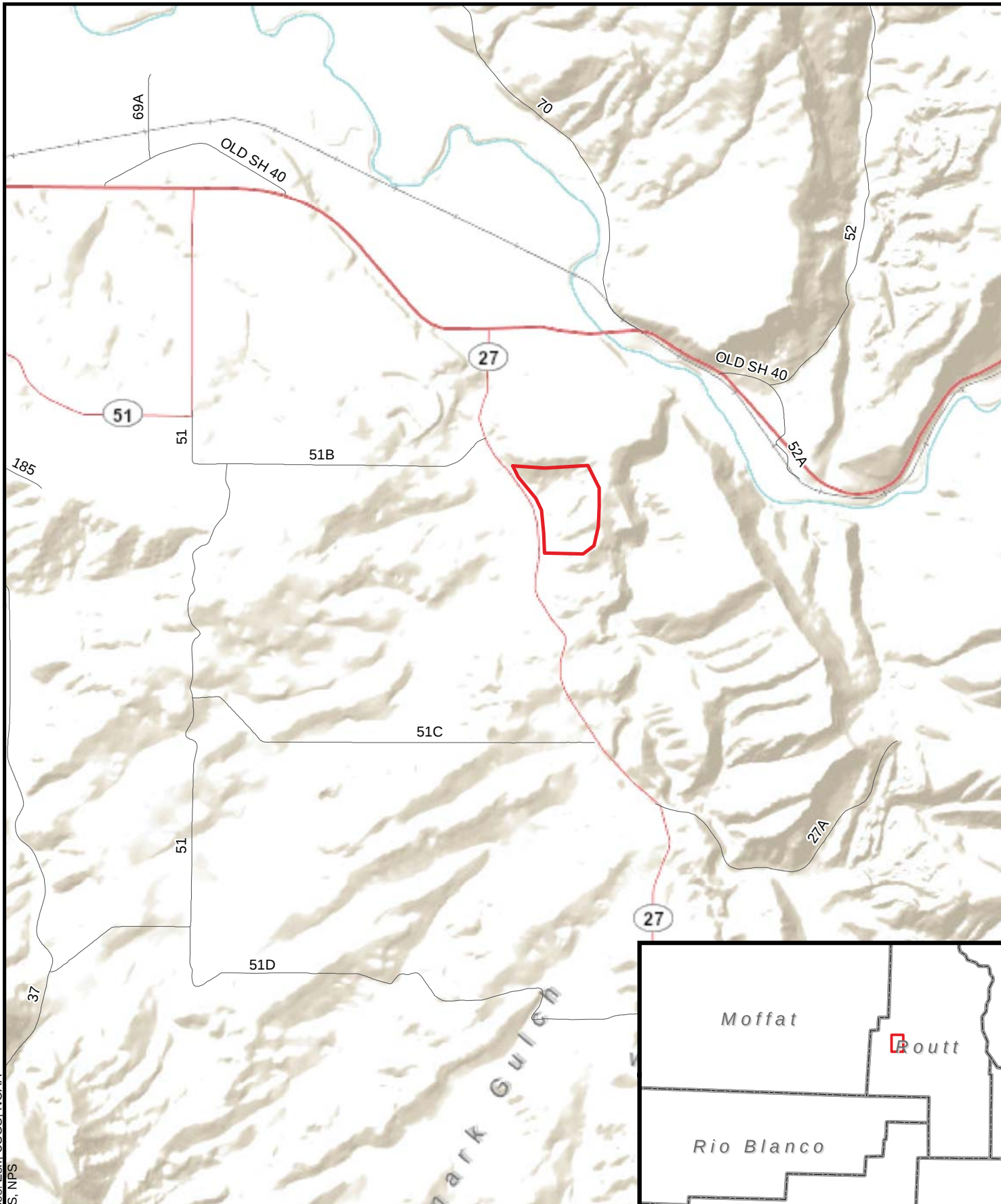
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FIGURES



ASH DISPOSAL FACILITY



0 1
Miles



FIGURE 1-1

FACILITY LOCATION
HAYDEN STATION
ASH DISPOSAL FACILITY

HAYDEN, COLORADO



LEGEND

- PROPERTY BOUNDARY
- X- EXISTING FENCE LINE
- X- EXISTING ELECTRICAL EASEMENT
- X- EXISTING OVERHEAD UTILITY LINE
- X- EXISTING HAUL ROAD
- X- EXISTING ROADS
- X- EXISTING 2" CONTOUR
- X- EXISTING 10" CONTOUR
- X- EXISTING FIBER OPTIC
- X- EXISTING GAS LINE
- X- SECTION LINES
- X- PERMITTED FACILITY BOUNDARY
- ⊕ ASH DISPOSAL AREA
- ⊕ EXISTING CCR WELL
- ⊕ CONTROL POINT
- ⊕ UTILITY POLE



FIGURE 1-2
FACILITY SITE PLAN
HAYDEN STATION
ASH DISPOSAL FACILITY
HAYDEN, COLORADO



APPENDIX A – FINAL GUIDANCE DOCUMENT

Final Guidance Document

Water Balance Covers in Colorado

Guidelines for Design, Construction, and Development of Water Balance Covers
According to the Regulations Pertaining to Solid Waste Sites and Facilities
6 CCR 1007-2, Part 1



Colorado Department Public Health and Environment
Hazardous Materials and Waste Management Division
Solid Waste and Materials Management Program

March 2013

Purpose of this Guidance

This guidance is intended to serve as clarification of and as a companion document for Section 3 (Standards for Solid Waste Disposal Landfill Sites and Facilities) of the Regulations Pertaining to Solid Waste Sites and Facilities, 6 CCR 1007-2, Part 1 (Solid Waste Regulations). Stakeholders, local governments and citizens have expressed interest in clear guidance by the Hazardous Materials and Waste Management Division that provides examples of approved design elements for water balance covers for solid waste facilities. This guidance is meant to assist in compliance with the Solid Waste Regulations by providing direction and structure for consultants, contractors, local governments, citizens, owners and operators who are involved in the permitting, design, operation, monitoring, and closure of a solid waste facility. These guidelines are designed to help ensure protection of the public health and the environment.

Guidance Acknowledgements

The Colorado Department of Public Health and Environment, Hazardous Materials and Waste Management Division (Department) would like to acknowledge the significant contributions of the people who helped develop this highly informative and useful guidance for solid waste facilities in Colorado. After struggling with the general design basis for some time, discussions between Margaret Talbott (Department) and Steven Rock (EPA/Office of Research and Development) led to the Environmental Protection Agency (EPA) offering the Department the use of EPA's technical contractor, The CADMUS Group, Inc. (CADMUS) for further conceptual development and performing numerical modeling. Prior to CADMUS undertaking these tasks, the theoretical foundation was refined through discussion and input from Craig Benson, Ph.D. (University of Wisconsin-Madison), Bill Albright, Ph.D., (Desert Research Institute) and Milind Khire, Ph.D. (Michigan State University). The CADMUS team, managed by Jeff Maxted, included Nupur Hiremath, Katy Beggs, Ph.D. and Daniel Mahr. The numerical modeling was performed by David Benson, Ph.D. (Colorado School of Mines), Mengistu Geza, Ph.D. (Colorado School of Mines) and Tarek Abichou, Ph.D. (Florida State University).

Once CADMUS completed its final report, Modeling Water Balance Covers for Colorado Ecozones (Appendix A), a stakeholders group was formed to develop the actual guidance. The stakeholders group—consisting of Department staff along with interested Colorado solid waste facility owners, technical consultants, industry representatives, federal, municipal, county, and other state regulators—participated in spirited discussions at numerous meetings throughout the guidance development process. It soon became apparent that while the stakeholders were well-versed in the regulatory, technical and mechanical aspects of the guidance, stakeholder expertise was lacking in a critical component needed for cover success—vegetation. To that end, Jim Self, Ph.D. (Colorado State University) and David Buckner, Ph.D. (ESCO Associates, Inc.) provided invaluable input and understanding concerning all things “green” that have been incorporated into this guidance.

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(Prepared by The Cadmus Group, Inc., 2011) |
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Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
AZ	Acceptable Zone
CQA	Construction Quality Assurance
CY	Cubic Yards
EPA	United States Environmental Protection Agency
LGP	Low Ground Pressure
NA	Not Applicable
pcf	Pounds per Cubic Foot
ppm	Parts per Million
QA	Quality Assurance
QC	Quality Control
UMTRCA	Uranium Mill Tailings Radiation Control Act
USDA	United States Department of Agriculture
USCS	Unified Soil Classification System

1.0 INTRODUCTION

The Colorado Department of Public Health and Environment (Department), Hazardous Materials and Waste Management Division recognizes that water balance cover designs at solid waste sites and facilities are a viable alternative to conventional final cover designs that rely on hydraulic barrier layers as described in the Regulations Pertaining to Solid Waste Sites and Facilities, 6 CCR 1007-2, Part 1 (Solid Waste Regulations). This guidance largely is based on the findings presented in *Modeling Water Balance Covers for Colorado Ecozones* prepared by The Cadmus Group, Inc. (Cadmus, 2011), included in Appendix A. As noted in the Cadmus report, water balance covers rely on the water storage capacity of finer textured soils and the water removal capabilities of vegetation to limit percolation of water through the cover. These covers are designed based on the ability to meet applicable percolation criteria and rely heavily on computer modeling of site-specific climate conditions, soil properties and vegetation characteristics.

To facilitate consistency in the design and approval process, these guidelines have been prepared by the Department to achieve the following:

- Allow facilities the ability to propose water balance cover designs that meet the requirements of the Solid Waste Regulations without having to complete extensive modeling;
- Reduce review time required for Department approval of a water balance cover design; and
- Provide guidance to stakeholders on the design, construction and development of water balance covers.

The Department has identified specific ecozones within Colorado where water balance covers are anticipated to be technically viable for the design approach described in Section 2.0. These guidelines present a streamlined design approach that specifies a final cover water storage soil layer thickness based on modeling, engineering judgment and other construction and quality requirements.

A site-specific water balance cover design approach may be used in areas where the streamlined approach is not applicable. The Department is developing separate guidance on water balance cover design parameters for sites that do not have soils and climate conducive for use of the streamlined approach. The site-specific guidance will include a discussion of capillary barriers.

When contemplating the installation of a water balance cover, the facility owner/operator and plan designer are reminded that land use restrictions associated with a water balance cover might impact the final use of the property after the post-closure period has ended.

1.1 Conventional Final Cover Designs

The Solid Waste Regulations establish minimum requirements for conventional final cover designs. A typical conventional final cover cross-section is shown on Figure 1.1-1. These minimum requirements are found in Section 3.5.3 of the Solid Waste Regulations and are summarized below:

“The final cover permeability shall not exceed that of the liner; and the final cover design shall be comprised of one (1) of the following types:

- (A) A soil final cover design shall consist of the following:*
 - (1) An infiltration layer consisting of a minimum of 18 inches of earthen material that has a permeability of less than or equal to the permeability of any bottom liner system or natural sub-soils present, or a permeability no greater than 1×10^{-5} centimeters per second (cm/sec) whichever is less, and*
 - (2) An erosion layer of earthen material a minimum of 6 inches in thickness that is capable of sustaining native plant growth.*
- (B) A composite final cover design shall consist of the following components:*
 - (1) A foundation layer to be comprised of a minimum six (6) inch soil layer, located immediately above the refuse, to provide a suitable foundation for placement of the geomembrane.*
 - (2) The barrier layer shall consist of a geomembrane, which has a minimum 30-mil thickness and displays properties adequate for its intended purpose.*

Factors to be considered in determining barrier adequacy shall include, but are not limited to, the following:

- (1) The effects of landfill settlement,*
 - (2) Permeability,*
 - (3) Seam strength,*
 - (4) Friction properties, and*
 - (5) Puncture resistance.*
 - (6) Rooting layer comprised of a soil capable of supporting a root system and of sufficient thickness to protect the barrier layer and a seedbed layer of soil capable of supporting plant germination. The minimum thickness of the former layer shall be eighteen inches and the latter layer shall be six inches.*
- (C) Alternatives to the above designs may be approved by the Department based on waste type and site specific technical information. Proposals for alternative designs shall demonstrate that the final cover system will minimize infiltration and erosion, and comply with Subsection 2.1.15 at the relevant point of compliance. Alternative designs include, but are not limited to the following:*
 - (1) Geocomposite materials,*
 - (2) Soil admixtures,*
 - (3) Polymers and*
 - (4) Variations of design components described in this Section 3.5.3.”*

The primary purpose of the erosion layer (i.e., protective layer) placed above the infiltration layer (i.e., barrier layer) in the conventional final cover design described in Section 3.5.3 (A) of the Solid Waste Regulations is to:

- A. Support plant growth thereby minimizing erosion; and
- B. Protect the barrier layer from damage due to desiccation, freeze-thaw cycles, and root penetration.

Section 3.5.3 (A) (2) of the Solid Waste Regulations indicates that a minimum 6-inch-thick erosion layer is required to overlay the barrier layer. Given Colorado's climate, however, a 6-inch-thick erosion layer is not adequate to protect the barrier layer from desiccation and frost penetration. Therefore, the protective erosion layer must be thick enough to put the barrier layer below the maximum depth of desiccation and frost penetration.

The required thickness of the erosion layer depends on factors such as maximum depth of frost penetration, calculated erosion rates, precipitation, potential for desiccation cracking and vegetation rooting depth. At higher elevations in Colorado (greater than about 6,000 to 6,500 feet above mean sea level), maximum frost penetration and root penetration may be the controlling factors. Frost penetration is a function of soil type, temperature, snow cover and exposure to sunlight. For example, one location known for deep frost penetration is the San Luis Valley where there can be little winter snow but prolonged cold temperatures. Frost penetrations on the order of 5 to 6 feet have been noted in this area, although 3 feet is more common (Doesken, 2010). Local requirements (e.g., building codes, etc.) may be used as guidelines for determining frost depth.

At lower elevations (less than about 6,000 to 6,500 feet above mean sea level), desiccation and root penetration likely will be controlling factors in determining erosion layer thickness requirements. Studies have shown that severe desiccation can occur at depths up to 36 inches and possibly deeper (Montgomery, et al., 1989, 1990; Corser, et al., 1991, 1992; Melchior, et al., 1994; Melchior, 1997a, b; Maine Bureau of Remediation and Waste Management, 1997; and Khire, et al., 1997, 1999). Given this information, the thickness of an erosion layer sufficient to limit desiccation damage to an engineered soil barrier layer at lower elevations in Colorado should be at least 36 inches. Evaluation of site-specific criteria affecting erosion layer thickness also is an option.

1.2 Alternative Final Cover Designs

A great deal of flexibility is available to facilities contemplating water balance cover designs or other innovative approaches. Section 3.5.3 (C) of the Solid Waste Regulations allows for alternative final cover designs that incorporate an alternative low-permeability barrier or water balance principles. A typical approach is similar to the conventional final cover design discussed in Section 1.1 of this guidance, but employs alternative materials or layer thicknesses (or both) with low permeability qualities that limit the percolation of liquid into wastes. The water balance cover designs discussed in this guidance are based on site-specific considerations (e.g., available soil types, climate, etc.) or innovative technologies (or both) and typically rely on the water storage capacity of the final cover soils as well as evaporation and plant transpiration (which is a critical component) for removing stored moisture and limiting the percolation of liquid into wastes. The water balance cover soils may be one thick layer (monolithic) or may consist of various thinner soil layers. This approach can include the addition of a capillary barrier to augment the water storage capacity of the final cover soils. A typical water balance cover cross-section is shown on Figure 1.1-1.

Another alternative cover design not addressed in detail in this guidance document is one that allows for the omission of vegetation altogether. As an example, six sites in western Colorado (Grand Junction, Gunnison, Maybell, Naturita, Rifle, and Slick Rock) have been closed with rip rap (rock) armoring of the side and top slopes and are intended to be devoid of all vegetation under the Uranium Mill Tailings Radiation Control Act (UMTRCA) Title I program. The Title I sites were designed with a radon barrier that also acts as a low hydraulic conductivity layer. The rip rap is specifically designed for erosion control over its extremely long design life. The Durango site, a seventh Colorado UMTRCA Title I site, incorporates a rock/soil matrix top deck that was re-seeded with native grasses.

Such non-solid-waste-site examples demonstrate that the Department can consider a large degree of variability in the final cover design for solid waste sites. The requesting facility, however, must provide sufficient justification (data and site-specific information) to support the suitability of the proposed cover design.

1.3 Site-Specific Water Balance Cover Equivalency Demonstrations

Site-specific water balance cover designs can be proposed if the cover design methodology presented in Section 2.0 of this guidance is not a viable alternative. In such circumstances, an equivalency demonstration will be required. As noted above, the Department is developing separate guidance on general water balance cover design parameters for sites that do not have soils and climate conducive for use of this streamlined approach. The new guidance will address equivalency demonstrations and the specifications required to ensure that the water balance cover meets the minimal requirements in the Solid Waste Regulations.

2.0 STREAMLINED DESIGN APPROACH FOR WATER BALANCE COVERS

This section provides guidance for a streamlined water balance cover design taking into account available cover soil characteristics, vegetation properties, climate and construction considerations in conjunction with regulatory acceptance of a similar alternative cover design approach at another site having conditions comparable to those at the site under consideration. Based on Cadmus (2011) and Department experience, an effective water balance cover at one site is a strong indication that a similar design may be appropriate at a comparable location. Therefore, the Department offers this streamlined design approach that uses the Cadmus ecozone concept as an alternative to performing site-specific computer modeling. Ecozones outline areas of the state with similar climate, vegetation and soil characteristics.

2.1 Recommended Borrow Source Analysis

The first step is to collect soil samples from borrow sources proposed for the water balance cover design to demonstrate that sufficient quantities of appropriate soils are available to achieve the design cover thickness and to support the financial assurance closure cost estimate required by Section 1.8 of the Solid Waste Regulations. Standard index testing for the properties summarized in Table 2.1-1 should be performed during initial site characterization at appropriate frequencies. Once the borrow source(s) has been selected, and prior to construction, additional standard index testing to supplement the initial testing for each selected borrow source should be performed at the frequencies summarized in Table 2.1-2. The testing frequency may be adjusted based on the homogeneity of the soil and the facility's previous experience with the same materials. Representative samples also should be tested for vegetative soil properties (see Section 2.3.3).

Table 2.1-1
Standard Soil Index Property Tests for Each Borrow Source During Initial Site Characterization

Property	Method	Requirement	Initial Site Characterization Frequency
Water Content	ASTM D 2216	See Section 2.2.4	As appropriate
Grain-Size Analysis	ASTM D 422 (with full hydrometer)	See Sections 2.2.1 and 2.2.2	As appropriate
Laboratory Compaction (Standard Proctor)	ASTM D 698	See Section 2.2.3	As appropriate

Table 2.1-2
Standard Soil Index Property Tests for Each Borrow Source During Excavation/Construction

Property	Method	Requirement	Selected Borrow Source Frequency
Water Content	ASTM D 2216	See Section 2.2.4	1 per 6,500 CY
Grain-Size Analysis	ASTM D 422 (with full hydrometer)	See Sections 2.2.1 and 2.2.2	1 per 6,500 CY
Laboratory Compaction (Standard Proctor)	ASTM D 698	See Section 2.2.3	1 per 6,500 CY

In addition to the sampling summarized in Table 2.1-2, see Section 2.4.2 of this guidance for discussion of testing to be performed during construction of the water balance cover.

2.2 Design Considerations

2.2.1 Soil Type

In addition to soil texture, other physical properties of the water storage layer contribute to a successful water balance cover. Minimizing preferential flow and maximizing the ability of the soil to store water are design criteria that are enhanced by specifying the soil's physical properties.

For water balance covers, use of the United States Department of Agriculture (USDA) Soil Textural Triangle (top portion of Figure 2.2.1-1) and USDA definitions for sand and fine-grained soils (i.e., silt and clay) are paramount. As shown in the graphical comparison of particle size scales on the bottom portion of Figure 2.2.1-1, USDA uses the No. 10 sieve to distinguish sand from gravel and the No. 270 sieve (> 53 microns) to define fine-grained soils. For comparison, the Unified Soil Classification System (USCS) uses the No. 4 sieve to distinguish sand from gravel and the No. 200 sieve to define fine-grained soils while the American Association of State Highway and Transportation Officials (AASHTO) uses the No. 10 sieve to distinguish sand from gravel and the No. 200 sieve to define fine-grained soils.

Through research and experience, soil used for the water storage layer of the water balance cover should meet the following requirements:

- Contain ≤ 15 percent gravel (> 2.00 millimeters, retained on the No. 10 sieve);
- Limit maximum particle size to < 2 inches in longest dimension;
- Limit maximum clod size to < 4 inches in longest dimension, with a clod defined as a soil aggregation that does not break down by hand;
- Should not contain frozen material at the time of placement; and
- Should not contain debris or deleterious materials¹.

2.2.2 Soil Thickness

Based on ecozone location (Figure 2.2.2-1) and predominant soil type (Figure 2.2.1-1), soil thickness for the water storage layer of the water balance cover can be determined using the acceptable zone (AZ) for Ecozones 1, 4, and 5 outlined in red on Figure 2.2.2-2 or the AZ for Ecozone 3 outlined in red on Figure 2.2.2-3. Note that a water storage layer thickness for Ecozone 2 is not presented in this guidance due to the lack of experience with alternative water balance covers in this ecozone combined with the deficiencies in the numerical modeling performed relative to this ecozone by Cadmus (2011).

2.2.3 Soil Density

To function properly, a water balance cover relies on a water storage layer to retain precipitation and support vegetation until the water is transpired or evaporated, thus reducing deep percolation. To take

¹ Isolated and very limited amounts of unacceptable material may be allowed provided the material is not concentrated in one area. These materials should be blended with suitable soils as much as practicable to limit potential adverse affects.

full advantage of the transpiration process, a well-developed and sustainable vegetative cover is desired (see Section 2.3.3 of this guidance). Research performed by Goldsmith, et al. (2001) has shown that when soil compaction levels are high, there is a threshold soil bulk density beyond which roots have difficulty penetrating due to the high physical resistance of the soil. This threshold density is called the growth-limiting bulk density and varies depending on soil texture and plant type. Typical growth-limiting bulk density values range from about 90 pounds per cubic foot (pcf) for predominately clayey soils to approximately 106 pcf for sandy soils (Goldsmith, et al., 2001; Schenk, 2002). Typical growth-limiting bulk density iso-density line values are shown on Figure 2.2.3-1, from Goldsmith, et al. (2001).

As a general rule of thumb for most soil textures, the growth-limiting bulk density is in the range of about 83 to 88 percent of the maximum standard Proctor density (ASTM D 698). In practice, the standard Proctor density specified for the water storage layer should be greater than or equal to 80 percent and less than or equal to 90 percent of the standard Proctor density for that soil type (Albright, et al., 2010). Additional design details might include measures to control erosion on side slopes (e.g., armored down-slope channel chutes, terraces, berms, etc.) and to enhance slope stability. Higher soil density specifications for side slopes and beneath structures may be appropriate.

2.2.4 Soil Moisture Content

During soil placement for a water balance cover, keeping the moisture below the soil's optimum moisture content facilitates a lower density fill. Therefore, incorporation of this requirement in the project specifications is considered good practice.

2.2.5 Soil Loose Lift Thickness

Soil for the water storage layer should be placed in loose lifts greater than 18 inches thick to avoid over-compaction. Consistent with industry standards, low-ground-pressure (LGP) equipment (i.e., less than approximately 7 pounds per square inch) should be used during soil placement.

2.3 Construction Considerations

2.3.1 Subgrade Preparation

For municipal solid waste landfills, subgrade typically is defined as a minimum 6-inch-thick foundation layer composed of earthen material (e.g., typically derived from intermediate or daily cover soils) that is situated between the disposed material and the water balance cover. For non-municipal solid waste landfills (e.g. ash monofills), subgrade may be defined as the top of the waste surface. Good practices for subgrade preparation are listed below.

- Proof-roll the subgrade and make repairs as needed to achieve a stable surface.
- Grade the subgrade to achieve a surface consistent with the approved design contours in preparation for water balance cover construction.
- Relatively steeper side slopes (> 5 percent) should be roughened using appropriate equipment prior to placement of cover soil.
- Survey the prepared subgrade surface prior to water balance cover construction to establish a basis for the lines, grades and total soil cover thickness to be achieved during water balance cover construction.

2.3.2 Cover Soil Placement

Good practices to achieve placement of a minimally compacted water storage layer (and topsoil layer, as applicable) are listed below.

- Excavate the soil from previously approved borrow sources. Each water storage layer borrow source should meet the gradation requirements for the ecozone as identified in Section 2.2.1, as well as the standard soil index property requirements identified in Sections 2.1 and 2.2.
- Place the water storage layer in thicker lifts, which is preferred over multiple thinner, lifts to minimize over-compaction. Placement of the water storage layer as a single lift has proven successful.
- Place the soil using non-wheeled equipment to minimize over-compaction.
- Use soil that is at less than (or “dry” of) its optimum moisture content as identified in Section 2.2.4 of this guidance because “dry” soil is relatively more difficult to over-compact.
- Spread, level and track-walk the soil using LGP equipment (ideally, a D6 LGP or D7 LGP bulldozer).
- Track-walk the soil during placement only enough to place and rough-grade the soil.
- If over-compaction occurs at locations, such as beneath haul roads, the soil might need to be ripped or disked and then re-compacted to within the appropriate growth-limiting bulk density range (Albright et al., 2010). Note that this practice is intended only to alleviate over-compaction and should not be used as a standard operating procedure for cover soil placement.
- Survey the prepared water storage layer/topsoil surface to verify that the desired lines, grades and thickness have been achieved during water balance cover construction. Water balance cover soil component thickness also may be determined by field measurements. In-place soil thickness field measurements should be documented under the supervision of the Construction Quality Assurance (CQA) Engineer.
- Use water sparingly (e.g., for haul road dust control).
- Perform revegetation activities while the placed soil still is “dry” of optimum moisture content as discussed in Section 2.3.3 of this guidance.

2.3.3 Borrow Source Soil Screening Guidance for Vegetative Properties

At the same time that representative soil samples from each borrow source are analyzed for the standard soil index properties in Section 2.1 of this guidance, an initial screening for the soil vegetative properties as summarized in Table 2.3.3-1 also should be performed. The testing described in this sub-section should be performed at the recommended frequency listed in the table for each borrow source.

The testing frequency may be adjusted based on the homogeneity of the soil and the facility’s previous experience with the same materials. It is important that when soils are placed in the water balance cover, suitable pH and calcium carbonate (CaCO_3) content should be attained throughout the entire depth of the water storage layer as opposed to just near the surface.

Table 2.3.3-1

Standard Soil Vegetative Property Screening Tests for Each Borrow Source

Property	Method	Requirement	QA/QC Frequency
pH	Environmental Protection Agency (EPA) Method SW-846 SW 9045C	6.0 – 8.4	1 per 6,500 CY
CaCO ₃	USDA Handbook Number 60	< 15 Percent, by Weight	1 per 6,500 CY

Notes: 1. The properties listed in the above table are for preliminary screening of borrow sources only.

2.3.4 Revegetation Plan

Successful revegetation is critically important to the establishment of a functional water balance cover. Therefore, selection of the appropriate native species seed mix (generally native grasses) for each site to establish a naturally sustaining plant cover that will thrive under ambient soil and climate conditions is essential. Revegetation activities should be performed in accordance with the recommendations of the suppliers of the selected vegetative species or, if applicable, the recommendations of a revegetation consultant retained by the facility. Other resources include the Natural Resources Conservation Service (formerly the United States Soil Conservation Service), the Colorado Department of Natural Resources, the Colorado State University Agricultural Extension Office, and local governing authorities.

Native Plant Revegetation Guide for Colorado, a compilation of best management practices relating to revegetation, was published in 1998 as the result of a cooperative effort between federal, state and local governments and Colorado State University. These guidelines are useful, but each site will require some customization due to the unique combination of environmental factors present. The facility shall submit a revegetation plan for review and approval by the Department. Some general guidelines for developing a revegetation plan are listed below.

- Maintaining adequate soil moisture is critical to germination and for promoting initial establishment of preferred vegetative species.
- Depending on soil conditions, soil amendment application may be necessary to address soil organic matter content, soil structure or nutrient status. The use of inorganic fertilizers generally is not advisable, however, because it might promote weed growth and off-site nitrate migration.
- Prepare a firm but not overly compacted seed bed and perform seeding in a manner that places seed at a rate of 20 to 50 seeds per square foot at a depth appropriate to the size of the seed. Mechanical (drill) seeding generally is the best approach, but broadcast seeding (typically at the rate of double the seeds per square foot of drill seeding) followed by careful raking or harrowing can be satisfactory. Hydraulic application of seed should be avoided.
- Apply and crimp weed-free mulch that can be expected to provide erosion control cover and seed bed protection for at least a year. The mulch should be crimped in furrows perpendicular to the slope. Small grain straw commonly is used, but has poor durability because of its smooth surface and short fiber length. It also could negatively affect germination and establishment of desired species. Use of hay mulch, even if certified weed-free, can result in unintended and numerous non-native, aggressive plants such as alfalfa, timothy, orchard grass, and smooth brome, which will out-compete the seeded native grasses. Alfalfa also has a long tap root, which typically is undesirable in a water balance cover. The ideal mulch should be certified weed-free straw mulch, which is much more inert than hay mulch. At least 70 percent (by weight) of the mulch should be greater than or equal to 10 inches in length. Hydraulic application of wood

fiber mulch at the rate of 2,500 to 3,000 pounds per acre in conjunction with a water-stable tackifier also can be satisfactory.

- With Department approval, the facility might consider irrigating revegetated areas during the first growing season to assist in the establishment of the new vegetation. Factors to be considered include proposed water application rate, weather conditions and other site-specific criteria. Maintenance of a moist seed bed is best accomplished by frequent light application of water. If irrigation is proposed, the facility should submit an irrigation plan for review and approval by the Department.
- After the first growing season, revegetated areas should be evaluated as discussed in Section 2.3.5.
- After a typical establishment period of three to four years, a site-appropriate stand of vegetation should be ready for comparison to performance standards established in the approved revegetation plan.

According to Albright et al. (2010), “Revegetation plans should define criteria (target values for plant species composition and abundance) for evaluating the success of the revegetation effort. The criteria or target values are based largely on the results of the baseline ecological survey—characteristics of the undisturbed plant community growing in the borrow soil type. However, given that succession to a mature and diverse plant community can take years, the revegetation success criteria must have a time component. The ecological basis for the criteria; time steps for the target values; and vegetation sampling designs, instrumentation, and statistical methods for field data collection and analysis should all be included in the revegetation plan.”

2.3.5 Revegetation and Soil Evaluation Techniques

2.3.5.1 Suggested Techniques for Conducting Evaluations

The following is a summary of suggested techniques for conducting revegetation and soil evaluations (i.e., assessments) to monitor conditions associated with optimal vegetative health (paraphrased from personal communications with Self, 2012; and Buckner, 2012). More detailed information is provided in Appendix B.

- 1) If possible, develop a test plot similar to the design of the water balance cover, or use an undisturbed area (i.e., reference area) nearby with similar physical characteristics (e.g., grade, length, and aspect of slope) for visual comparison of native species against vegetative growth on the cap over time. This practice allows for quick comparison of vegetation and how natural stress (e.g., drought) impacts vegetation so as not to draw inappropriate conclusions on the vegetative growth progress. Test soils for:
 - a. Salt content
 - i. Note that high concentrations of ionic salts (sodium, potassium, calcium, etc.) inhibit vegetation growth. Considerations include:
 1. Salt content of soils > 2 percent can be problematic for vegetation growth (see other sustainability criteria in Section 2.3.3);
 2. High gypsum content is an indicator that vegetative growth may be inhibited; and
 3. Manure can increase salt content and may not be an appropriate amendment if amendments are used.

- b. pH
 - i. pH > 8.0 (usually due to high sodium content) can cause soils to disperse resulting in drainage problems inhibiting vegetative growth;
 - ii. pH > 8.4 can inhibit vegetative growth; and
 - iii. pH < 6.0 can inhibit vegetative growth (suggestion: add lime, calcitic limestone, or dolomitic limestone to the soil).
 - c. Nitrogen, potassium, and phosphorus content
 - i. Nitrogen content (recommended): 5 to 30 parts per million (ppm). Note that nitrogen leaches readily and may require additional monitoring. Nitrogen is very important for initial growth and vegetative health but native plants typically are adapted to growth in low-nitrogen conditions. Nitrate nitrogen as low as 5 ppm in conjunction with 1.5 to 2.0 percent soil organic matter will be satisfactory for most major dryland native plants likely to be used on covers.
 - ii. Phosphorus content (recommended): 3 to 7 ppm. Note that phosphorus has a moderate leaching potential. Native plants are likely to prosper with about 3 ppm phosphorus.
 - iii. Potassium content (recommended): 120 ppm. Note potassium has a low leaching potential and generally stays in place until used by the vegetation.
 - d. Conductivity
 - i. The conductivity of soils should be < 4 millisiemens (millimhos) per centimeter. This conductivity is a good indicator of a soil capable of sustaining healthy vegetation.
- 2) Year One: Assess the young revegetated stand using a count of seedlings of desirable species per unit area. In general, a satisfactory stand for purposes of arriving at a satisfactory vegetation cover will be represented after the first year (i.e., end of first growing season) by at least four seedlings per square foot. Two to three seedlings per square foot likely will be sufficient but the vegetation will develop more slowly. One to two seedlings per square foot should be reviewed for possible re-seeding. Areas with less than one seedling per square foot are likely to be unsatisfactory in the long run and the situation should be evaluated to determine why the response was so sparse. A Year One evaluation is important to help predict long-term vegetative success.
- 3) Year Two and Beyond: Annually assess plant cover by species and compare the numbers to performance standards established in the approved revegetation plan as discussed in Section 2.3.4. Assessments may be performed by visual estimation or may be measured using point intercept sampling or other options as defined below. Visual estimation is highly variable by observer, so point intercept sampling is preferable (Buckner 1985, 2000). If a visual method is used for annual evaluations, then a more robust method agreed upon by the Department should be used to evaluate vegetative health every five (5) years.

Options that may be used to evaluate long-term vegetative success are listed below. More detail on these options is provided in Appendix B.

- a. Stand Height Measurement Method;
- b. Biomass Measurement Method;
- c. Soil Moisture Measurement Method;
- d. Small Area Evaluation Method; and
- e. Transect Liner Intercept Method.

2.3.5.2 Other Considerations

Other considerations to promote healthy revegetation development and promote an effective water balance cover are listed below (Self, 2012).

- 1) In many parts of Colorado, moisture content is more important for seed germination and healthy vegetative growth than are soil amendments. Therefore, considerations associated with maintaining moist (not soaked) soils may be a cost-effective strategy for the germination and development of healthy vegetation. Techniques to assure the maintenance of moisture content in soils to promote healthy vegetation include:
 - a. Align seeding activities with wetter periods or expected precipitation whenever possible. For example, seed prior to predicted high moisture periods such as winter snow (see below) or spring rain.
 - b. Develop and operate moisture sources such as sprinkler systems until vegetation is established. Note that the water balance cover should be kept moist, not soaked, to promote seed germination to allow young vegetation to establish itself. Avoid adding too much water. This additional water volume should not be so excessive that the water is able to percolate through the water balance cover and enter the waste.
 - c. Seed in the fall prior to snow. During winter, seeds will remain dormant below the snow pack and frozen ground and will then benefit during the spring from the slow infiltration of snow melt and thawing ground. This provides consistent moisture to assist with seed germination and initial vegetative growth.
- 2) Native grass species are ideal for maintaining effective moisture content of the water balance cover soils and minimizing infiltration to the waste. Grasses have extremely dense roots in the upper soil that can intercept and transpire moisture entering the soil cover. Litter accumulation (thatch) developed at the surface from a healthy growth of grass species assists with retaining the soil moisture near the surface especially during drier months. This effect allows the upper soil profile to retain the necessary moisture to promote and maintain healthy vegetative populations. Dense root establishment will naturally inhibit the ability of noxious weeds, shrubs, sage brush and tree species to invade and get established on the water balance cover. Note that:
 - a. Native grass species are recommended. Exact species are site specific. Selection should be based on consultation with persons experienced in the relationship of species to soils and other environmental conditions of the site.
 - b. Tree species should be avoided. Depending on the thickness of the water balance cover, native shrubs and sage brush may be appropriate (Albright, et al, 2010) provided they are adequately maintained (NRCS, 2011).

- c. Manual removal of any noxious weeds is required by federal law (the Plant Protection Act of 2000) and state law (Colorado Noxious Weed Act), which also established the state noxious weed list as well as the county-based system. Each Colorado county has its own weed coordinator and maintains a noxious weed list based on the Colorado list with which residents must comply. The county weed coordinators are responsible for enforcing compliance with the Colorado Noxious Weed Act. All land owners and land managers are responsible for compliance. The list of noxious weeds is updated regularly and can be found at:
<http://www.colorado.gov/cs/Satellite/Agriculture-Main/CDAG/1174084048733>.
- d. Manual removal of tree species is recommended as an annual water balance cover maintenance item. Depending on the thickness of the water balance cover and whether or not the species are native, shrubs and sage brush also might need to be removed. Removal of such vegetation when the species are young help prevent a major disturbance of the water balance cover soils because the root balls of the species will be smaller.
- e. Mowing the perimeter of the landfill area periodically is recommended as a maintenance practice to prevent noxious weeds and tree species from getting established along the perimeter of the cap, thereby reducing the ability of such species to encroach onto the water balance cover. Also see Section 2.3.5.

2.3.6 Other Revegetation Considerations

Management of wildlife on the water balance cover can be an important consideration. A perimeter fence can be an effective barrier against intrusion by larger animals such as deer, moose and elk. Visual barriers such as a border of shrubbery, a silt fence (as a temporary measure), or a border of bales of hay or straw (as a permanent measure) can be effective against intrusion by prairie dogs. Wildlife management resources include the Colorado Parks and Wildlife and the United States Fish and Wildlife Service.

2.3.7 Storm Water Controls

The long-term viability and success of a water balance cover depends on appropriate storm water controls. During the initial stages of the project and while awaiting establishment of the new vegetation, it is extremely important to install and maintain storm water and erosion controls to control storm water flow for the 24-hour, 100-year storm and to minimize storm-water-based erosion of the water balance cover. Storm water and erosion control measures must be identified on the design drawing and submitted to the Department for review and approval.

2.3.8 Other Construction Considerations

Other activities to consider during water balance cover construction and revegetation include the protection and extension of monitoring wells, landfill gas collection and control piping to meet the final elevation of the water balance cover and other relevant site-specific features. Details regarding these other activities and considerations must be identified on the design drawings and submitted to the Department for review and approval.

2.4 Quality Assurance / Quality Control

A CQA Plan must be prepared and submitted to the Department as part of the water balance cover design approval process. During water balance cover construction, Quality Assurance / Quality Control (QA/QC) personnel must observe and document activities and perform sampling and testing in accordance with the CQA Plan and relevant project requirements including the Solid Waste Regulations.

2.4.1 Observations and Documentation During and After Construction

2.4.1.1 During Construction

During construction, QA/QC personnel must observe and document activities in accordance with the requirements of the project-specific drawings, technical specifications and CQA Plan, as well as the Solid Waste Regulations and other relevant documents (e.g., “Technical Guidance Document for Quality Assurance and Quality Control for Waste Containment Facilities” [EPA, 1993]) that are appropriate to the specific site. The CQA Plan identifies the frequency of observations (e.g., part-time versus full-time) and project documentation requirements such as daily and weekly reports, sample locations, field forms for recording test results, etc.

Following completion of the field work, the owner or operator of the facility shall submit a CQA Report to the Department for review and approval. The CQA Report documents that construction has been completed in accordance with the approved design and specifications. The CQA Report shall be stamped and sealed by a professional engineer registered in the state of Colorado, approved by the Department and placed in the facility’s operating record.

2.4.2 Testing During Construction

2.4.2.1 Field Sampling and Laboratory Testing

Laboratory testing must be performed incrementally during construction following the sampling methods and testing frequencies summarized in Table 2.4.2.1-1. Testing frequencies may be increased or reduced based on the homogeneity of the soils. Soil samples collected for texture and laboratory compaction should be obtained from the same location at the same time. In addition, during excavation/construction of the water balance cover, the borrow source should be sampled and tested as summarized in Table 2.1-2 (see Section 2.1 of this guidance).

Table 2.4.2.1-1
Laboratory Testing During Placement

Property	Method	Requirement	QA/QC Frequency
Texture	ASTM D 422 (with full hydrometer)	Inside AZ	1 per 1,500 CY
Laboratory Compaction (Standard Proctor)	ASTM D 698	Not Applicable (NA)	1 per 3,000 CY (or change in soil type)

Notes: 1. AZ = Acceptable zone for applicable ecozone (see Section 2.2.2 of this guidance).

2.4.2.2 Field Testing

Field testing must be performed incrementally during construction following the sampling methods and testing frequencies summarized in Table 2.4.2.2-1.

Table 2.4.2.2-1
Field Testing During and After Placement

Property	Method	Requirement	QA/QC Frequency
Compacted Thickness	Per Design	Per Design	3 per Acre per Lift
Dry Density	ASTM D 6938	$\geq 80\%$ and $\leq 90\%$	3 per Acre per Lift
Moisture Content	ASTM D 6938	NA – Target less than OMC	3 per Acre per Lift

- Notes:**
1. QA/QC personnel should monitor the water balance cover during placement for moisture content.
 2. Non-nuclear methods (e.g., drive cylinder [ASTM D 2937]) may be allowed if approved by the Department.
 3. QA/QC personnel should record the moisture content and density for each test. The recording of the moisture content solely is to document the moisture content at the time of testing and is not to be used as an acceptance criterion for the water balance cover. Monitoring the moisture content of the water balance cover during placement is to verify that the water balance cover material is at or dry of optimum moisture content during placement. Density is the only acceptance criterion for the water balance cover during moisture-density testing.

2.4.3 Resolution of Failing Tests

2.4.3.1 Laboratory Testing

When placed soils fail to meet the project requirements regarding soil type and texture, QA/QC personnel should define the failed area by performing delineation sampling and testing, with one test in each of the four cardinal directions (north, south, east and west) at a distance of 10 to 20 feet from the original failed sample location. If the four delineation tests meet project requirements, the soils located in the area defined as halfway between the original failed sample location and each of the four passing delineation sample locations should be re-worked or removed and replaced with suitable material. After soil re-work/replacement is complete, the affected area should be re-sampled and re-tested. If the re-test passes, no further action is needed. If the re-test fails, the procedure should continue until the affected soils meet project requirements. If any of the delineation tests fail, delineation must continue until the extent of the failing area is determined. The soils located in the delineated failed area should undergo the re-work/replacement process and be re-tested until the delineated area meets project requirements. It is possible that local over-compaction can occur due to tracking of equipment and vehicles while resolving soil type and testing issues. Any over-compacted zones should be appropriately re-worked to assure that materials are below the growth-limiting bulk density (see Section 2.3.2 of this guidance).

2.4.3.2 Field Testing

When tests indicate that soils fail to meet the project requirements for in-place dry density, QA/QC personnel must define the failed area by performing delineation testing, with one test in each of the four cardinal directions at a distance of 10 to 20 feet from the original failed test location. If the four delineation tests meet project requirements, the soils located in the area defined as halfway between the original failed test and each of the four passing delineation tests should be re-worked or replaced. After the completion of remedial activities, the soils located in the affected area should be re-tested. If the re-test passes, no further action is needed. If the re-test fails, the area should be remediated and re-tested until the area meets project requirements. If any of the delineation tests fail, delineation must

continue until the extent of the failing area is determined. The soils located in the delineated area should be remediated and re-tested until the delineated area meets project requirements.

The EPA guidance anticipates the occurrence of outliers on cohesive soil liners with regard to various soil properties. Such outliers must not be concentrated in one lift or one area, and there must be a limit on the maximum allowable variation from the required dry density. These concepts may be translated to water balance covers. The Department notes that if these outlier concepts are incorporated into the CQA Plan, then sufficient data must be collected to establish the relevant statistical parameters identified in the EPA guidance (1993).

2.5 Closure Summary Report

As stated in Section 2.4.1.1 of this guidance, the owner or operator of the facility shall submit the CQA Report to the local governing authority having jurisdiction and to the Department for review and approval. The CQA Report should be submitted within 60 calendar days of the completion of a construction element. The Department has authority to approve the report in consultation with the local governing authority, although approval by the local governing authority also may be required in some cases. The CQA Report should include, but not be limited to, detailed information on the following:

- Description and disposition of items that did not meet the requirements of the approved project design;
- Copies of daily field reports;
- Photographs of the various construction components;
- Soil sample locations for laboratory testing;
- Results of laboratory testing;
- Field test and measurement locations;
- Results of field testing and measurements;
- Topographic survey and record drawings of the base of the final cover, final cover surface, and associated surface water control features (survey reports and record drawings must be stamped and sealed by a professional land surveyor registered in the state of Colorado);
- Seeding activities; and
- Significant changes (which require prior Department approval) to Department-approved drawings, specifications, and CQA Plan.

The as-built construction certification report (CQA Report) must contain a statement by the certifying engineer that construction has been completed in accordance with the approved engineering design plans, drawings, and specifications (as modified, if applicable). The certifying engineer must be a professional engineer registered in the State of Colorado and shall properly certify the CQA Report.

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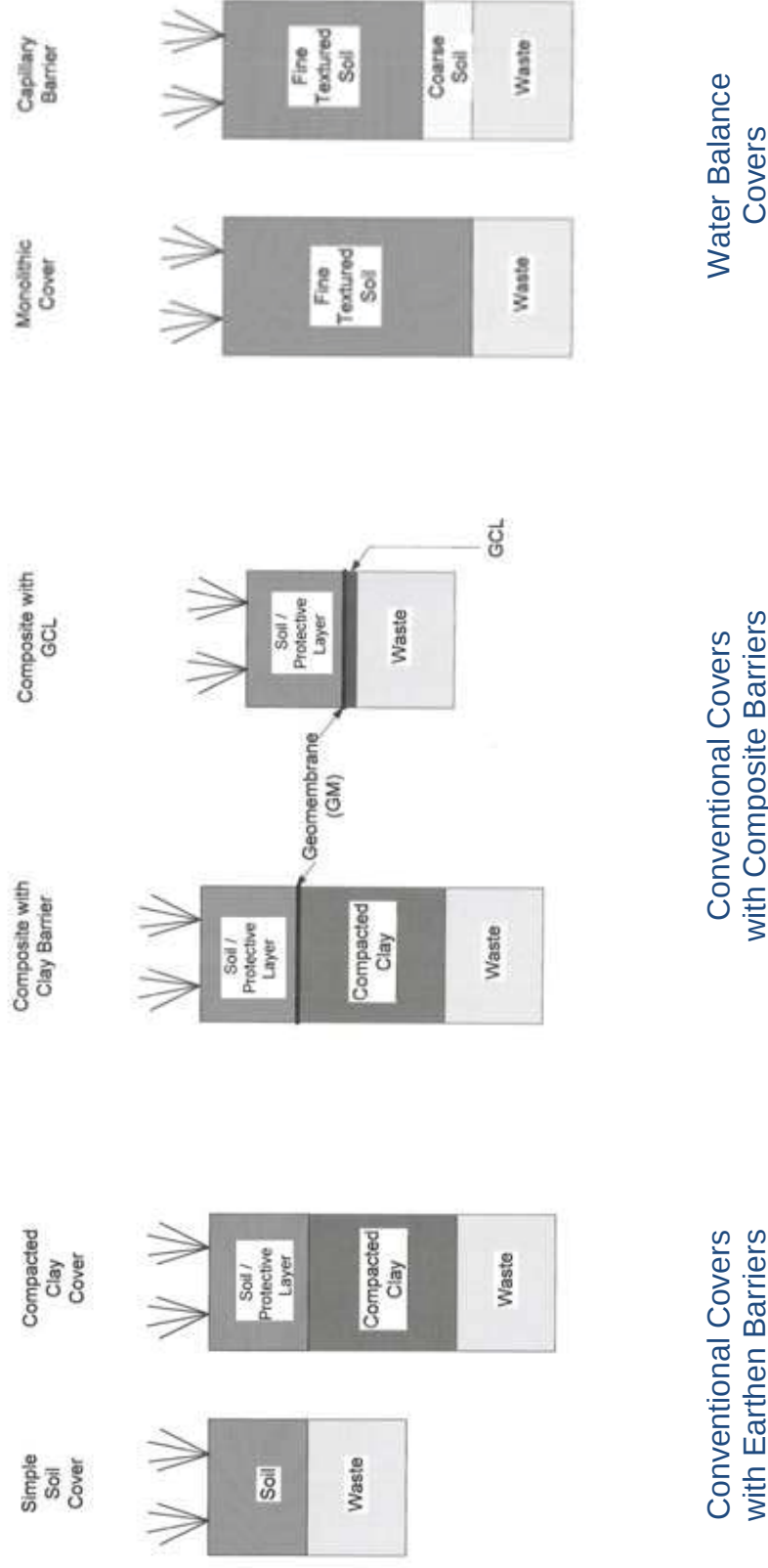
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FIGURES

FIGURE 1.1-1

**TYPICAL CROSS-SECTIONS OF
CONVENTIONAL AND WATER BALANCE COVERS**

Figure 1.1-1
Typical Cross-Sections of Conventional and Water Balance Covers



- Notes:**
1. The above cover typical cross-sections are conceptual presentations only.
 2. As discussed in Section 2.3.1: Subgrade Preparation, for municipal solid waste (MSW) landfills, subgrade typically is defined as a minimum 6-inch-thick foundation layer composed of earthen material (e.g., typically derived from intermediate or daily cover soils) that is situated between the disposed material and the WBC. For non-MSW landfills (e.g. ash monofills) subgrade may be defined as the top of the waste surface.

FIGURE 2.2.1-1

COLORADO ECOZONES AND
ACTIVE MUNICIPAL SOLID WASTE LANDFILLS

Figure 2.2.1-1 – Colorado Ecozones and Active Municipal Solid Waste Landfills

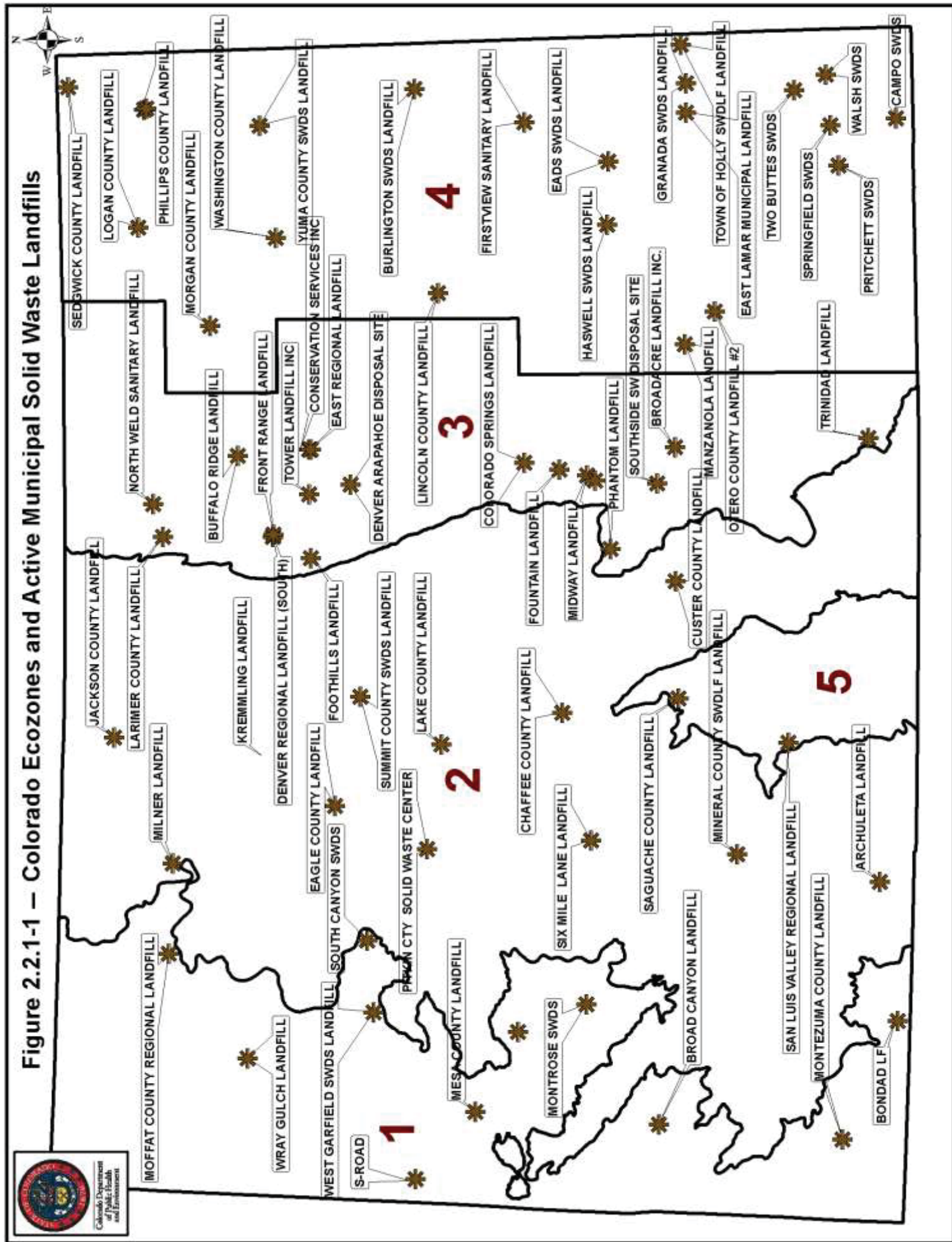
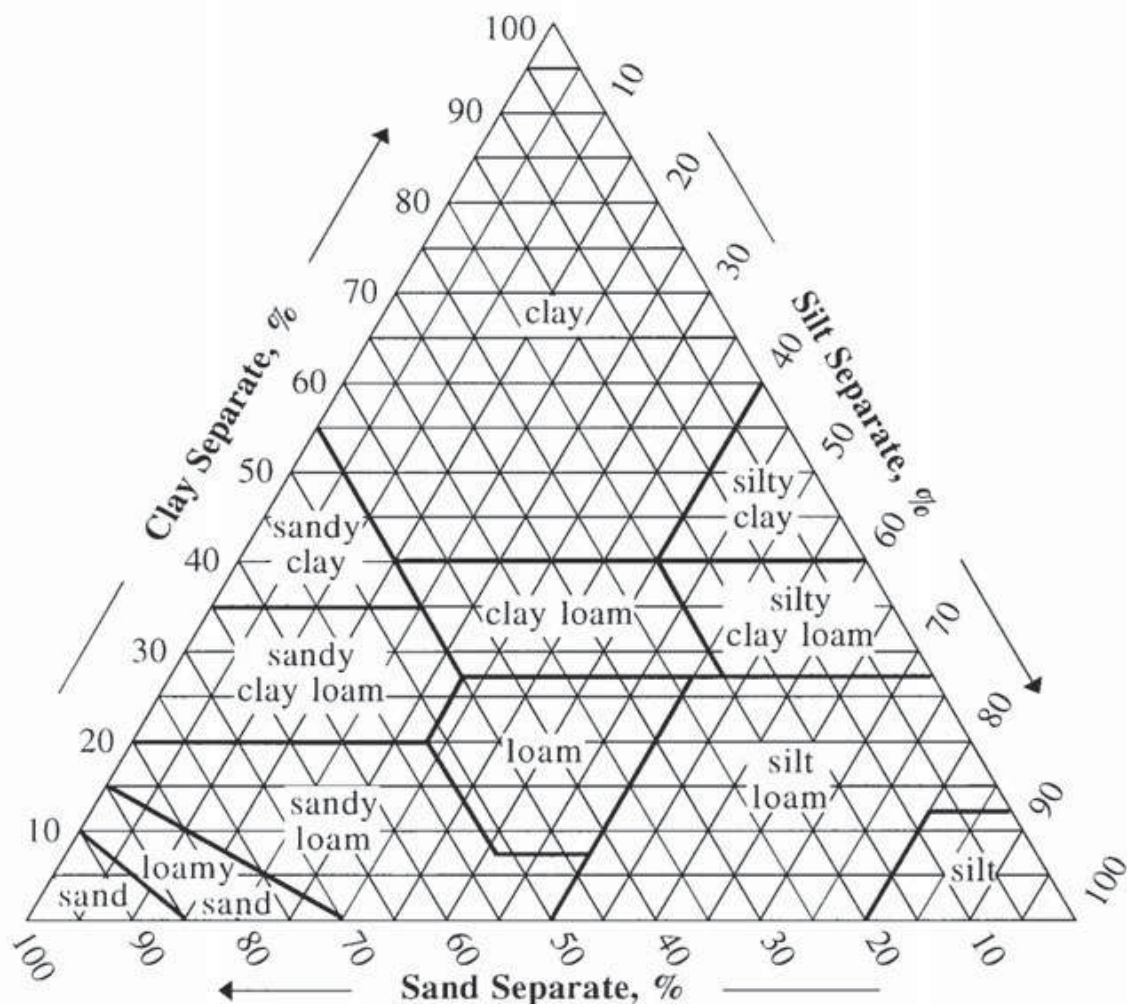


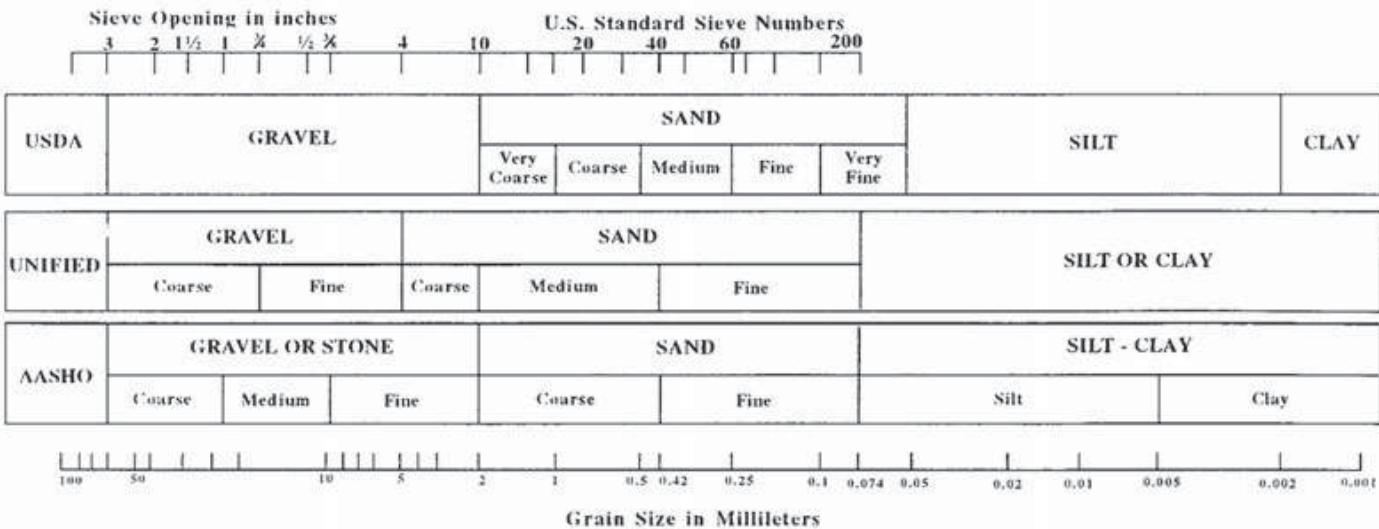
FIGURE 2.2.1-2

**USDA TRIANGLE AND USDA, USCS, AND
AASHTO PARTICLE-SIZE SCALES**

Figure 2.2.1-2
USDA Textural Triangle and
USDA, USCS, and AASHTO Particle-Size Scales



COMPARISON OF PARTICLE SIZE SCALES



Reference: United States Department of Interior, Bureau of Reclamation (1987) "Design of Small Dams."

FIGURE 2.2.1-3

**WATER STORAGE LAYER THICKNESS FOR
ECOZONES 1, 4, AND 5**

Figure 2.2.1-3
Water Storage Layer Thickness For
Ecozones 1, 4, and 5

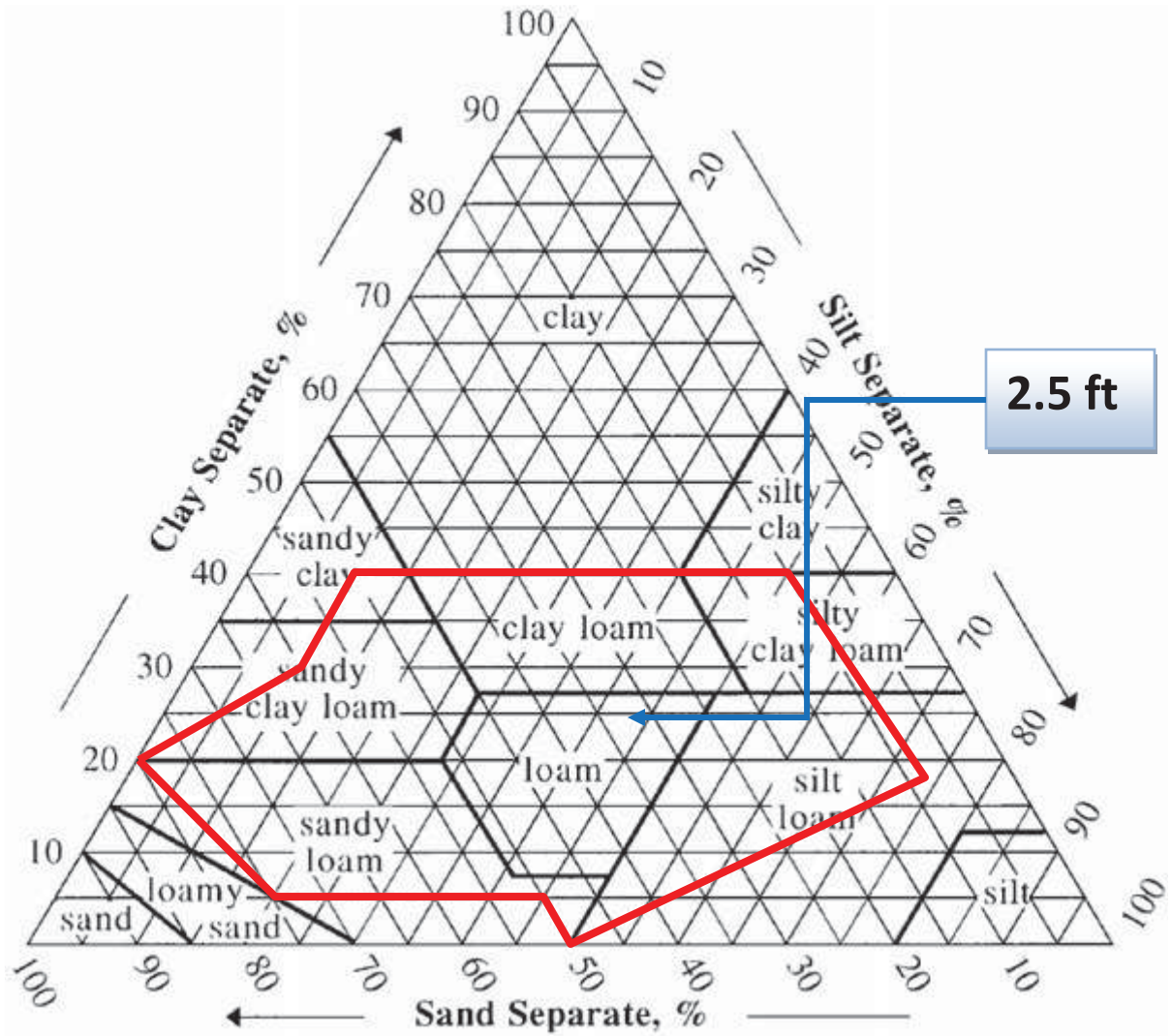


FIGURE 2.2.1-4
WATER STORAGE LAYER THICKNESSES FOR
ECOZONE 3

Figure 2.2.1-4
Water Storage Layer Thicknesses for
Ecozone 3

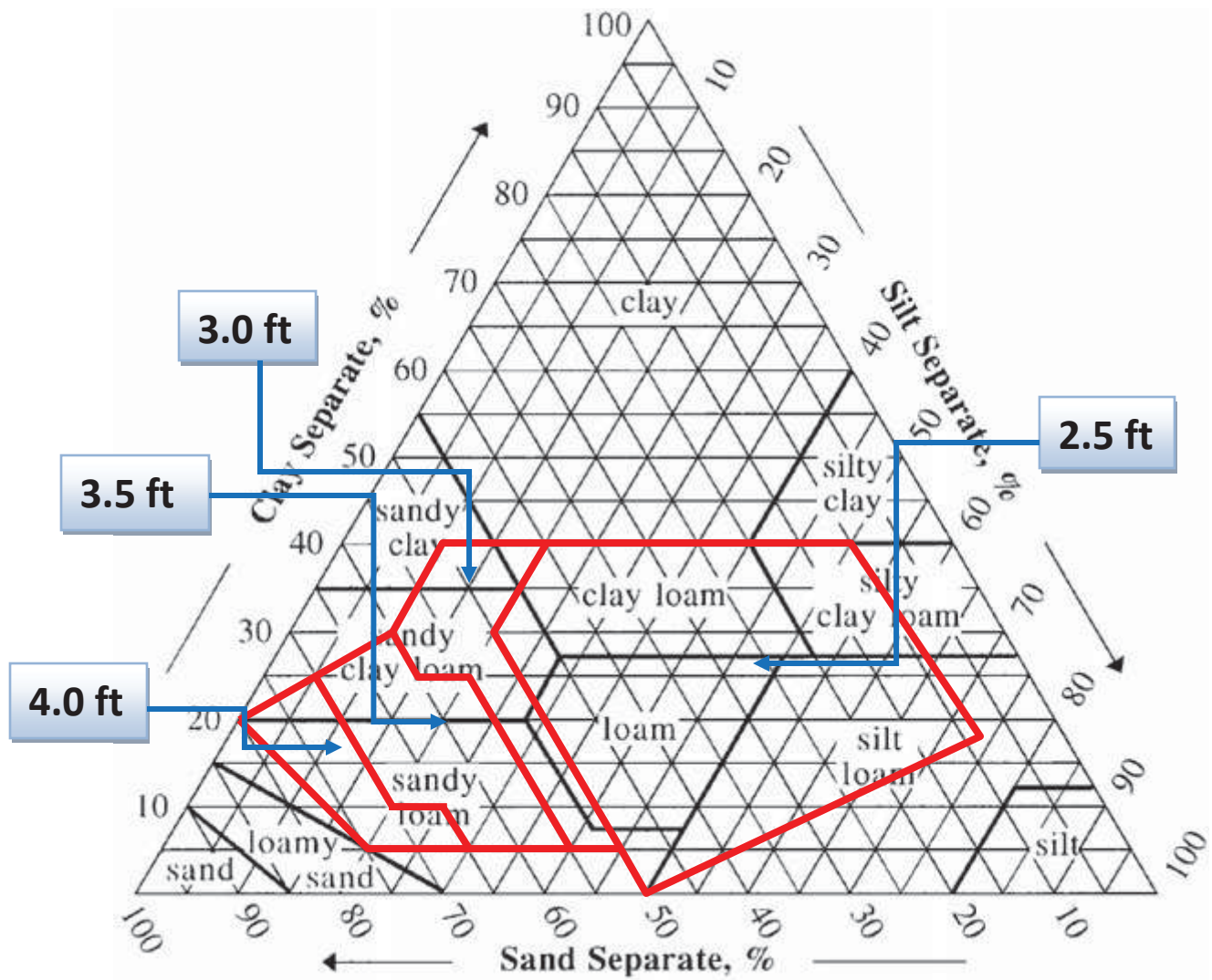
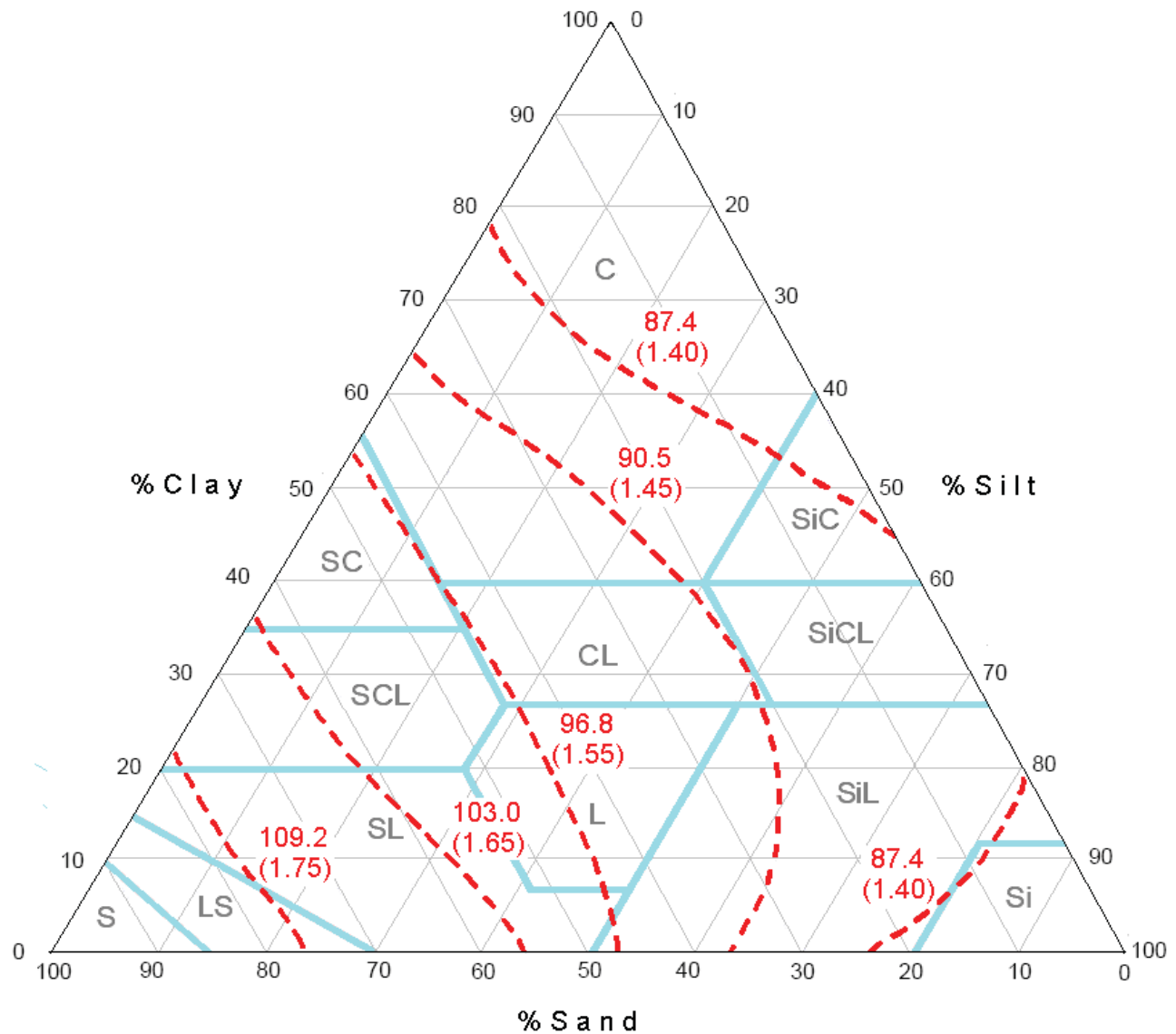


FIGURE 2.2.3-1

**GROWTH-LIMITING BULK DENSITY ISO-DENSITY LINES
SHOWN ON THE USDA TEXTURAL TRIANGLE**

Figure 2.2.3-1
Growth-Limiting Bulk Density Iso-Density Lines
Shown on the USDA Textural Triangle



Legend:

--- = Iso-Density Line

87.4 = Pounds per Cubic Foot
 (1.40) = Grams per Cubic Centimeter

Reference: "Determining Optimal Degree of Soil Compaction for Balancing Mechanical Stability and Plant Growth Capacity," by Goldsmith, Silva, and Fischenich (2001).

APPENDICES

APPENDIX A

MODELING WATER BALANCE COVERS
FOR COLORADO ECOZONES

Modeling Water Balance Covers for Colorado Ecozones

FINAL REPORT

September 28, 2011

*STREAMS Task Order 33, Work Order 8
Task 6 Deliverable*

Prepared for:

Office of Research and Development Engineering Technical Support Center
National Risk Management Research Laboratory
U.S. Environmental Protection Agency (EPA)

Prepared by:

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List of Acronyms and Abbreviations

ACAP	Alternative Covers Assessment Program
AFC	Alternative Final Cover
B-C	Blaney-Criddle
CDPHE	Colorado Department of Public Health and Environment
EPA	United States Environmental Protection Agency
ET	Evapotranspiration
ET _o	Reference evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographic Information System
LAI	Leaf Area Index
MSW	Municipal solid waste
NASIS	National Soil Information System
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
P	Precipitation
PE	Potential evaporation
PET	Potential evapotranspiration
PT	Potential Transpiration
RCRA	Resource Conservation and Recovery Act
S _r	Amount of water that needs to be stored
SSURGO	Soil Survey Geographic database
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WRC	Water retention curve

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1. Introduction

1.1 Background

1.1.1 Water Balance Covers

Final covers are frequently used to reduce the quantity of water that percolates into contaminated soils and/or waste deposits at solid waste facilities. Reducing the volume of percolating water can reduce the amount of leachate that is generated and the potential impacts on groundwater quality. At many sites, the applicable rules and regulations require that the covers employ resistive materials (i.e., layers having low saturated hydraulic conductivity such as compacted clay barriers or geosynthetic clay liners with or without a geomembrane). These materials are used to provide the hydraulic impedance that limits flow into underlying contaminated materials or waste. This design philosophy is often referred to as the “raincoat” or “umbrella” approach.

The Resource Conservation and Recovery Act (RCRA) describes the requirements for traditional, prescriptive landfill cover designs. The United States Environmental Protection Agency’s (EPA) and the state of Colorado’s final cover regulations, however, provide a provision for the use of alternative covers. The regulations state that the alternative cover must provide: 1) an infiltration layer that provides equivalent reduction in infiltration to that of the prescribed cover, and 2) an erosion layer that provides equivalent protection from wind and water erosion as the prescribed cover. However, these regulations do not specify allowable percolation rates through any type of cover.

One type of alternative cover is an earthen cover that exploits the water storage capacity of finer textured soils and the water removal capability of vegetation. These types of covers are referred to as evapotranspiration (ET) or water balance covers. Water that infiltrates into a water balance cover due to precipitation is stored by the soil and subsequently removed (either by vegetation via transpiration or through direct evaporation from the soil) and returned to the atmosphere, thereby limiting the percolation of water through the cover. The design of water balance covers consists of two basic steps: (1) selecting a soil profile that has sufficient capacity to store the infiltrating water while ensuring that percolation from the base of the cover is maintained below an acceptable maximum value and (2) selecting vegetation that will efficiently remove the stored water from the profile during the growing season.

When designing alternative earthen covers, such as water balance covers, often use models to simulate the flux through the design cover under certain input scenarios intended to stress the cover. Figure 1 shows a schematic of a water balance landfill final cover. From the water balance of earthen covers, percolation (P_c) is the net effect of the interactions of precipitation (P), runoff (R), ET, and change in soil water storage (ΔS_w) as follows:

$$P_c = P - R - ET - \Delta S_w$$

Water balance covers are selected and arranged such that runoff, evapotranspiration, and soil water storage are maximized. The design of these water balance covers is very site specific as it involves assessing local climatic conditions (such as precipitation and potential evapotranspiration), soil properties (such as hydraulic conductivity functions and storage

capacity), and the adequate characterization of the vegetation. Organic amendments such as compost, woodchips, or other local fine-textured by-products can be blended with soil to improve fertility and water storage capacity.

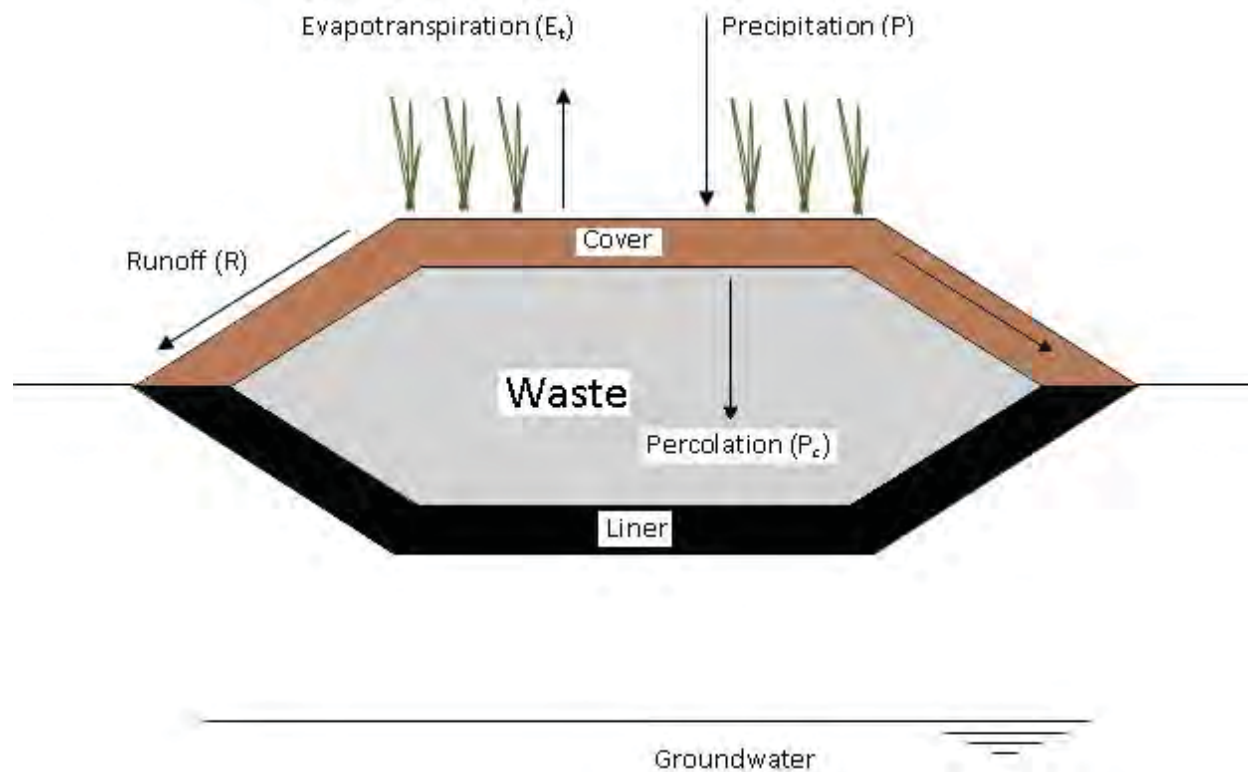


Figure 1. Schematic of a Monolithic Water Balance Landfill Cover

In general, water balance covers are not designed to a level of impermeability that can be measured in the field. Instead, they are designed based on performance to meet applicable percolation criteria. This type of design relies heavily on computer modeling to simulate the soil cover properties, climate, and plants. As a result, although the lifecycle cost of such covers is lower than a conventional cover, the design cost can be higher, making it difficult for many smaller landfills to afford the design.

1.1.2 Water Balance Covers in Colorado

In the Colorado Solid Waste Regulations (6-CCR 1007-2), there are three stated options for landfill final covers. Section 3.5.3(A) describes the conventional cover option, which consists of a low-permeability soil layer and an additional layer on top for plant growth. A second option under Section 3.5.3 (B) is a composite design using a geomembrane. The third option under 3.5.3 (C) is any other alternative that meets erosion and infiltration requirements and is approved by the agency; such covers are commonly referred to as Alternative Final Covers (AFCs).

Since the Colorado Solid Waste Regulations became effective in 1993, there have been few advances in prescribed cover designs. There have, however, been significant advances in the field of water balance covers. While compacted clay conventional covers are now being shown to lose their impermeable qualities over time in Colorado's arid climate, this same climate has

been shown to be ideal for water balance covers (Albright et al., 2010). Studies and observations of fully vegetated water balance covers at Fort Carson (McGuire et al., 2009) and at the Rocky Mountain Arsenal over the past decade have demonstrated the utility of these designs. Several water balance cover designs have been proposed and built for various solid waste landfill cells in Colorado. However, standards for these designs have not been unified.

Colorado's arid/semi-arid climate is ideal for water balance covers because of low average precipitation and high potential evapotranspiration. Percolation rates estimated by a regression model and National Oceanic and Atmospheric Administration (NOAA) climatic data suggest that percolation rates in the state will be in the range of 0-4 mm (Albright et al., 2010). Colorado has a complex and varied climate that reflects the state's diverse topography. Despite this variability, Colorado can be divided into regions with similar soil types, climate, and vegetation. Thus, water balance cover designs for a specific area may be applicable to other, similar areas.

1.2 Objectives of this Study

The objective of this study is to develop a set of baseline design parameters (soil type and cover thickness) specific to Colorado for monolithic water balance covers. These baseline design parameters will help to streamline the permitting process and allow landfill owners and operators to avoid additional modeling for their landfills if their site-specific climate, vegetation, and soil conditions are similar to those used for the development of the baseline design parameters. These design parameters may be incorporated into a guidance document produced by the Colorado Department of Public Health and Environment (CDPHE) for the design of water balance covers throughout the state.

Although modeling provides an estimate of percolation through water balance covers, it is one of many factors that must be considered when designing water balance covers. Other factors that are not discussed in this report, including maintenance and use of appropriate vegetation, also affect the performance of water balance covers and should be considered when incorporating the results of this study into water balance cover designs.

1.3 Overview of Methodology

This report documents the modeling results for monolithic water balance covers in the state of Colorado. The following sections describe the methodology used to delineate ecozones and model water balance covers. Section 2 describes the process of delineating five ecozones in Colorado using EPA's ecoregions and publicly available spatial data on climate, vegetation, and soil characteristics. Section 3 describes the steps taken to process the various input data, the assumptions made for the HYDRUS-1D model, and the resultant downward, upward, and net flux from water balance covers in each ecozone. Section 4 presents a discussion of the challenges faced during this study, the decisions made and the rationale behind them, and potential alternative adjustments that could be made in future studies. Finally, Section 5 presents a summary of the results. An overview of the methodology is presented in Figure 2.

Most current landfill technologies are intended to minimize percolation into buried waste, where contaminants may be mobilized. Although leachate from landfills is routinely collected and treated in modern landfills, minimizing the production of leachate through the use of properly

designed landfill covers can enhance efforts to protect the environment. In contrast to more common “umbrella” covers that provide a percolation barrier, water balance covers are often constructed without a true barrier layer. As a result, water may periodically infiltrate into the waste layer, especially when local climatic extremes occur. The potential for percolation under local climatic extremes necessitates a conservative approach to designing generic water balance covers. This conservative approach is used in the methodology presented in this report, and it focuses generally on modeling cover performance under conditions that favor percolation. It is assumed that if the modeled cover is predicted to perform well under extreme conditions, then performance during typical years is also likely to provide the needed environmental protection.

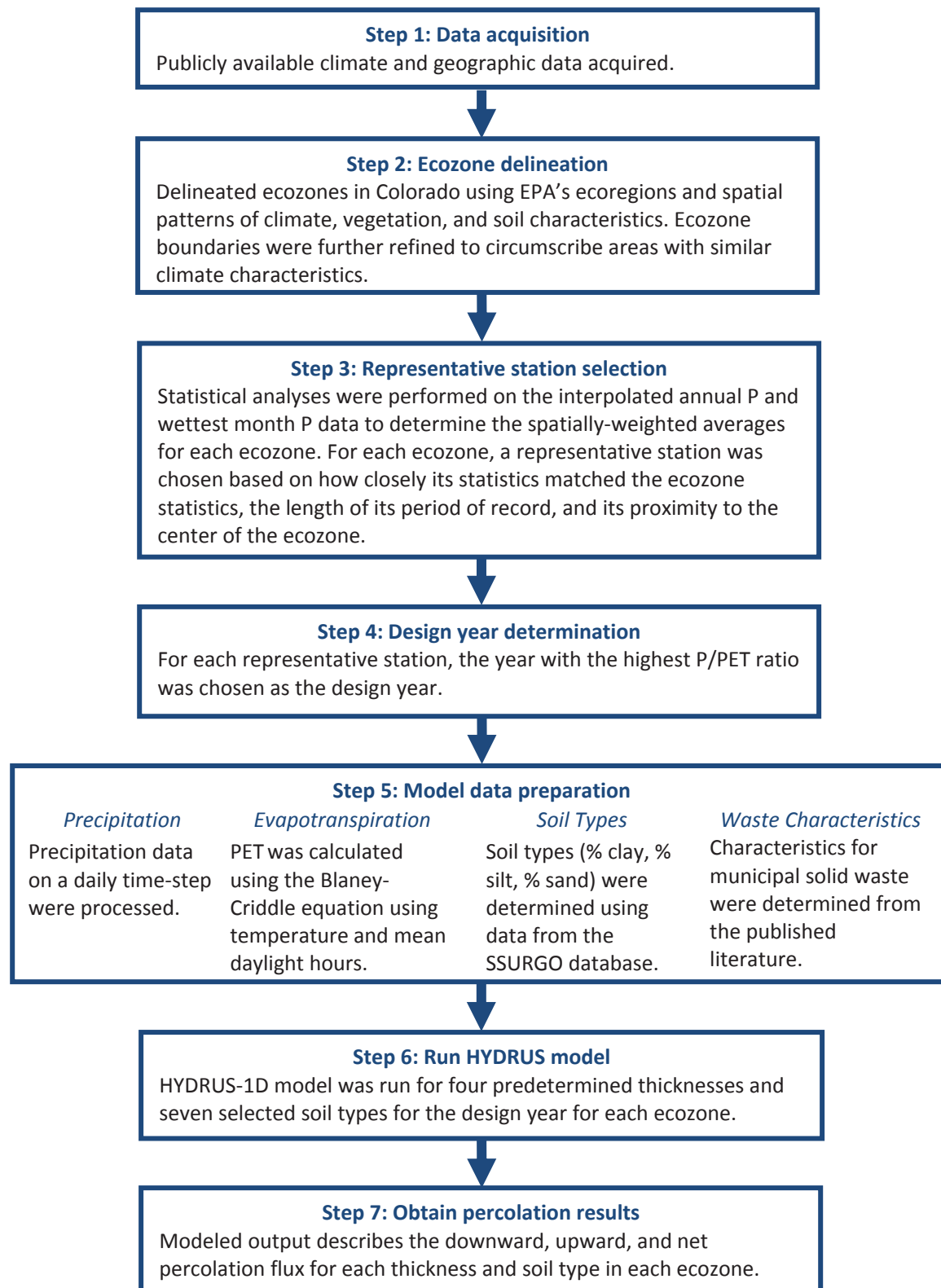


Figure 2. Overview of Methodology for Modeling Water Balance Covers in Ecozones

2. Delineation of Ecozones

There is tremendous ecological diversity in Colorado resulting from variation in topography, geology, soils, and climate. Though known for its mountains, Colorado's terrain also includes high plains, mesas, and foothills. Precipitation in the state falls as a mix of snow and rain, with snow as the dominant form of precipitation at higher elevations. Intense localized summer thunderstorms are common to the east of the Continental Divide. The statewide average annual precipitation (rainfall plus snow water equivalent) is 432 mm, but the value ranges from 178 mm in the San Luis Valley in south Central Colorado to over 1,524 mm in some isolated mountain locations (Doesken et al., 2003). In general, temperature decreases and precipitation increases with elevation, although slope orientation and topography also play a role. Humidity is generally low throughout the state, which favors rapid evapotranspiration (Doesken et al., 2003).

The climate diversity in Colorado necessitates a modeling approach that accounts for differences in the amount of water that must be stored and ultimately released by the cover. This effort evaluated spatial variation in the physical parameters (precipitation, evapotranspiration, elevation) that govern the effectiveness of water balance covers and delineated areas where these parameters are similar. These 'ecozones' served as the spatial framework for subsequent percolation modeling. The ecozones used in this study were initially delineated based on the six Level III ecoregions in Colorado described in Section 2.1 (Chapman et al., 2006). The boundaries were then compared to a suite of physical parameters (described in Section 2.2), with an emphasis on the spatial patterns of precipitation and evapotranspiration in Colorado. Where appropriate, individual ecozone boundaries were then further refined to circumscribe areas with similar precipitation and evapotranspiration characteristics and to enhance future implementation efforts.

2.1 Colorado Ecoregions

In general terms, ecological units delineate areas with similar environmental characteristics and are intended to provide a spatial framework for ecosystem-based management decisions (Cleland et al., 1997). Numerous systems for classifying ecological units have been developed, ranging in applicability from local to regional scales. These systems have been developed for a variety of purpose, ranging from a general need to coordinate ecosystem management strategies across various agencies to very specific management applications.

One of the most commonly used ecological frameworks, dubbed 'ecoregions' was developed by Omernik (1995). These "general purpose regions" generally circumscribe areas with similar vegetation, elevation, and climate. The relative importance of these characteristics varies from one ecoregion to the next. Ecoregions are structured in a hierarchical framework, with 'Level I' regions presented at the most coarse scale and progressively higher resolution ecoregions (Level II, Level III, etc.) nested within those regions. There are six Level III ecoregions that intersect the state of Colorado, as shown in Figure 3 (Chapman et al., 2006).

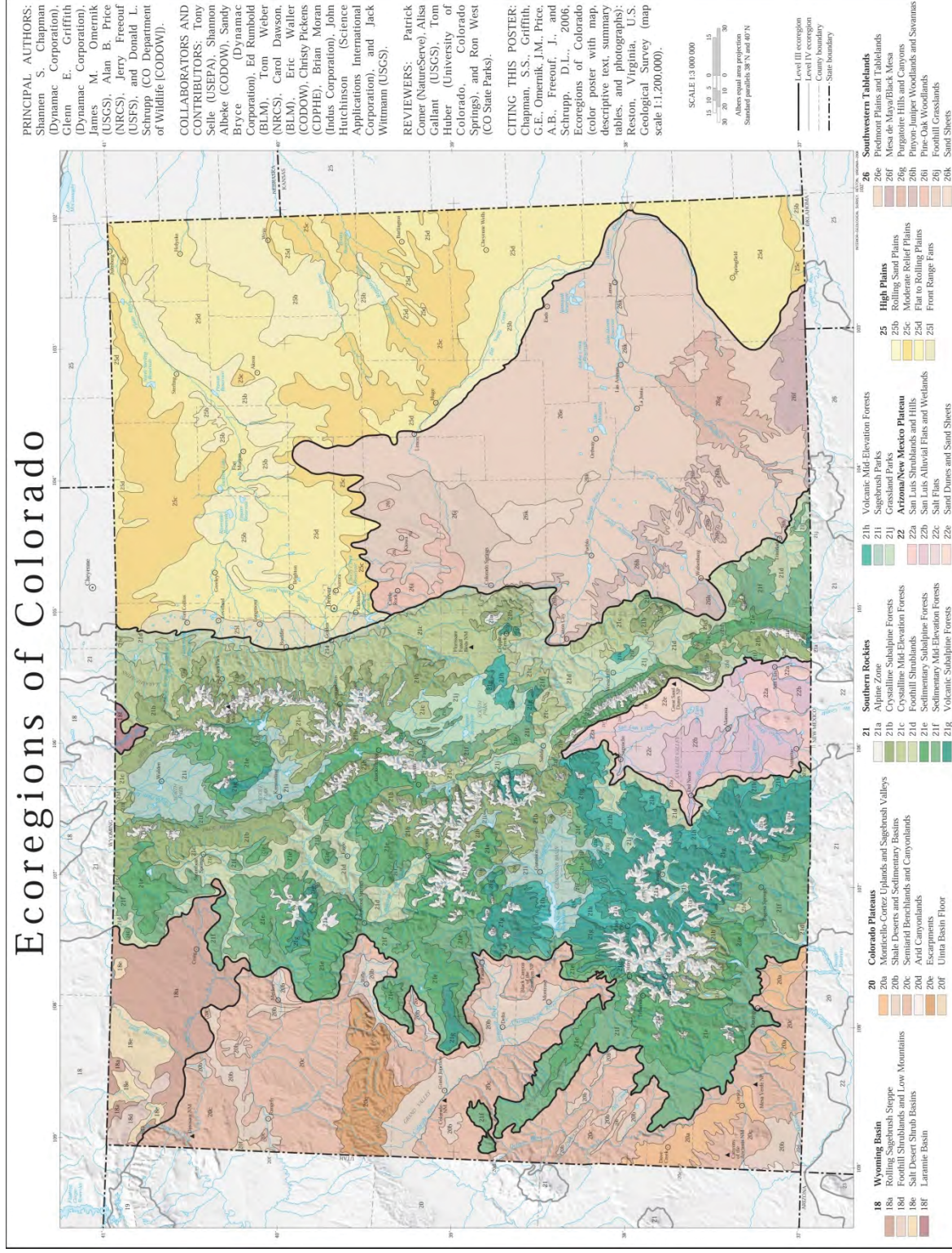


Figure 3. Ecoregions of Colorado

Source: Chapman et al., 2006

The objective of this study required a balance between the need to generalize areas with similar environmental characteristics and the need to distinguish critical regional differences in the factors that affect the performance of water balance covers. Although ecoregions are not intended to denote homogenous zones of P and PET, they do generally circumscribe areas with similar vegetation, soils, land use, hydrology, and climate. As such, the Level III ecoregions generally correspond to factors of relevance to this study, leading to the use of ecoregional boundaries as a starting point for the delineation of ecozones.

2.2 Climate and Physical Geography

Additional data were acquired (Table 1) and analyzed to verify the spatial agreement between ecozones and other climatic and physical parameters relevant to the performance of water balance covers.

Table 1. Climatic and physical parameter datasets

Variable	Data Set	Temporal Resolution	Frequency	Format of Data	URL to Data (if any)
Precipitation ¹	NOAA National Climate Data Center (NCDC)	1980 - 2010	Daily	Comma-separated (tabular)	http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.html
Temperature ²	NOAA NCDC	1980 - 2010	Monthly	Comma-separated (tabular)	http://cdss.state.co.us/DNN/Home/tabid/36/Default.aspx
Soil	United States Department of Agriculture (USDA) - Soil Survey Geographic database (SSURGO)	2003 - 2009	N/A	Shapefile	http://SoilDataMart.nrcs.usda.gov/
Elevation	USGS - National Elevation Dataset (NED)	1990 - 2009	Every 2 months	Raster	http://nationalmap.gov http://seamless.usgs.gov
Crop Cover	USDA - National Agricultural Statistics Service Crop Land Data Layer	1997 - 2006	N/A	Raster	http://www.nass.usda.gov/
Land Cover	USEPA - National Land Cover Dataset (NLCD)	2001	N/A	Raster	http://www.mrlc.gov/

1 Period of record varies by station.

2 Period of record varies by station. Average temperature was used in the Blaney-Criddle equation to calculate PET.

.2.2.1 Precipitation

Monthly precipitation and snowfall data for all Colorado stations (n=354) were downloaded for the years 1980-2010 and imported into Microsoft Excel. Years with incomplete data were deleted. In addition, all stations with less than 10 years of complete data were removed from the dataset with the exception of those located near a new station in the same local area (e.g., Station Delta [COOP ID 52192] collected data from 1980-1999, and Delta 3E [COOP ID 52196] collected data from 2000-2010).

For the remaining stations (n=239), average annual precipitation and average annual snowfall were calculated. In addition, “typical years” at each station were defined as years within ½ standard deviation of the average annual P. For each typical year, the wettest month was calculated as the month with the highest percentage of the total annual rainfall. The average wettest month (in terms of P [mm] and percent contribution to total annual P) was calculated for the typical years.

The values calculated at each station for average annual P, wettest month P, and average annual snowfall were used to interpolate precipitation data for Colorado. Interpolation was conducted with the ArcGIS v.10 and Spatial Analyst geographic information system (GIS) software applications. Interpolation was performed through Kriging, using a variable search distance (12 points) and a spherical semivariogram model. Interpolated results for average annual P, wettest month P, and average annual snowfall are shown in Figures 4, 5, and 6 respectively.

Following the interpolation of snowfall and P, the ratio of snow/P was calculated using the Raster Calculator in ArcGIS. This calculation assumed equivalent water content in the snow across all snow events. These results are shown in Figure 7.

2.2.2 Evapotranspiration (PET)

Temperature data from NCDC were downloaded for 294 stations in Colorado. Average annual reference evapotranspiration (ET_0 , hereafter referred to as PET)¹ values were calculated for 188 stations that had at least 10 complete years of temperature data. The Blaney-Criddle (B-C) equation was used to calculate PET using available temperature data from NCDC (Blaney and Criddle, 1950). The B-C formula used in this study (calculated for grass that is 8-15 cm high and receiving adequate water), is:

$$PET = p (0.46 T_{\text{mean}} + 8)$$

Where:

PET = Reference crop evapotranspiration (mm/day) as an average for a period of 1 month

T_{mean} = mean daily temperature (°C)

p = mean daily percentage of annual daytime hours

¹ ET_0 and potential evapotranspiration (PET) are terms which are often used interchangeably, although PET is a more general term and does not specify a particular crop type. The definition of ET_0 in this study is the rate of ET calculated for green grass, with an assumed height of 0.12 m, which is well watered and completely shades the ground as the reference crop (Allen et al., 1998). The term PET is used throughout this report to refer to ET_0 .

The values calculated at each station for average annual PET were used to interpolate PET for Colorado (Figure 8). Interpolation was conducted with the ArcGIS v.10 and Spatial Analyst GIS software applications. Interpolation was performed through Kriging, using a variable search distance (12 points) and a spherical semivariogram model.

Following the interpolation of P and PET, the ratio of P/PET was calculated using the Raster Calculator in ArcGIS. These results are shown in Figure 9.

2.2.3 Elevation

Elevation data (Figure 10) were extracted from the National Elevation Dataset at a resolution of 1/3 arc-second, projected to UTM Zone 13 North, and re-sampled to a resolution of 300m. No additional processing of the elevation data was required.

2.2.4 Supporting Data

The ecozone delineation process was primarily driven by spatial variability in P, PET, and elevation due to significant spatial variation in supporting datasets, including soils shown in Figure 11 (Soil Survey Staff, 2011) and land cover shown in Figure 12 (Homer et al., 2004). For example, the amount of soil variation within the relatively large extent of individual ecozones made it impractical to delineate based on soil characteristics; however, soil variation within the ecozones informed the selection of soil types during the subsequent modeling tasks.

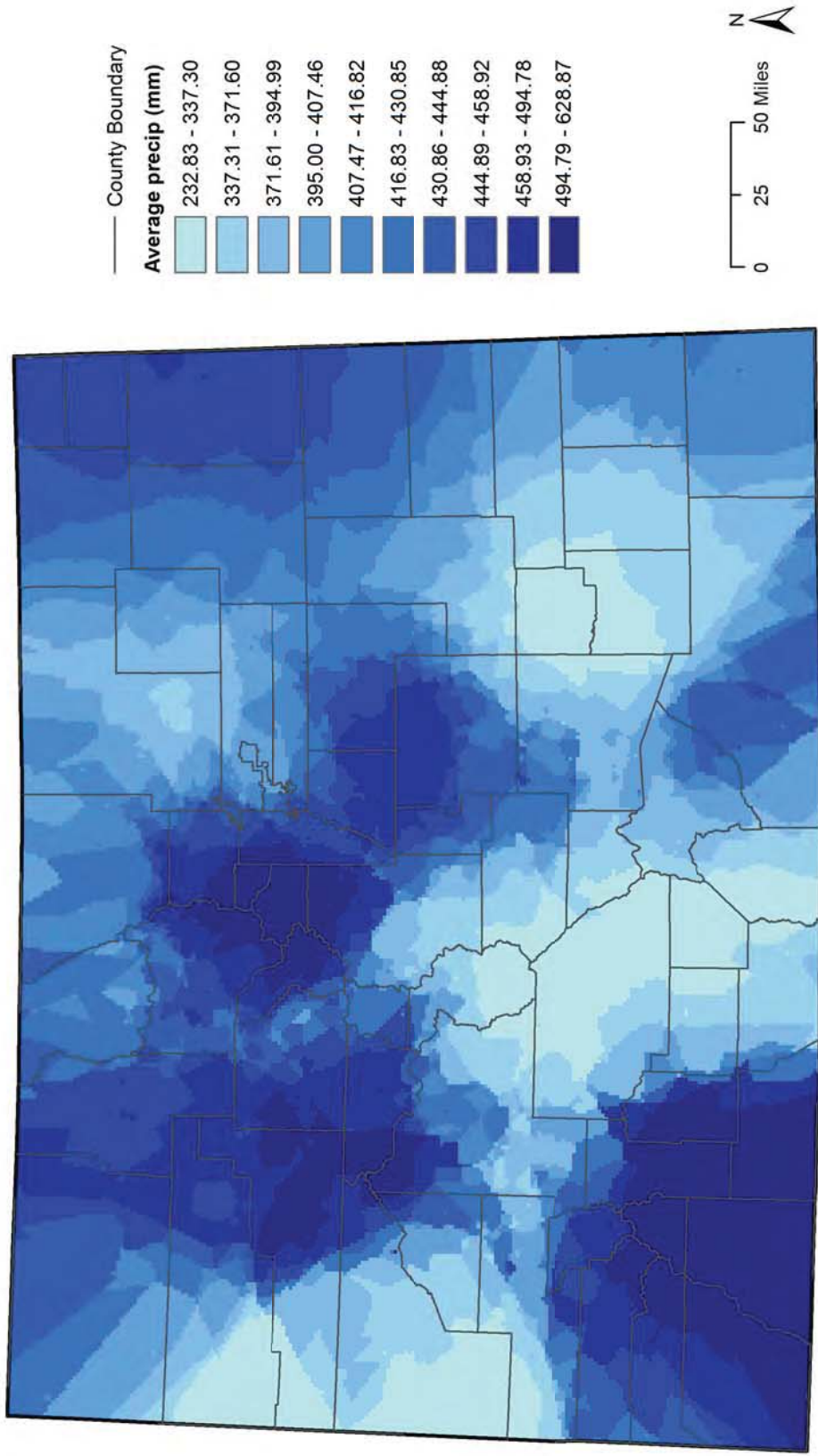


Figure 4. Average Annual Precipitation in Colorado (in mm of water and snow water equivalent)

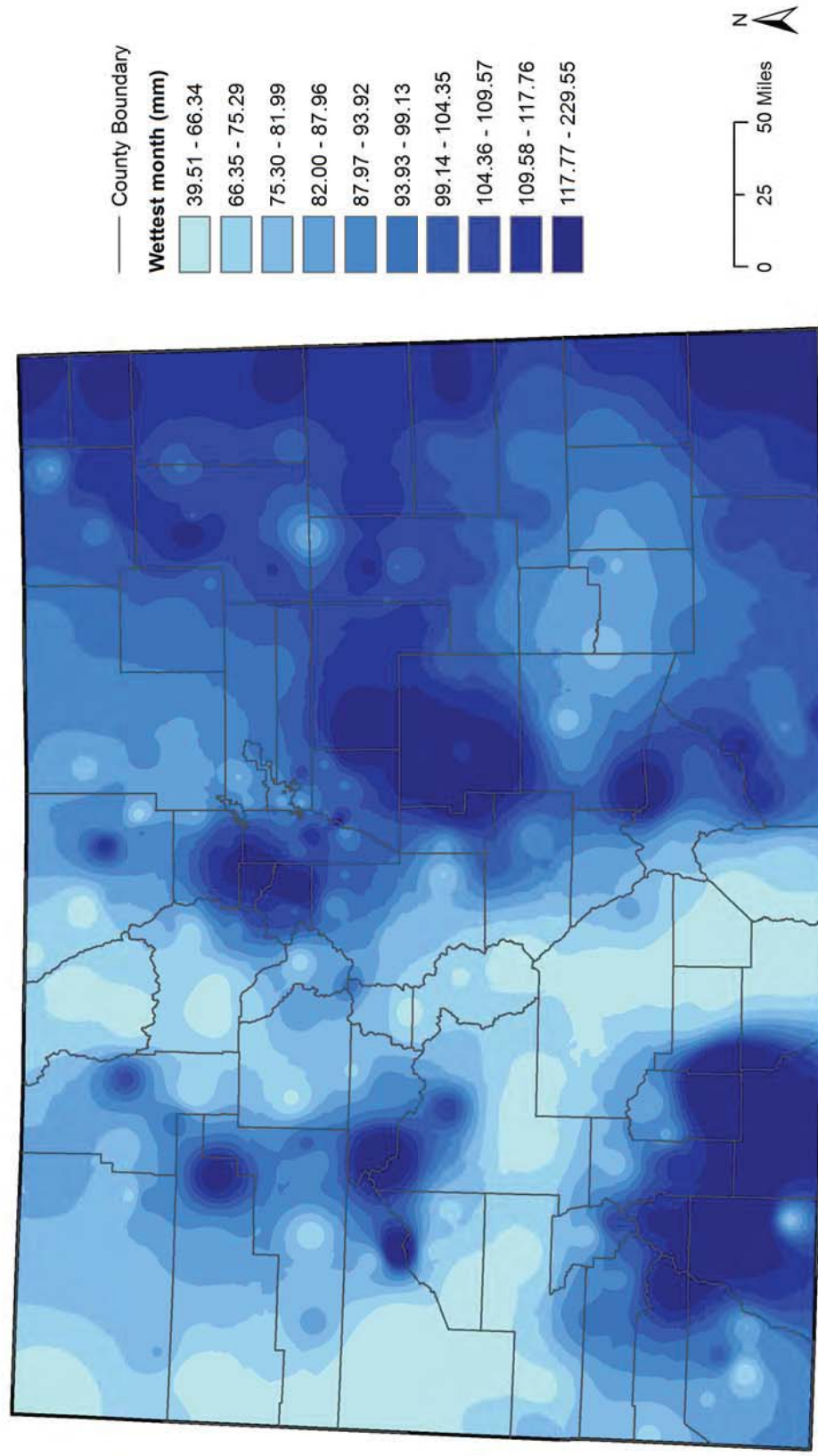


Figure 5. Average Annual Precipitation in Colorado in the Wettest Month of the Year (in mm)

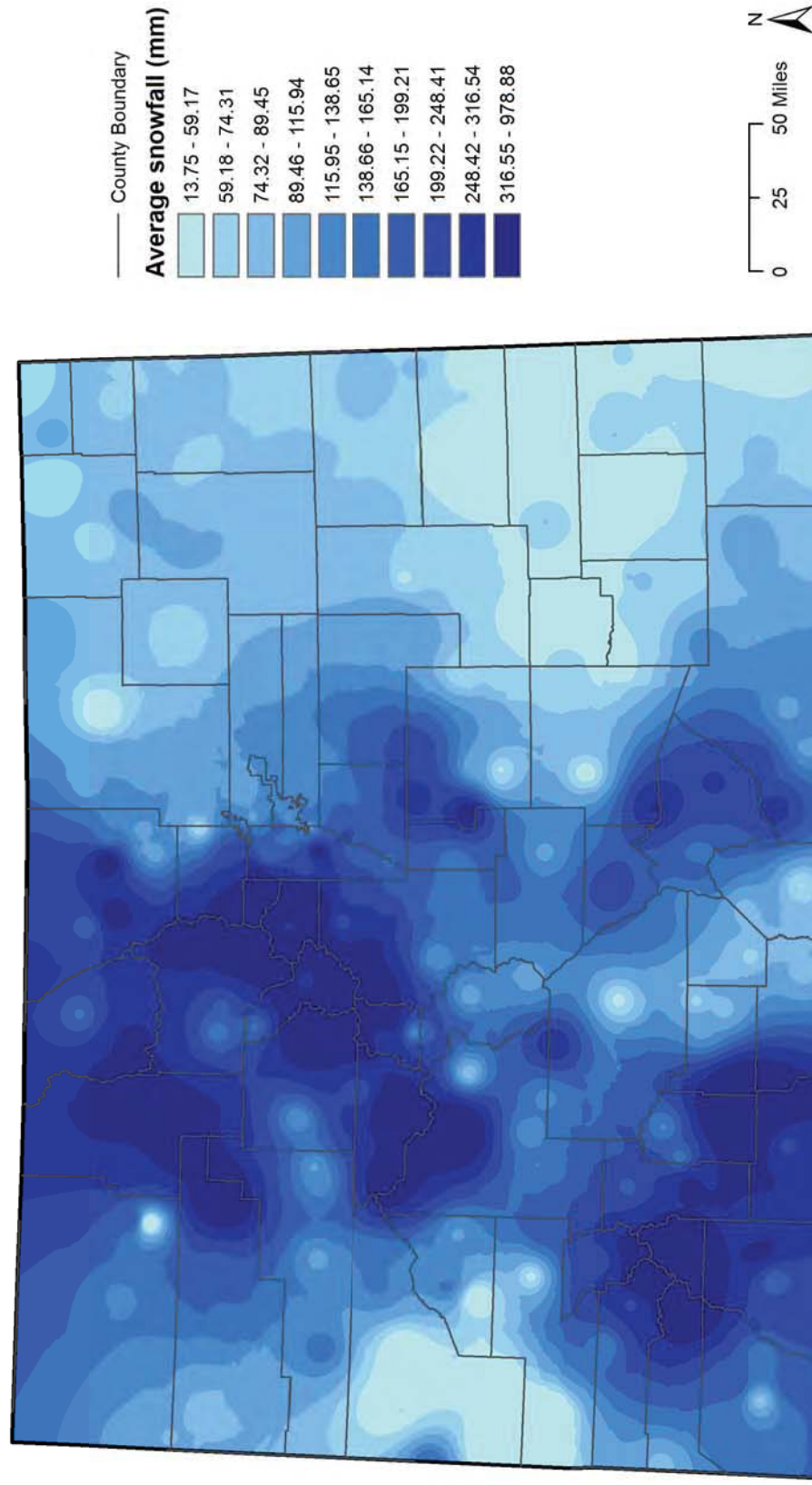


Figure 6. Average Annual Snowfall in Colorado (mm of snow)

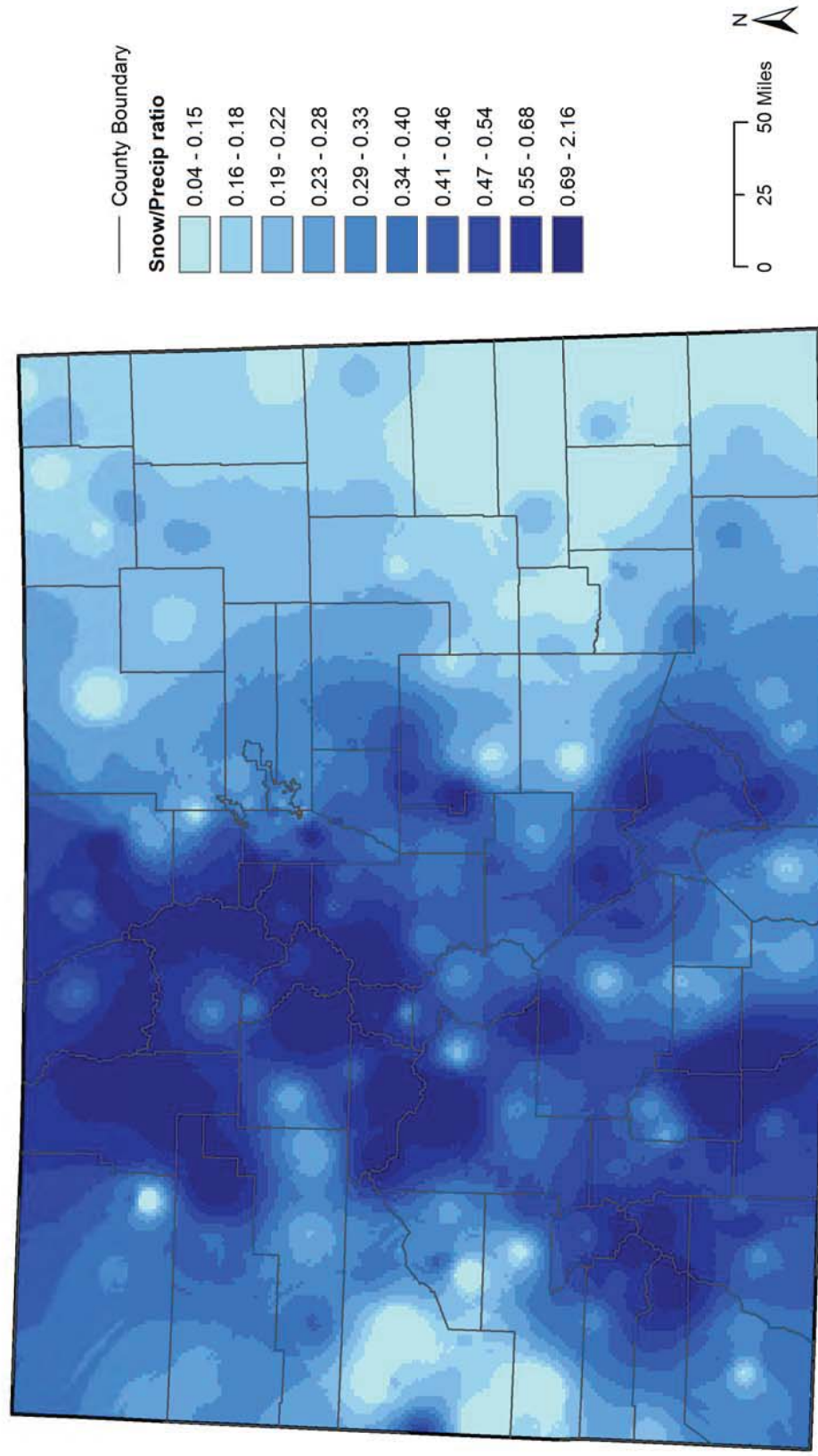


Figure 7. Ratio of Average Annual Snow (in mm) to Average Annual Precipitation (in mm) in Colorado

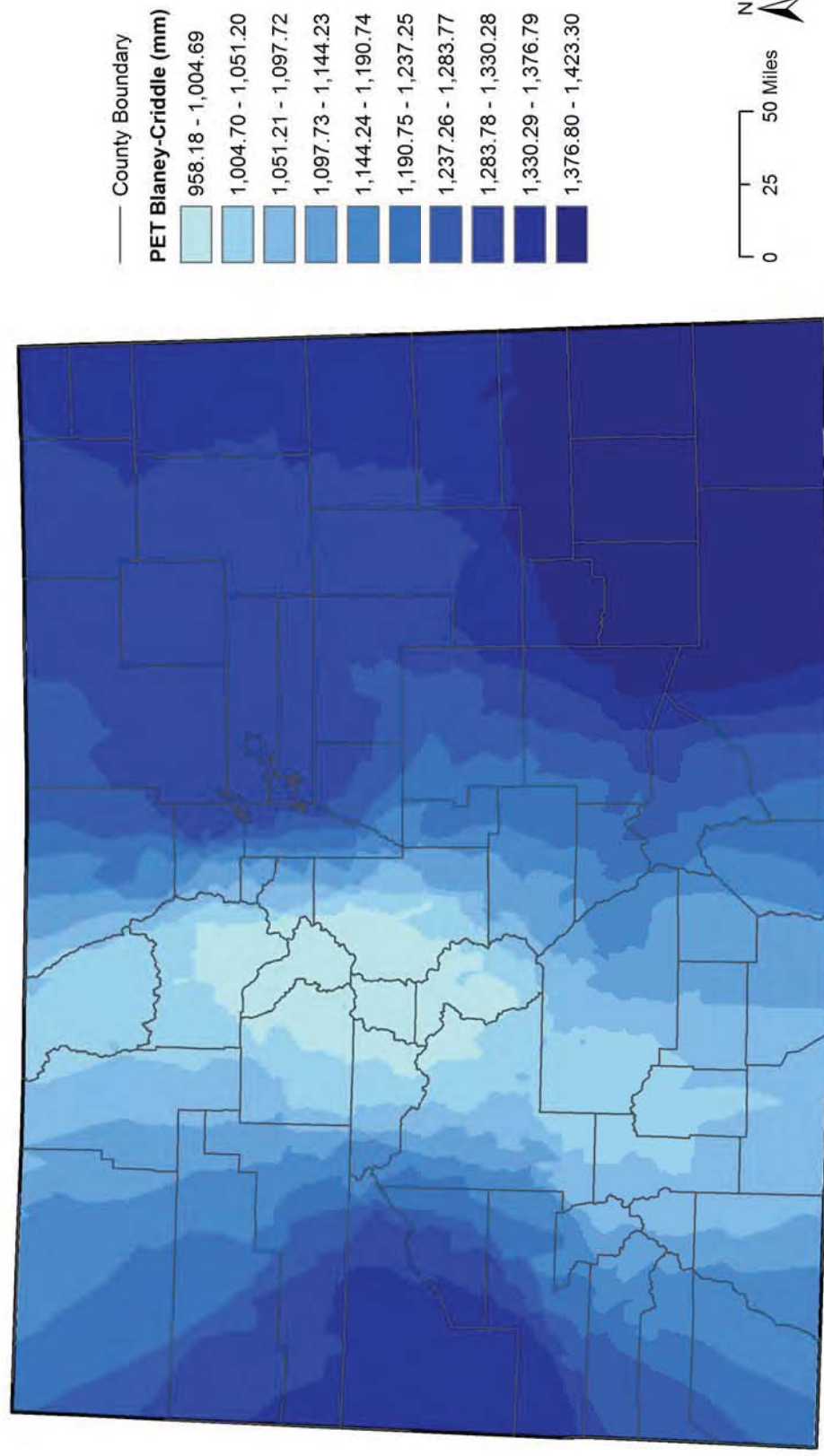


Figure 8. Average Annual Potential Evapotranspiration (Blaney-Criddle) in Colorado (in mm)
Evapotranspiration was calculated using measured temperature data from NCDC stations in the Blaney-Criddle Equation for calculating reference ET.

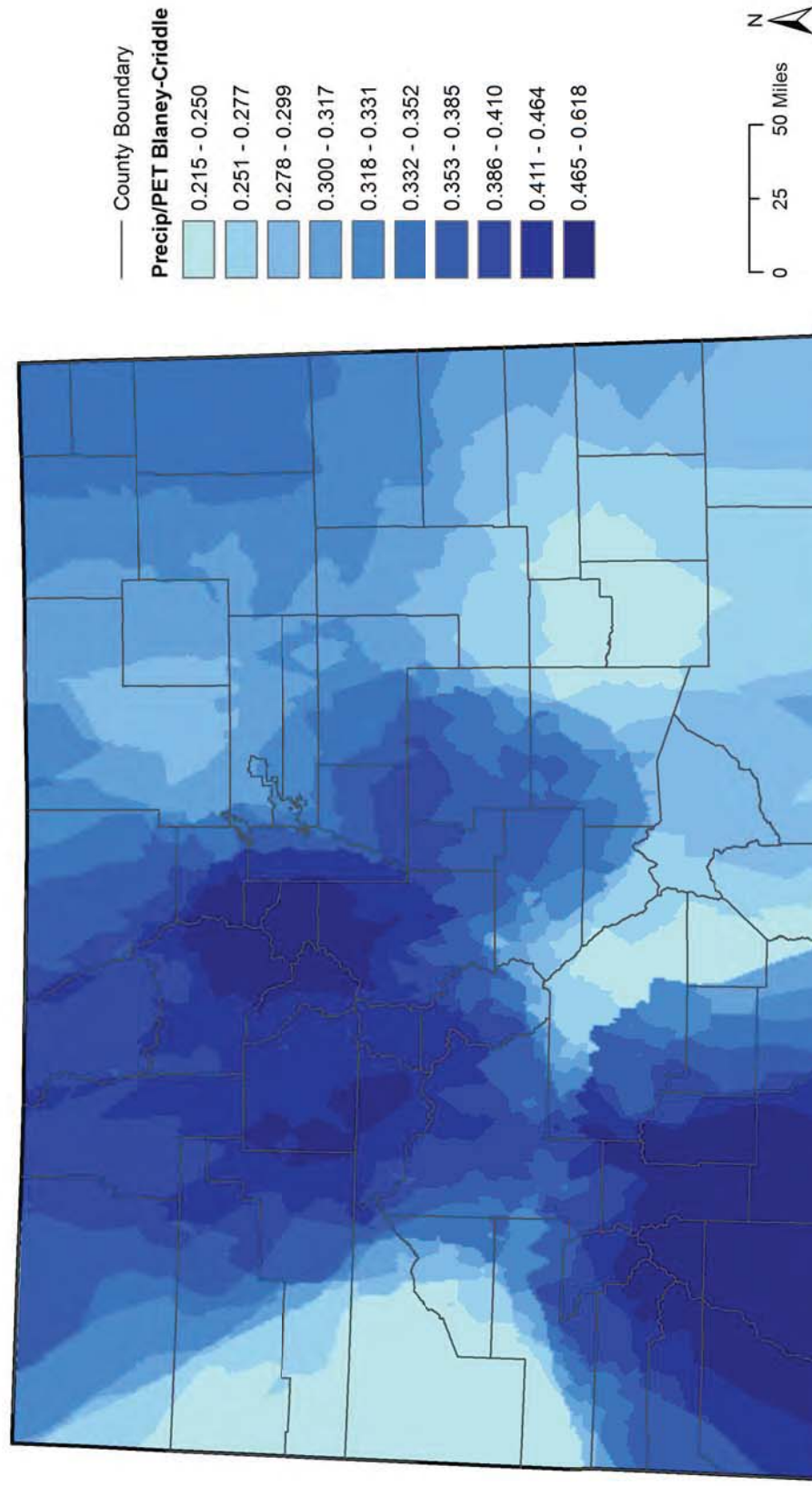


Figure 9. Ratio of Average Annual Precipitation to Average Annual Potential Evapotranspiration (Blaney-Criddle) in Colorado

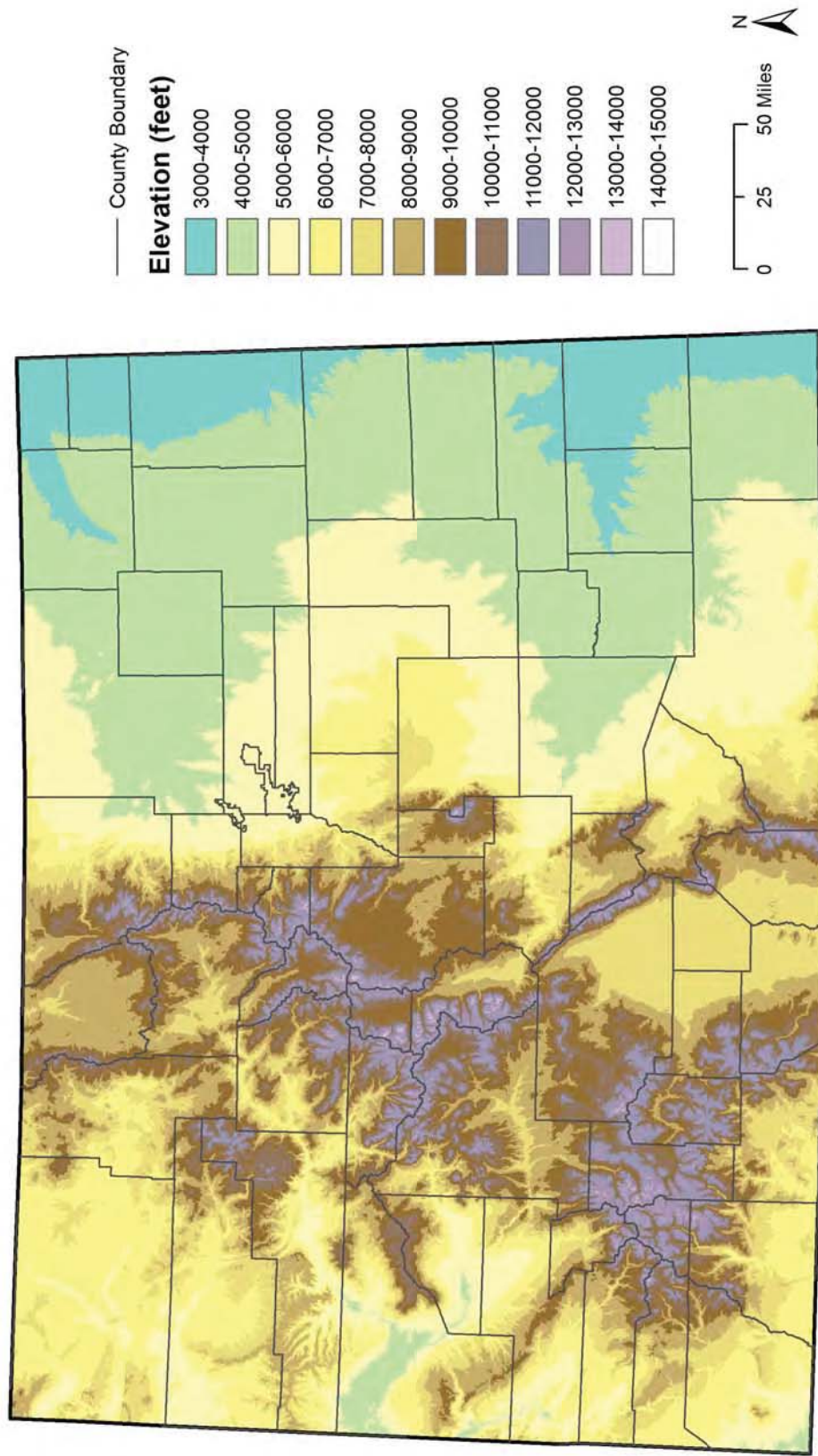


Figure 10. Elevation in Colorado (feet above mean sea level)

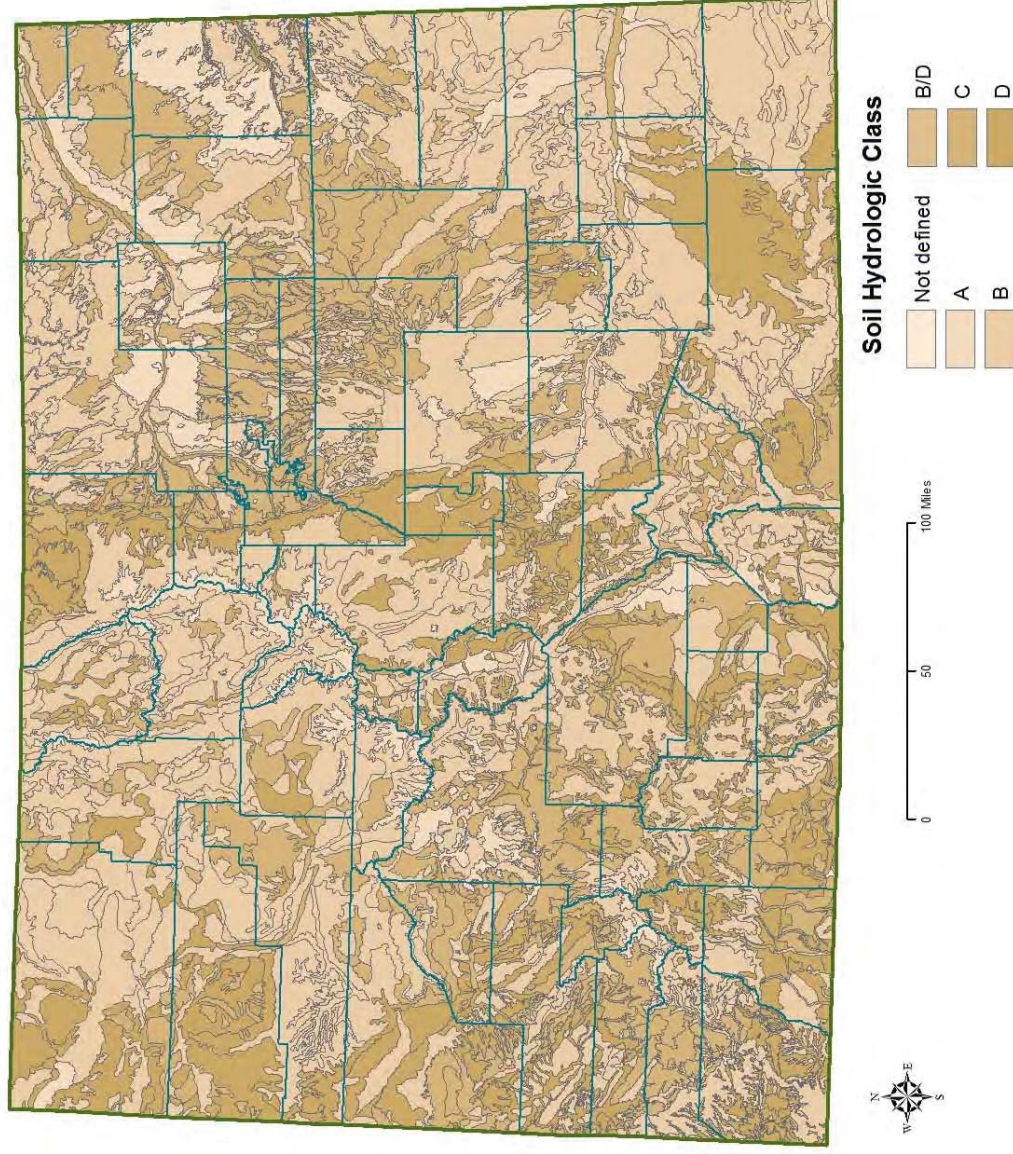


Figure 11. Soil Cover in Colorado

Hydrologic soil groups are a classification system used by the U.S. Natural Resources Conservation Service to describe soil infiltration rates. The soil classes include Category A (high infiltration rate), Category B (moderate infiltration rates), Category C (low infiltration rates), and Category D (very low infiltration rates). The classes shown on the map represent the predominant surficial soil characteristics.

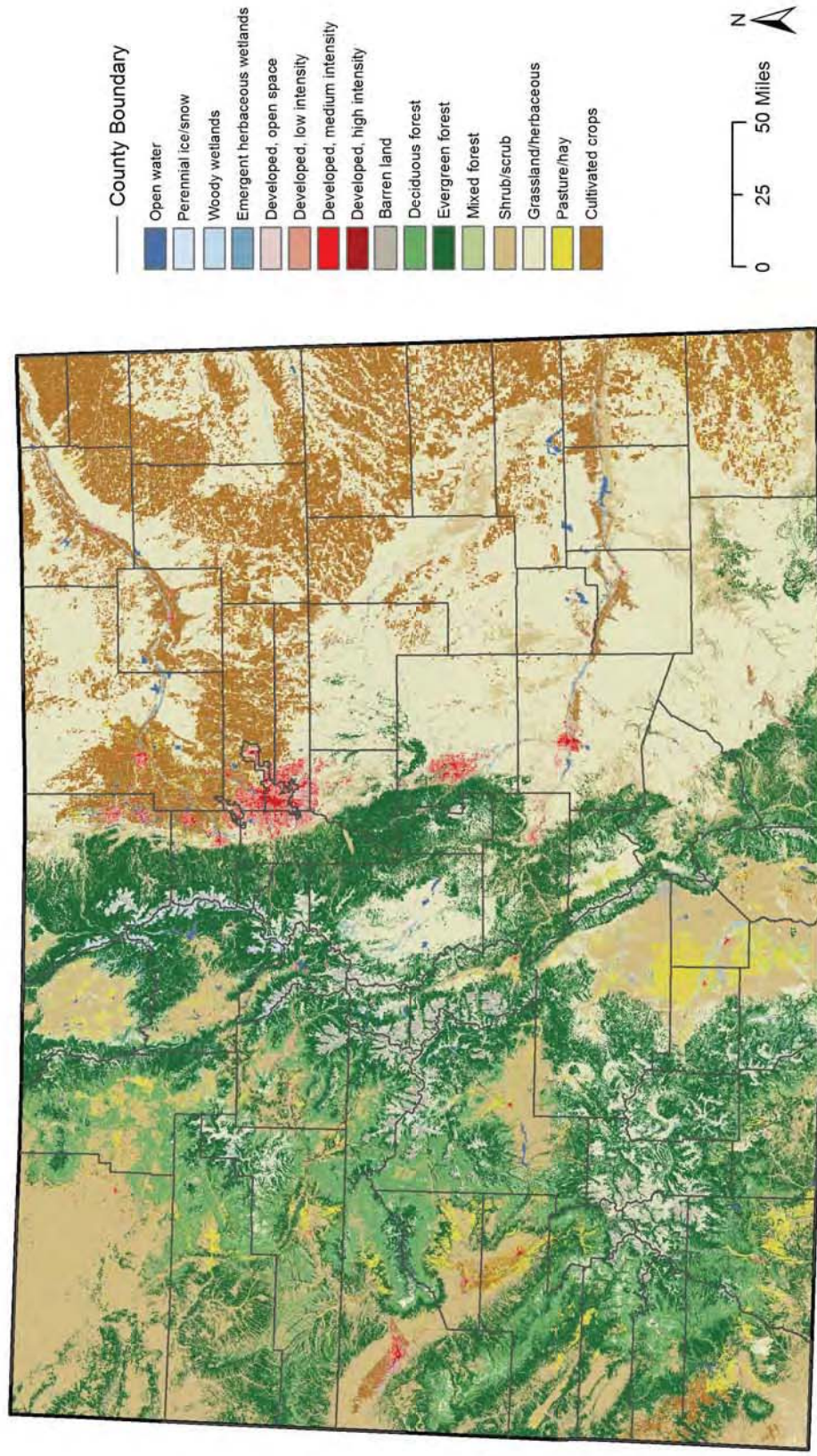


Figure 12. Land Cover in Colorado

2.3 Ecozone Boundary Determination

A comprehensive review of the Level III ecoregions, elevation data, and climate data, including an emphasis on the interpolated P/PET dataset, resulted in the development of five separate ecozones in Colorado. Based on population and landfill locations, the boundary between ecozones 3 and 4 was drawn along the 107 degree longitude line. The resulting ecozone boundaries with elevation (Figure 13) and the P/PET ratio (Figure 14) are presented below.

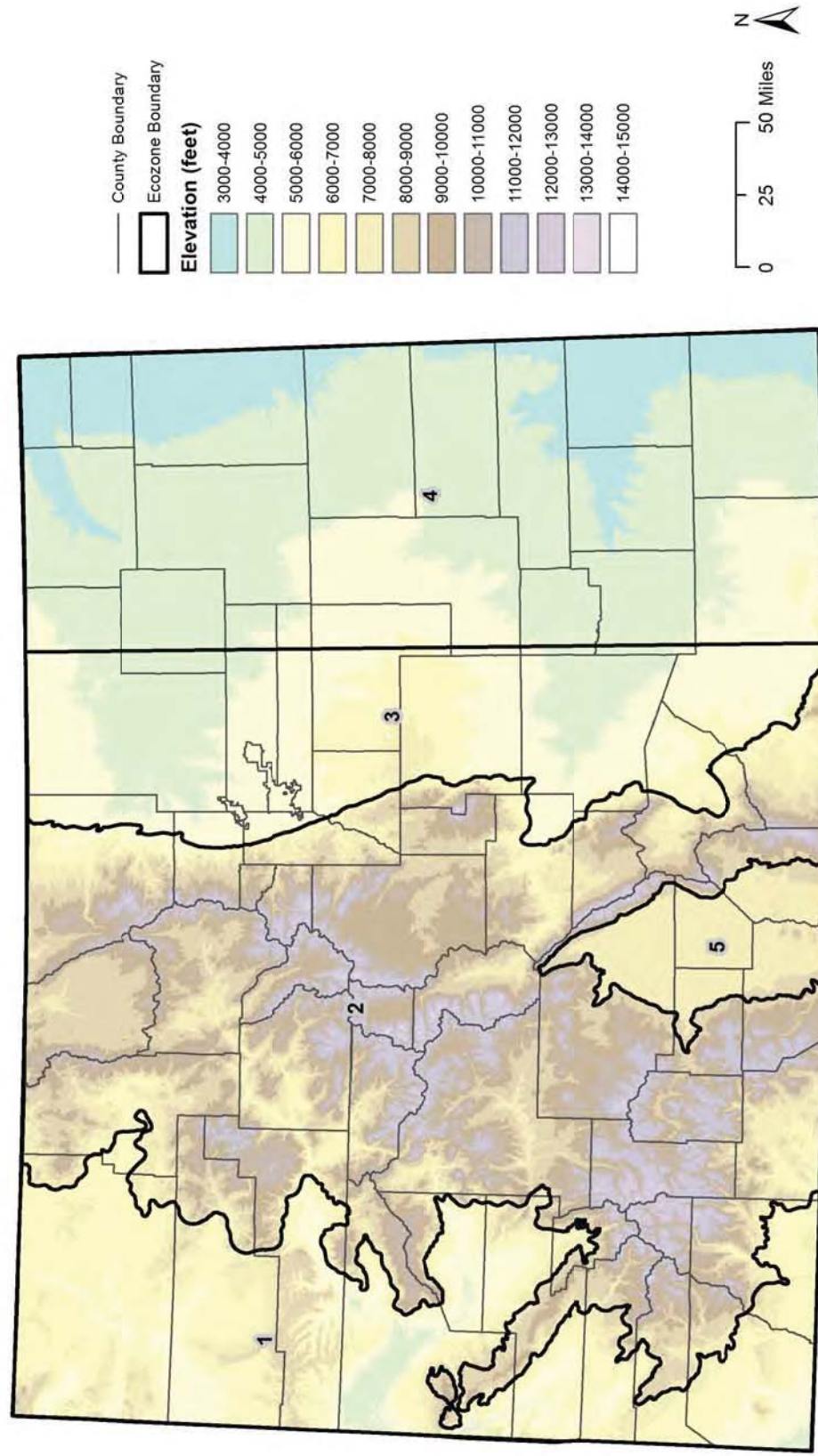


Figure 13. Final Colorado Ecozone Boundaries with Elevation

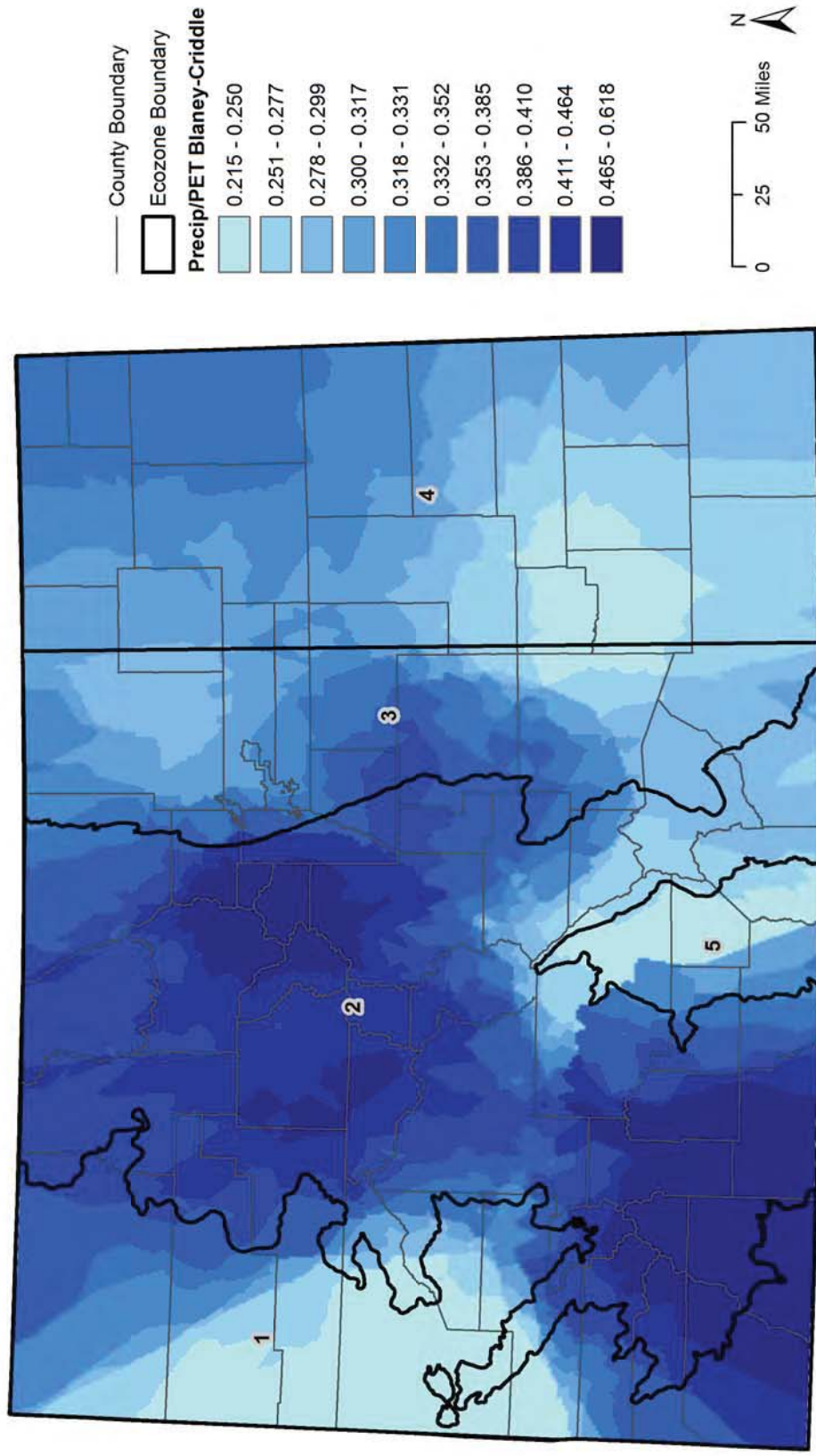


Figure 14. Ratio of Average Annual Precipitation to Average Annual PET in Colorado Ecozones

3. Modeling for Generic Water Balance Covers for Ecozones

Unlike conventional final covers, water balance cover designs do not have well-defined regulation-based requirements for materials and layer thicknesses (Albright et al., 2010). Instead, water balance cover designs are based on required performance, often defined as meeting a predetermined acceptable maximum annual percolation rate (Albright et al., 2010). Acceptable percolation rates, however, have not been formally established in many locations, including the state of Colorado. Furthermore, water balance covers may periodically allow for upward flow of water from the waste layer into the cover, reducing the amount of water collected by the leachate collection system. This section discusses percolation as ‘downward flux,’ which does not account for any upward water movement, and as ‘net percolation,’ which is the net movement of water between the cover and the underlying waste layer. To predict net percolation, the modeling approach described here includes a discussion on modeling water into (and out of) the waste layer.

In areas where acceptable percolation rates are defined, one modeling approach is to model iteratively for selected soil types, changing the thickness with every model run until the predefined percolation rate is achieved. The combinations of thickness and soil type that achieve the desired percolation rate may then be used in the design guidance. If an acceptable rate has not been defined, an alternative approach is to model a range of thicknesses for selected soil types and use the resulting percolation rates to determine a threshold for an acceptable cover thickness. This second approach provides percolation values for a range of cover thicknesses and soil types. In addition, the variation in percolation rates over a range of thicknesses may provide insights into the sensitivity of percolation rates to soil type and other parameters. This report presents modeling guidelines for the latter approach, using predefined thicknesses as model inputs. Other model inputs include climate data from a representative station within each ecozone, and soil and waste properties.

3.1 HYDRUS-1D Overview

Computer models can determine the expected performance of water balance covers. Suitable models take into account the movement of water within the soil profile and define appropriate upper and lower boundaries for the cover. The movement of water through the soil profile should be simulated in a rigorous manner and should include water lost to uptake by roots. To achieve this, the model should be based on a solution to Richards’ equation for unsaturated water flow (Richards, 1931). The surface boundary conditions should simulate the interactions at the soil-atmosphere interface (i.e., precipitation, infiltration, evaporation, runoff) and should be driven by user-provided climatic inputs. The lower boundary should account for the interactions that may occur between the cover and the waste. There are a number of flow models available that meet these criteria and may be used for water balance cover modeling, including LEACHM (1D)², UNSAT-H (1D)³, Vadose/W (1&2D)⁴, SVFLUX (1,2&3-D)⁵, and HYDRUS (1,2&3-D)⁶.

²Model available online at: http://www.flinders.edu.au/science_engineering/environment/our-school/staff-postgrads/academic-staff/hutson-john/leachm.cfm

³Model available online at: <http://hydrology.pnl.gov>

⁴Model available online at: <http://www.geo-slope.com>

⁵Model available online at: www.soilvision.com

⁶Model available online at: www.pc-progress.com

HYDRUS-1D, developed by Simunek et al. (1996) is one of the most widely used models for unsaturated flow and solute transport modeling. It is a finite element model that solves Richards' equation for unsaturated flow. It has options for non-isothermal liquid and vapor flow and heat transport. Constitutive relationships include van Genuchten and Brooks-Corey water retention functions. Information on soil texture can be used along with pedo-transfer functions to determine water retention and hydraulic conductivity parameters. The upper boundary condition includes standard constant pressure and constant flux conditions in addition to meteorological forcing. In the simulations presented in this study, a meteorological boundary condition was used as the upper boundary to simulate the interaction between the cover soil and the atmosphere. Options for the lower boundary condition include the unit gradient and seepage face. In this study, the unit gradient was used for the lower boundary.

Developed as a collaborative effort between the U.S. Salinity Laboratory and the University of California at Riverside, HYDRUS-1D is computationally efficient, well-supported, continually updated, and available free of charge. A graphical user interface can be used for data input and to view simulation results. The code has been used to solve a wide variety of problems, such as water balance modeling, recharge estimation, engineered cover performance, nitrate and pesticide leaching, and chlorinated hydrocarbon transport. For these reasons, and the modeler's experience, HYDRUS-1D was chosen to model water balance covers in this study.

3.3 Climate Data for Modeling

3.3.1 Representative Station Selection

The modeling effort requires daily P and PET data for one representative station per ecozone. Representative stations were chosen based on three criteria: the P statistics of the ecozone, the location of the station in the ecozone, and the length of the period of record at the station. Table 2 provides the P statistics for each ecozone, calculated from the raster interpolations of data from the stations.

Table 2. Ecozone Precipitation Statistics

Ecozone	Average Annual P (mm)	Average Wettest Month P (mm)
1	415	70
2	442	78
3	416	95
4	408	104
5	308	61

First, the top 4-5 stations whose values for average annual precipitation and average precipitation in the wettest month of a typical year most closely matched the ecozone-wide statistics were selected. Typical years may be defined as those with an annual P within $\frac{1}{2}$ standard deviation of the station average. Next, a subset of these stations that were located closer to the center of each ecozone was selected. Finally, if two or more selected stations had similar average values, the station with more years with complete P data coverage during the period of 1980 – 2010 was selected as the representative station for that ecozone.

Table 3 provides an overview of the selected representative stations, and Figure 15 shows a map of the selected stations.

Table 3. Overview of Representative Stations

Ecozone	Representative Station	Location (County)	Data Availability	Average Annual P (mm)	Average Typical Year Wettest Month P (mm)	Average Annual PET (mm)	Average Annual P/ PET
1	Paradox 1W and 2N	Montrose	1980-1995; 2005-2010	396	81	133	0.30
2	Sugarloaf Reservoir	Lake	1980-2010	433	81	926	0.53
3	Colorado Springs Muni AP	El Paso	1980-2010	423	114	1292	0.33
4	Flagler 1S	Kit Carson	1980-2010	424	118	1302	0.34
5	Del Norte 2E	Rio Grande	1980-2010	271 ⁷	70	1121	0.24

3.3.2 Missing Data

Some of the representative stations had incomplete daily P datasets, with data missing for individual days in a year. For these stations, missing values were replaced with simulated values. Simulated values were calculated using the mean and standard deviation of all P events for the same day of the year from other years for which data were available. The specific values to replace the missing ones were selected randomly from a normal distribution. All non-positive values were recorded as zero P for that date.

⁷ This value is 37 mm below the ecozone-wide average for Ecozone 5 (Table 2). The interpolated precipitation values used to calculate the ecozone-wide statistics were higher than observations recorded at individual monitoring stations likely due to the influence of the neighboring mountainous region. Del Norte was selected as the representative station because it had the highest average annual precipitation (i.e. closest to the calculated average value) for all stations in Ecozone 5.

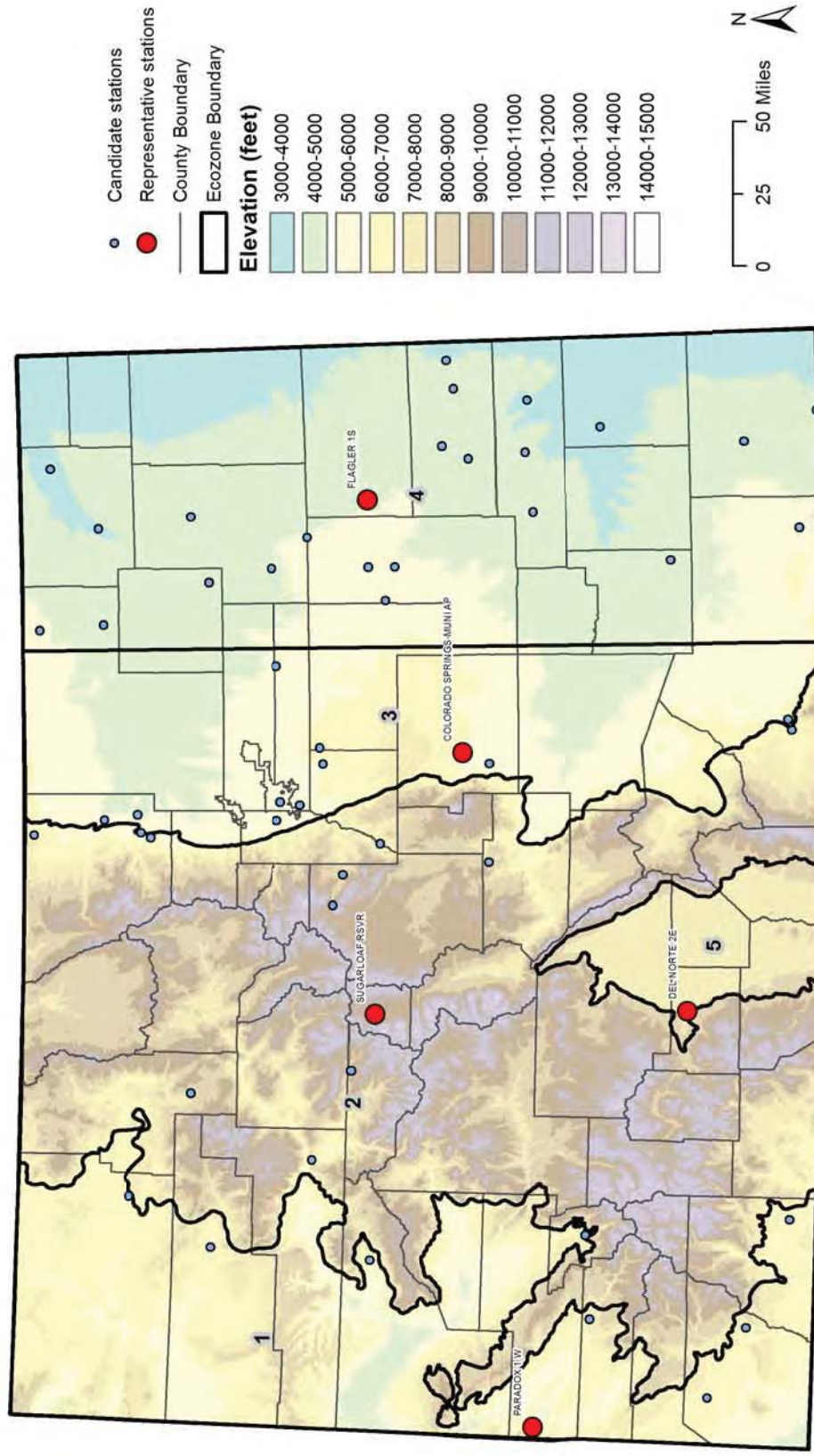


Figure 13. Map of Representative Stations

Candidate stations had an average annual precipitation value within 25.4 mm (or 1 inch) of the ecozone average (shown in Table 2).

3.4 Design Year and Initial Conditions

Previous research studies in arid and semi-arid climates recommend using data from the wettest 10 year period on record for developing a water balance cover design (Benson and Khire 1995; Khire et al., 1997). Other studies simulate consecutive years of either average climatic data or climatic data from the wettest year on record (Winkler, 1999). Albright et al. (2010), recommend selecting the year with the highest P/PET ratio as the design year based on the results of a study by Apiwantragoon (2007) which suggests that the P/PET ratio is the best metric for determining when water will accumulate in the soil.

For this study, the design year for all simulations was chosen as the year with the highest P/PET ratio. Using the maximum P/PET ratio is a conservative approach because the conditions modeled represent the highest potential quantity of water accumulation. Table 4 shows the selected design year for each ecozones, including P, PET, and their ratio. The design year for ecozone 1 is 1983. For ecozones 2 and 4, 1995 was selected. For ecozone 3, 1999 was selected, and 1985 was selected for ecozone 5. The lowest P/PET ratio was 0.38 (ecozone 1), and the highest was 0.73 (ecozone 2).

Table 4. Design Year P and PET Data for Representative Stations

Ecozone	Representative Station	Design Year	Design Annual P (mm)	Design Annual PET (mm)	Design Annual P/ PET
1	Paradox 1W and 2N	1983	488	1274	0.38
2	Sugarloaf Reservoir	1995	676	923	0.73
3	Colorado Springs Muni AP	1999	701	1303	0.54
4	Flagler 1S	1995	694	1305	0.53
5	Del Norte 2E	1985	507	1155	0.44

In addition to the P/PET ratio, the amount of water that needs to be stored (S_r) was calculated for each ecozone in accordance with Albright et al. (2010). This parameter is a good index of the amount of water that needs to be stored by the soil cover, and it was calculated as follows:

$$S_r = \sum_{m=1}^6 \{ (P_m - \beta_{FW} PET_m) - \Lambda_{FW} \} + \sum_{m=1}^6 \{ (P_m - \beta_{SS} PET_m) - \Lambda_{SS} \}$$

Fall-Winter Months Spring-Summer Months

Where:

- P_m = monthly precipitation
- PET_m = monthly PET
- β_{FW} = ET/PET in fall-winter
- β_{SS} = ET/PET in spring-summer
- Λ_{FW} = runoff & other losses in fall-winter
- Λ_{SS} = runoff & other losses in spring-summer

Note that only the months where the threshold of (P/PET) is exceeded are summed in the calculation of S_r (Albright et al., 2010). These thresholds are shown for two types of climates in Table 5.

Table 5. P/PET Ratio by Climate Type and Season

Climate Type	Season	Threshold
No Snow & Frozen Ground	Fall-Winter	P/PET > 0.34
	Spring-Summer	P/PET > 0.97
Snow & Frozen Ground	Fall-Winter	P/PET > 0.51
	Spring-Summer	P/PET > 0.32

Two sets of β and Λ parameters, fall-winter and spring-summer, are assigned for a given climate type (Albright et al., 2010) (Table 6). All ecozones were assigned a “Snow and Frozen Ground” climate type.

Table 6. ET/PET Ratio and Runoff and other losses parameters by Climate Type and Season

Climate Type	Season	β (-)	Λ (mm)
No Snow & Frozen Ground	Fall-Winter	0.30	27.1
	Spring-Summer	1.00	167.8
Snow & Frozen Ground	Fall-Winter	0.37	-8.9
	Spring-Summer	1.00	167.8

Table 7. Summary of Climatic Conditions in Each Ecozone

Ecozone	S_r (mm)
1	84
2	326
3	340
4	275
5	71

The S_r values calculated for each ecozone are presented in Table 7. Ecozones 1 and 5 have the lowest values for S_r as well as low P/PET values, which is an early indication that thicker water balance covers in these two ecozones may not be necessary. The high S_r and P/PET values for ecozones 2 and 3 indicate the need for additional care when designing water balance covers and suggest that thicker covers may be required to achieve low percolation rates.

The solution of Richard’s equation requires the specification of initial condition $\theta(z, t=0)$. The initial water content of the entire soil and waste profile layers was assumed to be 0.20. This is a somewhat arbitrary set of values that may have an effect on the model output. Thus, to eliminate the effect of the initial conditions on the modeling results, each simulation was conducted for 20 consecutive years of the design year. Only the results of the 20th year are reported as the long term performance of each cover design.

3.5 Cover Geometries

Monolithic covers were simulated in this study in which uniform soil is placed directly over the waste. Soil thicknesses of 2.5, 3, 3.5, and 4.0 feet were simulated for each of the five ecozones. Each of these covers was modeled with seven representative soil types, each with different properties to cover a range of cover designs. The waste within the landfill also has the ability to transmit water, both downward and upward back into the soil when hydraulic conditions permit. Therefore, a layer of 10 feet of waste below each soil cover design was simulated in the model. Fluxes were calculated at the boundary between the cover soil and the waste.

3.6 Soil and Waste Properties

3.6.1 Soil Hydraulic Properties

Required soil-related model input parameters for HYDRUS-1D include saturated hydraulic conductivity (K_s), residual water content (θ_r), saturated water content (θ_s) (equivalent to soil porosity), and a series of parameters (α , m , n and l) used in the van Genuchten and Mualem functions that describe the functional relationship between soil moisture, matric potential, and unsaturated conductivity. Each of these is an empirical constant; α is inversely related to the air-entry pressure value, m and n are related to the pore-size distribution, and l is a pore interaction term that describes connectivity. In HYDRUS-1D, unsaturated hydraulic functions are based on a combination of the van Genuchten (1980) function with the Mualem (1976) pore-size distribution model. Some research on the conductivity parameter (l) suggests that a value of $l = -2$, suggested by Burdine (1953), fits data reasonably well and is conservative for storage cover design (Albright *et al.*, 2010).

Soil data for the entire state of Colorado were obtained from the Soil Survey Geographic (SSURGO) Database. The SSURGO database is linked to a National Soil Information System (NASIS) attributes database, which provides the proportionate extent of component soils and properties for polygonal units known as map units. Each map unit consists of 1 to 3 soil components identified by the taxonomic classification listed in SSURGO. SSURGO map units were compared to the ecozone boundaries in GIS software application ArcGIS v.10 to tabulate the total area of each map unit in each ecozone. The map unit areas were multiplied by the component proportions to determine the total area covered by each soil component in each map unit. These areas were then summed to determine the total area of each component within each ecozone.

Based on the above analysis, the most commonly observed soil components in each ecozone were identified from the SSURGO soils database. An official soil description report, titled the National Cooperative Soil Survey report, was obtained from the same database for each identified soil component. This report was then used to determine the predominant USDA soil textures within the ecozone. Soil textures, along with the areal extent of each soil type, were used to develop vertices (points) on the USDA soil textural triangle. Vertices were first determined for each ecozone, then merged to form a single set of vertices that could be applied to all 5 ecozones. The results of this analysis are shown in Figure 16. These points represent likely soil types that may be encountered in the Colorado ecozones and that potentially could be used as cover material. A total of 7 vertices, which represent 7 soil types, were obtained.

Soil-related model input parameters were estimated for the vertices shown in Figure 16, using the Rosetta program built into HYDRUS-1D (Schaap et al., 2001). Rosetta employs hierarchical pedotransfer functions to obtain unsaturated hydraulic conductivity parameter inputs (Table 8) using either soil particle-size distribution and bulk density or soil textural class alone.

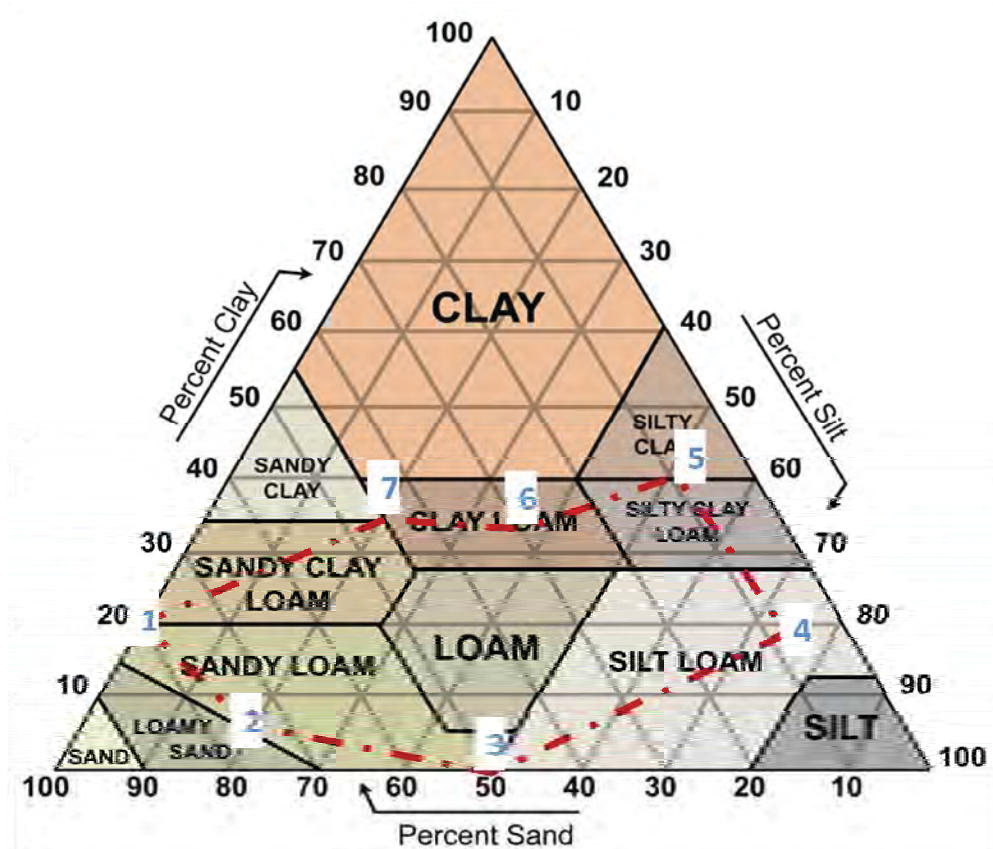


Figure 14. Summary of Location of the Seven Selected Soils on USDA Chart

Table 8. Summary of Rosetta Estimated Soil Parameters

Soil Type	% clay	% sand	% silt	θ_r	θ_s	α	n (1/cm)	K_s (cm/day)	K_s (cm/sec)
Soil 1	20	80	0	0.0662	0.3642	0.0224	1.4545	25.74	2.98E-04
Soil 2	5	75	20	0.0354	0.3894	0.0424	1.5315	72.76	8.42E-04
Soil 3	0	50	50	0.0247	0.4385	0.0135	1.5012	95.23	1.10E-03
Soil 4	18	8	74	0.0726	0.4566	0.0057	1.6341	15.47	1.79E-04
Soil 5	40	10	50	0.0967	0.4892	0.0111	1.425	13.3	1.54E-04
Soil 6	35	30	35	0.0841	0.4435	0.0129	1.3892	7.58	8.77E-05
Soil 7	35	45	20	0.0797	0.4132	0.0225	1.2918	6.86	7.94E-05

The ability of a soil to retain water is defined as the unit soil water storage capacity. The unit soil water storage capacity for a specific soil is determined by the difference between field capacity and wilting point. Field capacity is the amount of soil moisture or water content held in soil after excess water has drained away and is defined as the water content at a suction of 330 cm of

water. The wilting point is defined as the minimal point of soil moisture the plant requires not to wilt and defined as the water content at a suction of 150,000 cm of water.

The field capacity, wilting point, and unit soil water storage capacity were calculated for each soil using the van Genuchten function:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = (1 + (\alpha \psi)^n)^{-m}$$

Where:

θ_r = residual water content

θ_s = saturated water content

α = Curve fitting parameter related to air entry suction

ψ = matric potential

m, n = Curve fitting parameters related to pore-size distribution

Table 9 shows the field capacity, wilting point, and the unit soil water storage capacity of the seven soils selected for the modeling task. Soil 2 has the lowest unit soil water storage capacity (0.07 cm³ of water per cm³ of soil), and Soil 4 has the highest (0.20 cm³ of water per cm³ of soil). Data in Table 9 indicate that, according to the unit soil water storage capacity, simulations with Soil 1 and Soil 2 should result in higher percolation rates, especially for ecozone 2 and ecozone 3 (i.e., for ecozones with High P/PET ratio and high S_r).

Table 9. Field Capacity, Wilting Point, and Unit Soil Water Storage Capacity for all Selected Soils

	Field Capacity cm ³ water/cm ³ soil	Wilting Point cm ³ water/cm ³ soil	Unit Storage Capacity cm ³ water/cm ³ soil
Soil 1	0.18	0.09	0.09
Soil 2	0.12	0.05	0.07
Soil 3	0.21	0.05	0.16
Soil 4	0.30	0.10	0.20
Soil 5	0.31	0.14	0.17
Soil 6	0.28	0.13	0.15
Soil 7	0.26	0.14	0.12

3.6.2 Waste Properties

The van Genuchten parameters determined for the soil moisture characteristic curve are also required for the waste layer. To determine appropriate values for this study, a review of saturated hydraulic conductivity of waste from previous laboratory studies was completed. For layers of municipal solid waste (MSW) just below the cover, a saturated hydraulic conductivity that is on the high end of the reported values was selected (1×10^{-3} cm/sec (86.4 cm/day)) because the top of layer of waste tends to have the lowest density.

Korfiatis et al. (1984), Benson and Wang (1998), Jang et al. (2002), Kazimoglu et al. (2006), and Stoltz and Gourc (2007) report water retention curve (WRC) data for MSW. Korfiatis et al. (1984) used tensiometers inserted in multiple specimens prepared to the same dry unit weight and different water contents to produce waste parameters. Benson and Wang (1998), Jang et al. (2002), Kazimoglu et al. (2006), and Stoltz and Gourc (2007) used the pressure plate extraction (e.g., ASTM D 6836V Method B) method to measure waste parameters. Han et al. (2011) used a specially designed pressure plate apparatus to measure the WRC and $K(\theta)$ of shredded newsprint. Among the range of parameters for the waste in readily-available reports, parameters for van Genuchten WRC measured by Kazimoglu et al. (2006) produced an intermediate percolation rate and were used in this modeling study. Parameter values used for the waste are summarized in Table 10.

Table 10. Summary of Unsaturated Parameters of Waste Layer

	θ_r	θ_s	α	n (1/cm)	K_s (cm/day)	K_s (cm/sec)
Waste	0.17	0.58	0.065	1.95	86.4	1.00E-03

3.8 Potential Evapotranspiration (PET), Potential Evaporation (PE) and Potential Transpiration (PT)

HYDRUS-1D requires separate values for potential transpiration (PT) and potential evaporation (PE) for the atmospheric boundary conditions. The model calculates values of transpiration and evaporation based on the availability of water in the soil profile. Leaf Area Index (LAI) estimates are used to partition PET into Potential Transpiration (PT) and Potential Evaporation (PE) using the following formula known as the Ankeny Function:

$$PT = 0.52 \times PET \times \sqrt{LAI}$$

LAI is defined as the ratio of leaf surface area to the soil surface area. In most cases, only maximum seasonal LAI are reported (since daily LAI data were unavailable) along with root length density and the length of the growing season (Allen et al., 1996). However, for most plants, LAI is very small at the beginning of the growing season and increases exponentially during the early growing season. After reaching a maximum value, the LAI decreases and approaches zero towards the end of the growing season. Maximum LAI and leaf duration are reduced by environmental stresses such as temperature and lack of water or nutrients. However, the effects of such stresses were not considered in the reported values of LAI. While LAI values are reported for a number of vegetation types, “grass” and “shrubs and grass” were the only two options considered for vegetating water balance covers. It was also assumed that LAI and Root Density are similar for both vegetation scenarios. The root density was assumed to vary from 1.0 at the top of the cover to zero at the bottom of the cover.

LAI estimates for grass were obtained by the method described by Allen et al. (1996) as follows:

$$\text{Average LAI} = 0.5 \times \text{LAI}_{(\text{max})}, \text{ for grass}$$

Allen et al. (1989) approximated LAI (max):

$$LAI = 5.5 + 1.5 \times \ln(h)$$

where h is height and must be greater than 0.03 m. The LAI (max) for grass with an average height of 0.30 m is 3.6 and the associated average LAI is 1.8. Figure 17 shows the assumed variation of LAI during the year.

To determine seasonal LAI values, the growing season must first be defined. For ecozones 1, 3, 4, and 5, the growing season was determined to last from March 15th to November 15th. LAI was assumed to increase linearly from zero on March 15th to a maximum value of 1.8 on May 15th. LAI then remains constant for four months (until September 15th), before decreasing linearly to reach zero on November 15th. For mountainous ecozone 2, the growing season is shorter because of more extreme climatic conditions, and was determined to start May 15th to September 15th (Sievering et al., 1992). LAI for ecozone 2 is assumed to reach the maximum of 1.8 on June 15th (Figure 17). LAI remains at 1.8 until August 15th, and then decreases linearly to zero on September 15th. During the non-growing season months, it was assumed that transpiration was not occurring and that all water losses were due to evaporation. The root density function was considered to vary linearly with depth (from fully rooted at the top of the soil profile to zero roots at the bottom of the cover). It was assumed that this root distribution is reasonable for modeling purposes.

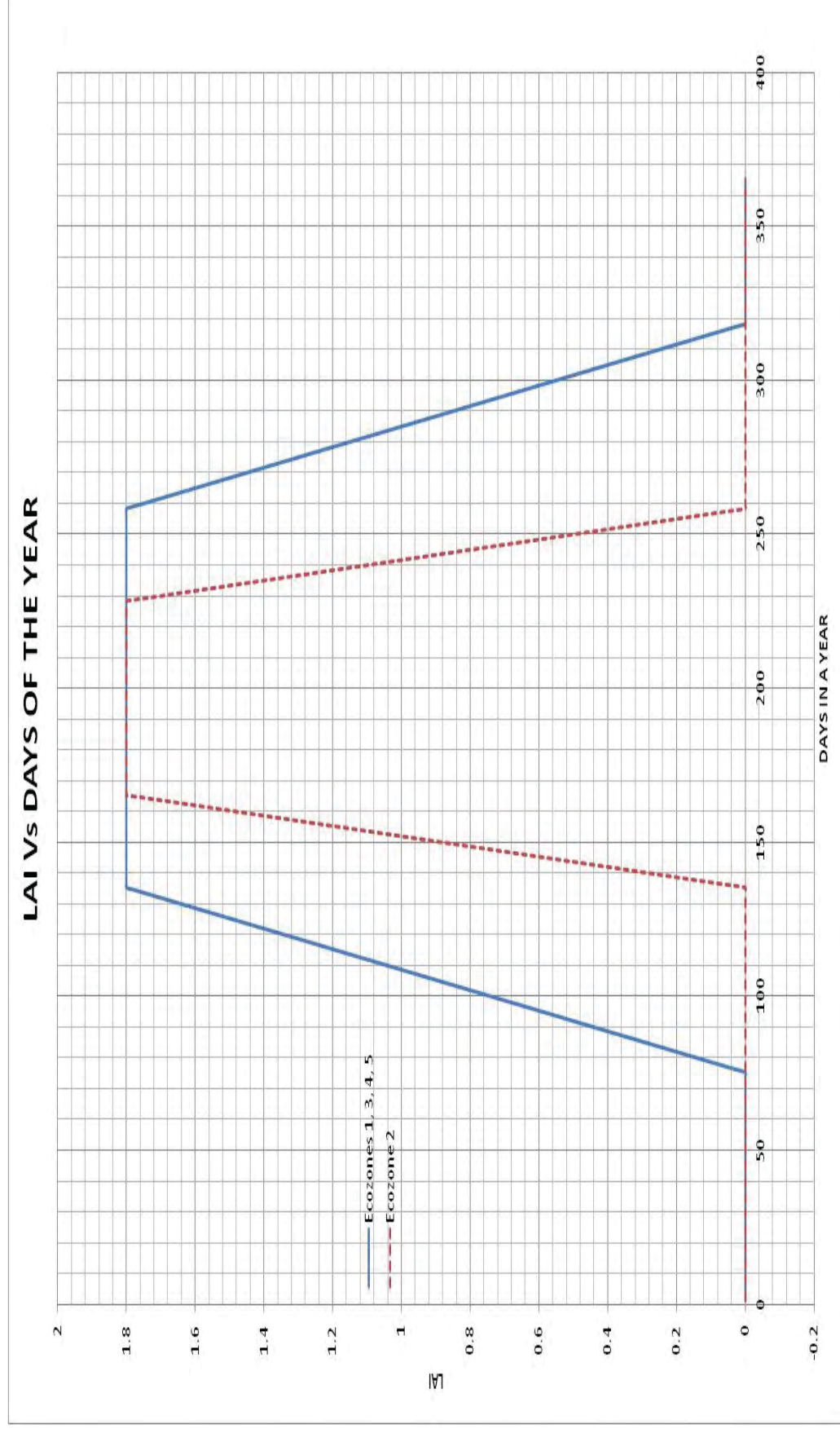


Figure 15. Daily Variation of LAI During an Example Design Year for Ecozones 1, 2, 3, 4, and 5

3.9 Plant Uptake Limitations

HYDRUS-1D calculates actual evaporation and transpiration from the PET using Root Water Uptake Models. The model option developed by Feddes et al. (1978) was used. In the Feddes et al. approach, water uptake is assumed to be zero when the soil is close to saturation (i.e., wetter than some arbitrary point, h_1). Root water uptake is also zero for pressure heads less than the Wilting Point (h_4). Water uptake is considered optimal between pressure heads h_2 and h_3 (Figure 18a), whereas for pressure heads between h_3 and h_4 (or h_1 and h_2) water uptake decreases (or increases) linearly with pressure head. Water uptake parameters for grass using the Feddes et al. (1978) model are presented in Table 11.

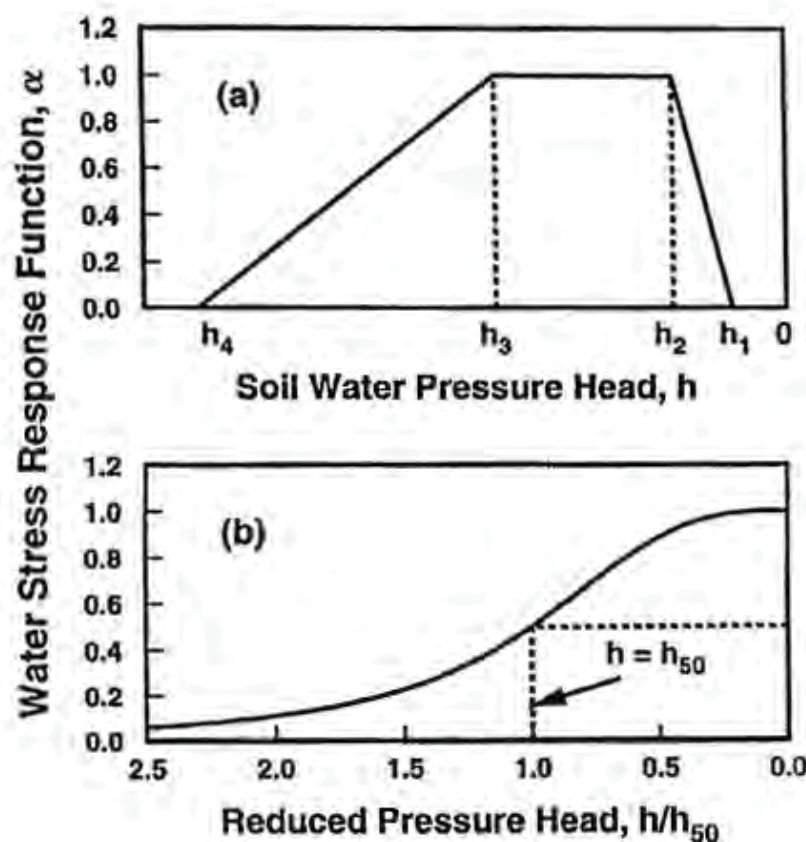


Figure 16. Schematic of the plant water stress response function, α , as used by a) Feddes et al. (1978) and b) van Genuchten (1985).

Table 11. Water Uptake parameters for Grass using Feddes et al. (1978) model

Symbol	Definition	Grass Value
h_1	Value of the soil water pressure head below which roots start to extract water from the soil.	-10 cm

Symbol	Definition	Grass Value
h_2	Value of the soil water pressure head below which roots extract water at the maximum possible rate.	-25 cm
h_{3H}	Value of the limiting soil water pressure head, below which roots cannot longer extract water at the maximum rate (assuming a potential transpiration rate of r_{2H}).	-300 cm
h_{3L}	As above, but for a potential transpiration rate of r_{2L} .	-1000 cm
h_4	Soil water pressure head below which root water uptake ceases (taken at the wilting point).	-8000 cm
r_{2H}	Potential transpiration rate (LT^{-1}).	0.5 cm/d
r_{2L}	Potential transpiration rate (LT^{-1}).	0.1 cm/d

PT rates (LT^{-1}) r_{2L} and r_{2H} (currently set at 0.1 cm/day and 0.5 cm/day) are specified in order to make the variable h_3 a function of the potential transpiration rate. These values merely define the shape of the transpiration curve and are not related to the PT values used in the model.

3.10 Results by Ecozone

The modeling was executed using the following assumptions:

- The climate data used in this analysis are representative datasets for each ecozone and do not represent specific landfill locations.
- Soil properties were estimated using the Rosetta method as a function of soil gradation (%clay, %sand, %silt).
- The growing season for ecozones 1, 3, 4, and 5 was assumed to be the same and extend from March 15th to November 15th.
- The growing season for ecozone 2 was assumed to start on May 15th and end on September 15th.
- The root density distribution was assumed to vary linearly from fully rooted at the top of each cover design to no roots the bottom of the cover.
- No snowmelt analysis was used. Instead, total precipitation was used, which includes rain and snow water equivalent data.
- Frozen ground characteristics were not explicitly modeled.
- All precipitation, whether snow or rain, was assumed to be available for infiltration on the day it occurred.

Considering these assumptions, the results of the analysis are to be used only as a general guidance. To further evaluate a specific site, site-specific climatic data should be used to predict the percolation rate from a specific water balance cover at a specific location.

A total of 140 simulations were performed. The downward and upward water fluxes at the interface of the soil cover and the waste boundary are shown in Table 12 for all ecozones, soil types, and cover thicknesses, and Figures 19 – 23 show the downward percolation rates for each ecozone. Also shown is the net percolation from the soil cover to the waste. A negative value for net percolation indicates net upward movement of water, from the waste into the soil cover.

3.10.1 Ecozone 1

For ecozone 1, the net percolation is negative for all simulations. These results indicate that the low value of the P/PET ratio of 0.38 and S_r of 8.4 cm seem to govern the net percolation rate. When looking only at the downward flux, values for the 4 ft and 3.5 ft covers are less than 1 mm/year for all soils. For the 3 ft thick covers, the downward fluxes are below 1 mm/year for Soils 4, 5, 6, and 7. The downward fluxes are 1.06, 2.96, 3.30 mm/year for covers for Soils 1, 2, and 3, respectively. The highest downward flux for ecozone 1 is approximately 4.5 mm/year (Soils 3 and 4, cover thickness of 2.5 ft). These results are an indication that water balance covers that are 3 ft or thicker in ecozone 1 are likely to result in minimal percolation, even using sandier soils such as Soils 1 and 2.

3.10.2 Ecozone 2

For ecozone 2, the net percolation rate is in the range of 1 mm/year for simulations with Soils 3 and 4 (all thicknesses), with Soil 5 (4 ft, 3.5 ft, and 3 ft), and with Soil 6 (4 ft only). For soils 1, 2, and 7, however, the net percolation rate is significantly higher for all thicknesses. For these three soils, the minimum net percolation rate is 16.4 mm/year. Soil 1, Soil 2, and Soil 7 have the lowest soil water storage capacity, which explains these higher net percolation rate.

For ecozone 2, the downward fluxes for Soil 1, Soil 2, and Soil 7 varied from 34 mm/year to 96 mm/year as the thickness decreased from 4 ft to 2.5 ft. The downward flux for thicknesses of 4 ft and 3.5 ft for Soils 3, 4, 5, are less than 5 mm/year. The downward fluxes for the 3 and 2.5 thick covers were all higher than 10 mm/year.

3.10.3 Ecozone 3

For ecozone 3, the net percolation rate varied from negative to 1.67 mm/year for all cover thickness with Soils 3, 4, 5, and 6. For Soil 7, only the 4, 3.5, and 3 ft thick covers yielded such low net percolation. The 2.5 ft cover for Soil 7 had a net percolation rate of 6.79 mm/year. For Soil 1, the net percolation increased from 1.51 to 24.99 mm/year as the thickness decreased from 4 to 2.5 ft. For Soil 2, the net percolation increased from 4.78 to 36.44 mm/year as the thickness decreases from 4 to 2.5 ft.

After reviewing the results for Soils 1 and 2, it was determined that most of the percolation occurred during three large storm events which occurred during the design year. These three events are responsible for the associated percolation events, especially with the lower water storage capacity of these two soils. The downward fluxes for Soils 1 and 2 varied from 11.15 to 93.20 mm/year for all cover thicknesses. For Soils 3, 4, 5, 6, 7 the downward fluxes varied from 10.42 to 34.42 mm/year for the covers with thicknesses of 3 and 2.5 ft. The downward fluxes for the 3.5 and 4 ft covers varied from negative to 1.81 for Soils 4, 5, 6, and 7. Simulations with Soil 3 resulted in downward fluxes of 3.43 and 5.82 mm/year for thicknesses of 4 ft and 3.5 ft, respectively.

3.10.4 Ecozone 4

For ecozone 4, the net percolation rates were all negative or less than 1 mm/year for all soils and thicknesses, except for the simulation of a 2.5 ft cover with Soil 2, which has a net percolation rate of 1.14 mm/year. These results suggest that water balance covers in ecozone 4 are likely to result in minimal percolation and may be built with several soil types.

However, looking only at downward flux values provides a slightly different perspective. Water balance covers that are 4 and 3.5 ft thick have low downward flux values (less than 1 mm/year) when modeled with Soils 3, 4, 5, 6, and 7. A cover modeled with Soil 1 has downward flux values of 0.81 mm/year and 1.72 mm/year with thicknesses of 4 and 3.5 ft, respectively. A cover modeled with Soil 2 has downward flux values of 1.97 and 3.79 mm/year for thicknesses of 4 and 3.5 ft respectively. When the thickness is 3 ft, only a cover with Soil 7 leads to a downward flux less than 2 mm/year. The rest of the soils produce downward fluxes ranging from 2.76 mm/year to 10.90 mm/year. The 2.5-ft covers have higher downward fluxes, varying from 5 mm/year (Soils 5, 6, and 7) to more than 10 mm/year for the other soil types. In ecozone 4, a cover of at least 3 ft cover is needed to achieve lower downward flux values.

3.10.5 Ecozone 5

For ecozone 5, the net percolation values were negative for all soil types and thicknesses. These results are consistent with the low P/PET ration in ecozone 5. The downward flux values were also low and did not exceed approximately 5 mm/year. These low downward fluxes are a more conservative indication that water balance covers are likely to result in minimal percolation in this ecozone with a variety of soils.

Table 12. Summary of Model Simulations (all climates, soil types, and thicknesses) in mm/year of flux

Ecozone 1																						
DEPTH	SOIL1			SOIL2			SOIL3			SOIL4			SOIL5			SOIL6			SOIL7			
	ft	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET
4	0.34	0.00	-0.34	0.38	0.02	-0.36	0.37	0.01	-0.36	0.38	0.02	-0.36	0.34	0.00	-0.34	0.34	0.00	-0.34	0.34	0.00	-0.34	0.34
3.5	0.35	0.00	-0.34	0.40	0.04	-0.36	0.31	0.27	-0.03	0.40	0.04	-0.36	0.35	0.00	-0.35	0.34	0.00	-0.34	0.35	0.00	-0.35	0.35
3	0.98	0.66	-0.32	1.33	1.06	-0.27	3.06	2.96	-0.10	3.38	3.30	-0.08	0.85	0.47	-0.38	0.56	0.22	-0.34	0.41	0.07	-0.34	0.34
2.5	1.35	1.15	-0.20	2.07	1.86	-0.21	4.50	4.47	-0.03	4.50	4.49	-0.01	1.18	1.12	-0.06	0.69	0.35	-0.34	0.54	0.20	-0.34	0.34
Ecozone 2																						
DEPTH	SOIL1			SOIL2			SOIL3			SOIL4			SOIL5			SOIL6			SOIL7			
	ft	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET
4	18.32	34.73	16.41	20.86	50.16	29.30	2.34	2.30	-0.04	1.18	0.95	-0.22	2.58	2.54	-0.02	6.34	7.44	1.11	17.06	41.97	24.91	24.91
3.5	21.22	49.03	27.81	22.65	65.43	42.78	3.66	3.91	0.25	1.65	1.51	-0.15	4.30	4.66	0.36	10.89	14.48	3.59	19.52	57.80	38.28	38.28
3	28.62	64.20	35.58	29.38	79.73	50.34	13.52	14.88	1.36	10.16	10.60	0.44	11.62	12.76	1.13	18.46	23.38	4.92	24.52	67.12	42.60	42.60
2.5	26.41	85.84	59.44	31.00	96.30	65.31	13.73	14.79	1.05	13.73	14.79	1.05	18.52	22.75	4.22	25.93	44.40	18.48	26.41	85.84	59.44	59.44
Ecozone 3																						
DEPTH	SOIL1			SOIL2			SOIL3			SOIL4			SOIL5			SOIL6			SOIL7			
	ft	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET
4	9.64	11.15	1.51	17.66	22.44	4.78	4.29	3.43	-0.86	1.14	0.84	-0.30	1.09	0.80	-0.29	0.75	0.44	-0.31	0.50	0.18	-0.32	-0.32
3.5	18.66	23.96	5.30	26.91	39.37	12.45	6.63	5.82	-0.81	1.56	1.28	-0.27	1.98	1.81	-0.17	1.61	1.60	0.00	1.91	1.70	-0.21	-0.21
3	37.82	46.75	8.93	45.92	64.74	18.82	15.64	16.42	0.78	12.66	12.76	0.10	11.61	12.25	0.64	9.95	10.42	0.47	11.28	11.93	0.66	0.66
2.5	51.85	76.85	24.99	56.76	93.20	36.44	16.14	17.16	1.02	16.14	17.16	1.02	18.44	18.71	0.27	17.85	19.52	1.67	27.63	34.42	6.79	6.79
Ecozone 4																						
DEPTH	SOIL1			SOIL2			SOIL3			SOIL4			SOIL5			SOIL6			SOIL7			
	ft	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET
4	1.07	0.81	-0.27	2.12	1.97	-0.15	0.75	0.41	-0.34	0.63	0.27	-0.35	0.44	0.10	-0.34	0.39	0.05	-0.34	0.34	0.00	-0.34	-0.34
3.5	1.87	1.72	-0.15	3.68	3.79	0.11	0.97	0.64	-0.33	0.75	0.40	-0.35	0.55	0.22	-0.33	0.50	0.16	-0.34	0.40	0.06	-0.34	-0.34
3	6.93	7.10	0.17	10.37	10.90	0.53	8.28	8.28	-0.01	7.72	7.85	0.13	3.88	3.59	-0.29	2.95	2.76	-0.20	2.14	1.84	-0.30	-0.30
2.5	11.47	11.94	0.46	16.42	17.56	1.14	9.85	10.49	0.64	9.85	10.49	0.64	5.70	5.64	-0.06	4.50	4.33	-0.16	4.44	4.35	-0.08	-0.08
Ecozone 5																						
DEPTH	SOIL1			SOIL2			SOIL3			SOIL4			SOIL5			SOIL6			SOIL7			
	ft	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET	UP	DOWN	NET
4	0.36	0.02	-0.34	0.45	0.08	-0.36	0.43	0.05	-0.38	0.45	0.00	-0.45	0.34	0.00	-0.34	0.34	0.00	-0.34	0.34	0.00	-0.34	-0.34
3.5	0.39	0.04	-0.35	0.53	0.17	-0.36	0.46	0.08	-0.38	0.47	0.08	-0.39	0.35	0.00	-0.35	0.35	0.00	-0.35	0.35	0.00	-0.35	-0.35
3	1.79	1.15	-0.28	2.65	2.49	-0.17	4.15	4.06	-0.09	4.27	4.18	-0.09	1.46	1.12	-0.34	0.73	0.39	-0.35	0.35	0.00	-0.35	-0.35
2.5	2.81	2.65	-0.16	4.07	4.04	-0.03	5.41	5.15	-0.26	5.41	5.15	-0.26	2.15	1.88	-0.27	1.16	0.81	-0.35	0.44	0.09	-0.35	-0.35

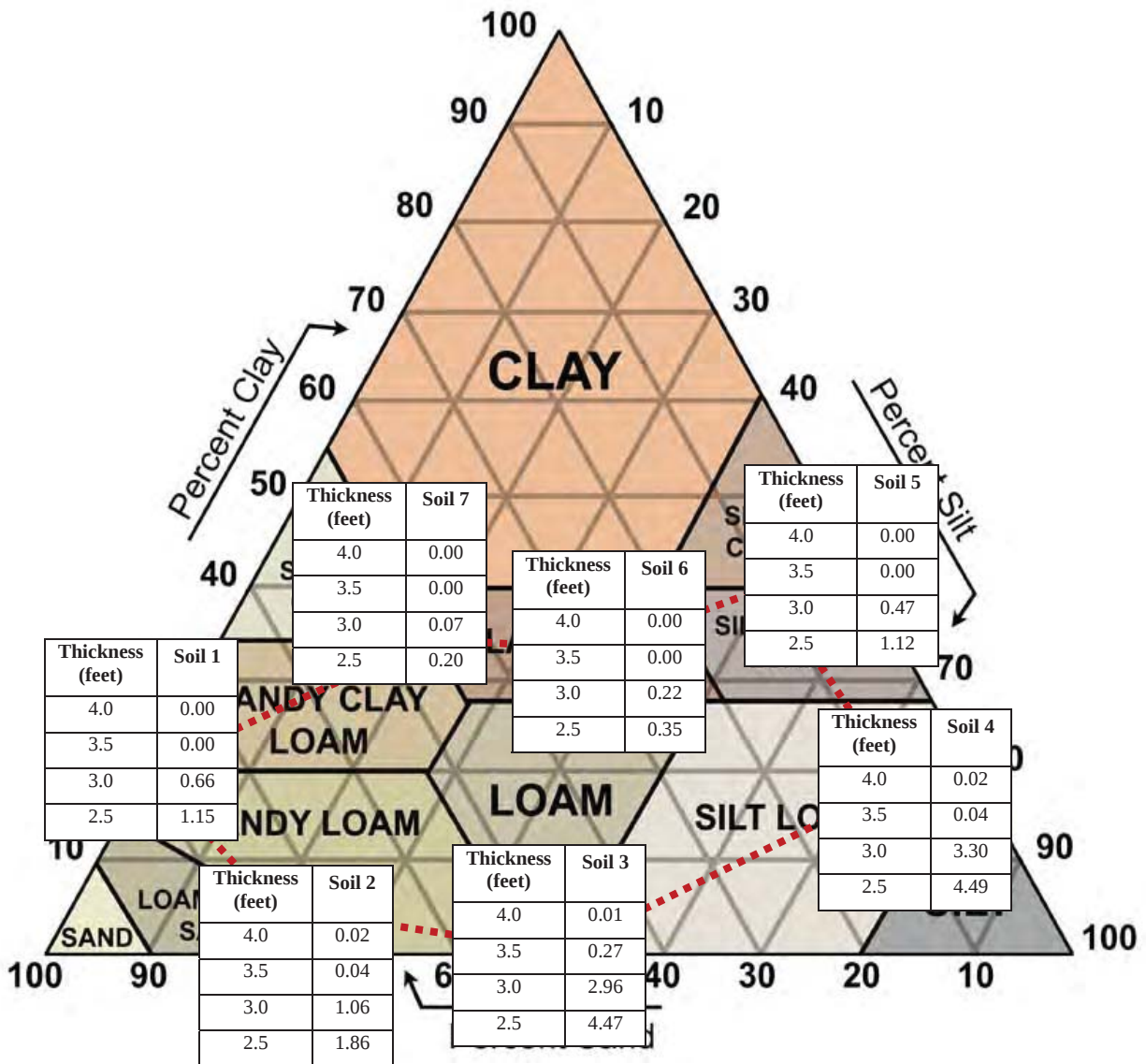


Figure 17. Summary of Simulation Results for Ecozone 1
Downward percolation rates shown are in (mm/year).

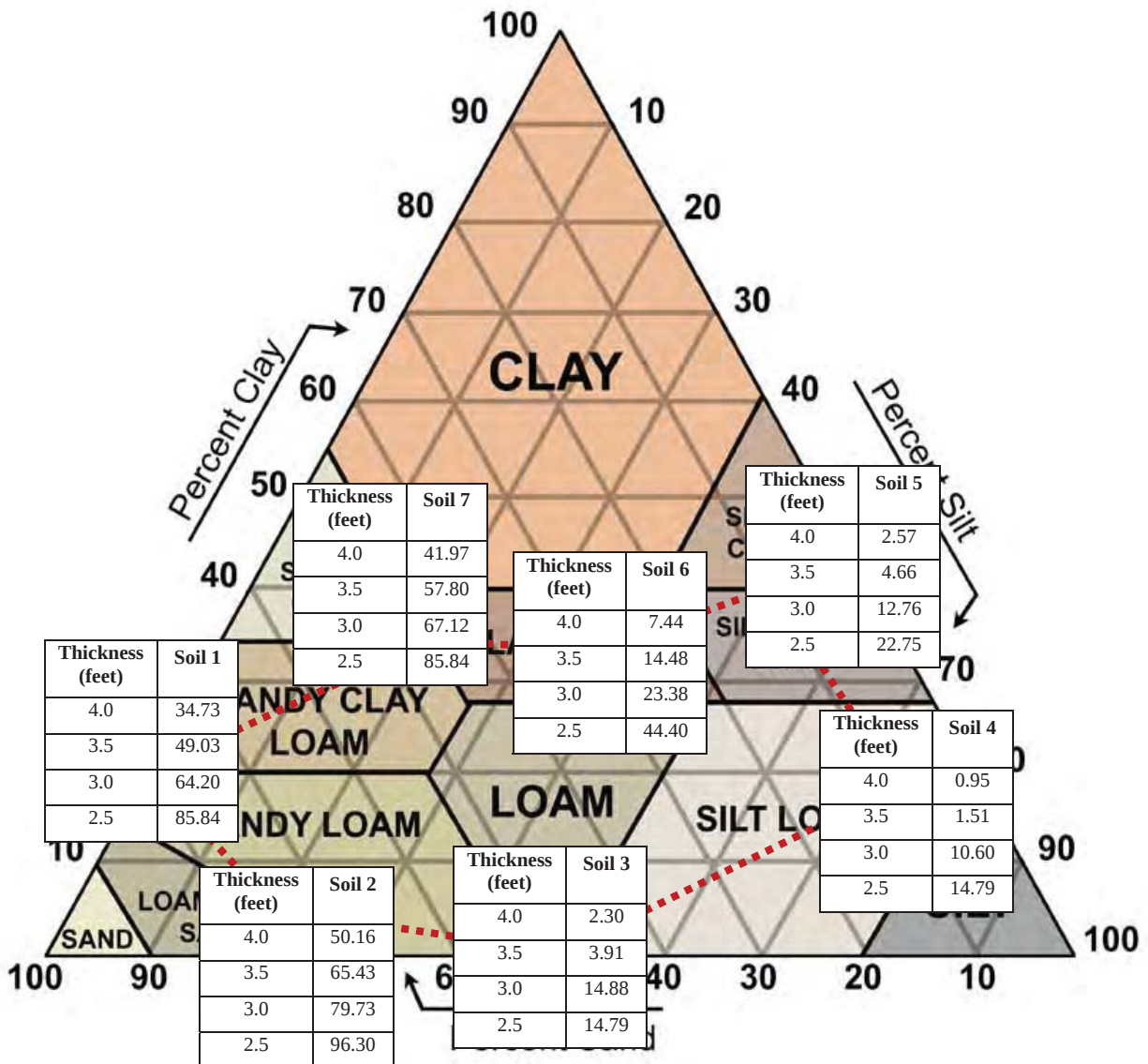


Figure 18. Summary of Simulation Results for Ecozone 2
Downward percolation rates shown are in (mm/year).

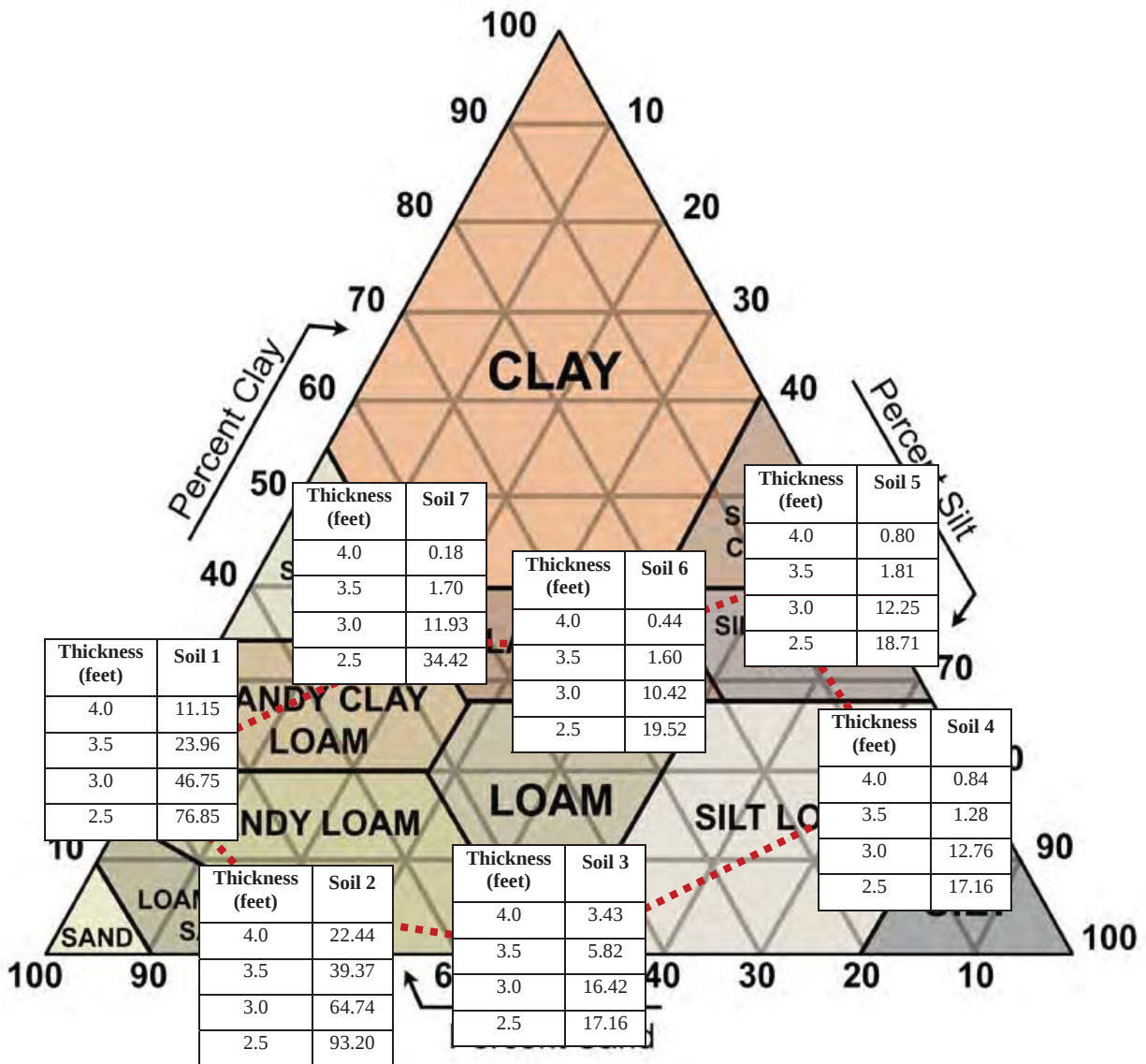


Figure 19. Summary of Simulation Results for Ecozone 3
Downward percolation rates shown are in (mm/year).

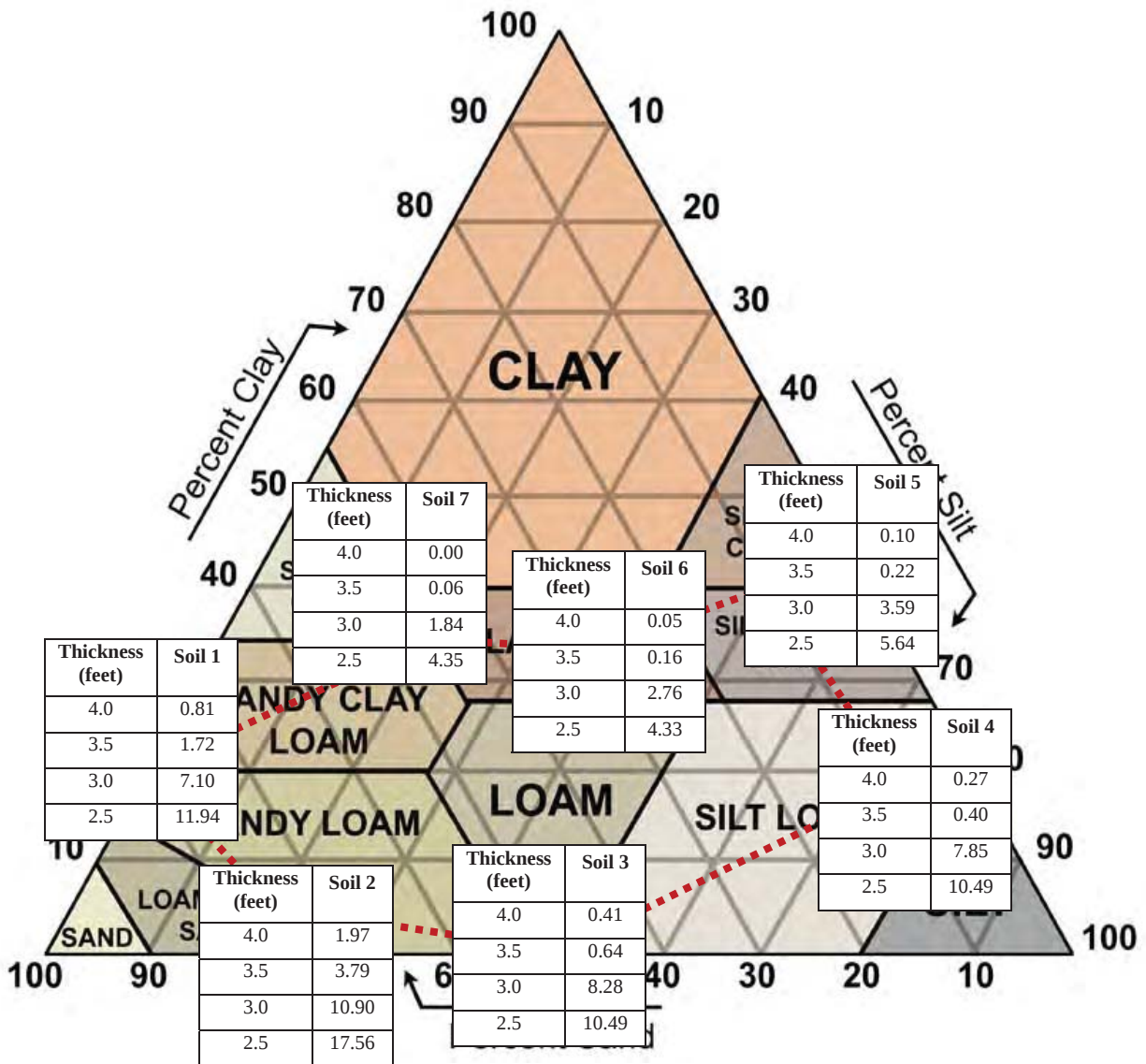


Figure 20. Summary of Simulation Results for Ecozone 4
Downward percolation rates shown are in (mm/year).

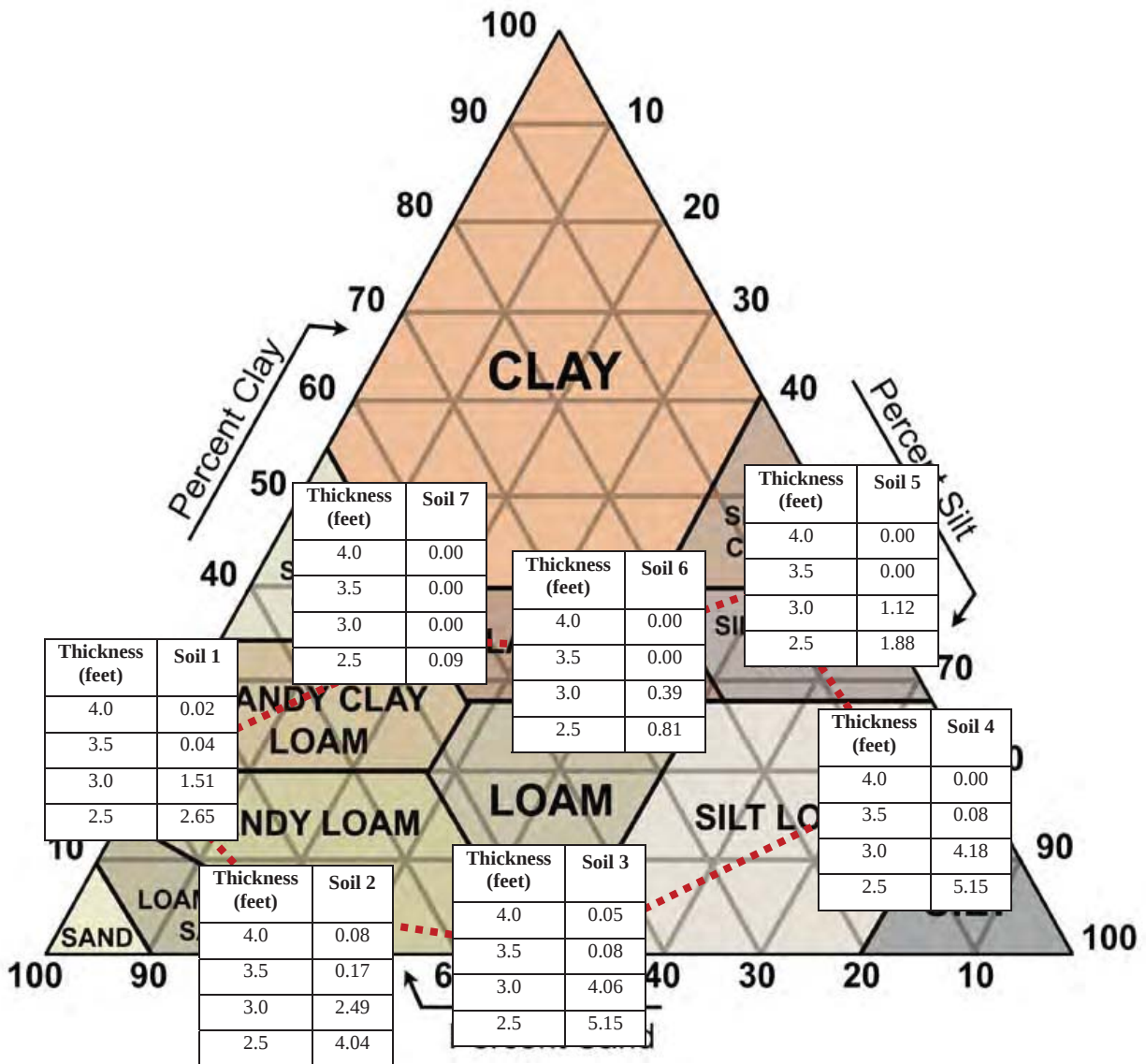


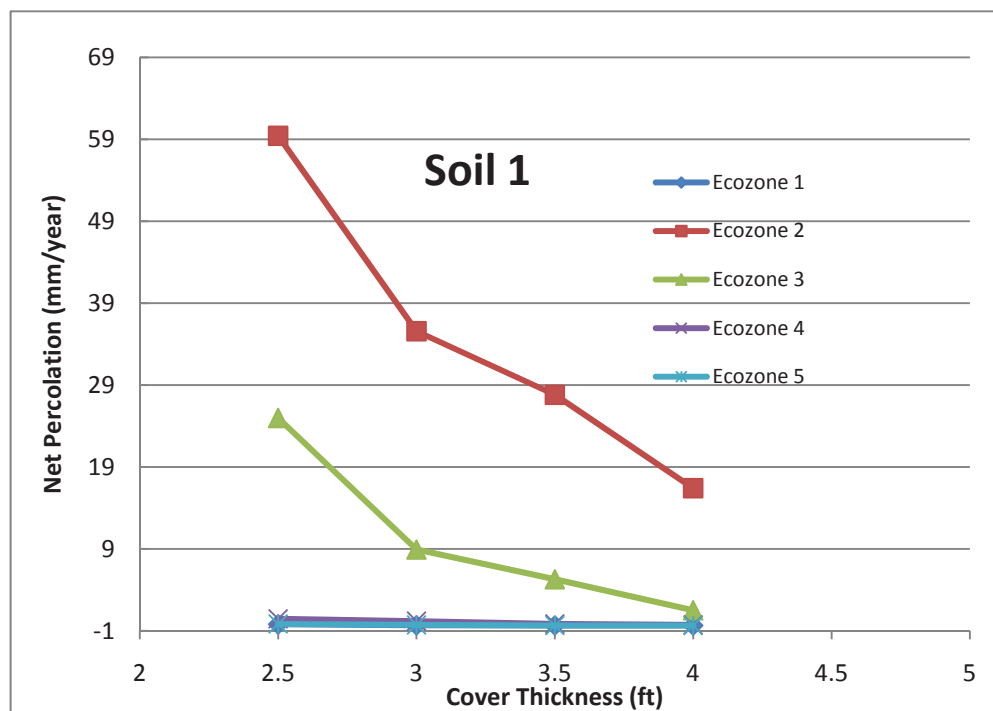
Figure 21. Summary of Simulation Results for Ecozone 5
Downward percolation rates shown are in (mm/year).

3.11 Results by Soil Type

The results in Table 12 were also used to plot net percolation rate and downward flux versus cover thickness for all simulated scenarios to produce one plot per soil type (Figures 24 to 30). These plots provide a graphical format to show the decrease of expected percolation rates and downward fluxes with thickness for each soil type separately. The rate of decrease of net percolation rate with cover thickness is different for each ecozone. As expected, the rate of decrease of downward flux with thickness is more notable because it does not account for upward water movement from the waste to the cover soil.

The general trend in the results for net percolation is that net percolation decreases with the thickness of the cover. For Soils 3, 4, 5, and 6, very low net percolation rates (around 1 mm/year) were obtained for ecozones 1, 3, 4, and 5 for all simulated thicknesses. Simulations using Soils 1 and 2, however, only yielded low net percolation rates for all cover thicknesses using the climatic data for ecozones 1, 4, and 5. For ecozone 2, no percolation rates in the 1 mm/year range were obtained using Soil 1, Soil 2, and Soil 7. Soil 1 yielded a low net percolation rate only when the cover is 4 ft thick for ecozone 3. Moreover, for Soil 3, the net percolation rate slightly increases (from 1 to 1.4 mm/year) as the thickness increases from 2.5 ft to 3 ft. This might be due to numerical issues as the increase is negligible. One should consider that the net percolation rate essentially stays the same for the 2.5 and 3 ft covers. This is a reasonable approach because the net percolation accounts for both upward and downward flow. In ecozone 3, net percolation rates for Soil 2 were higher than 4 mm/year for all thicknesses.

(a)



(b)

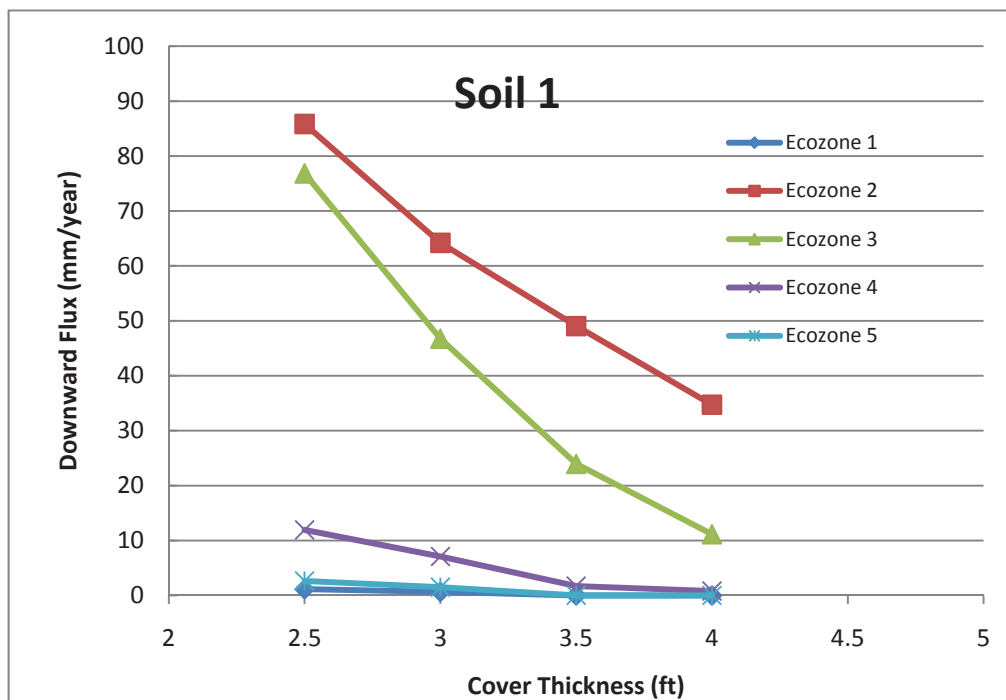
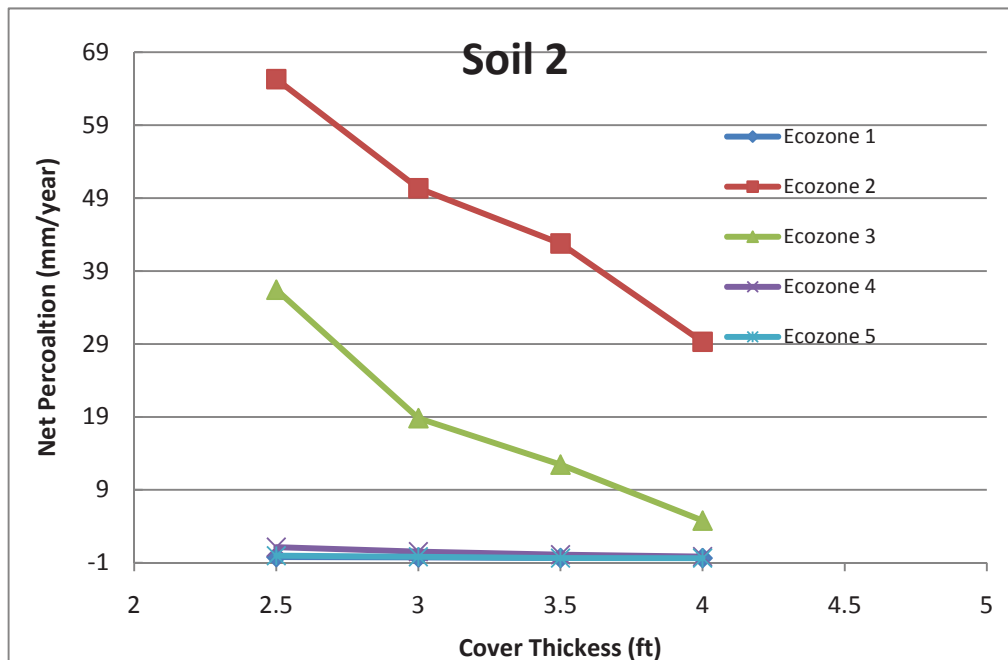


Figure 22. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 1

(a)



(b)

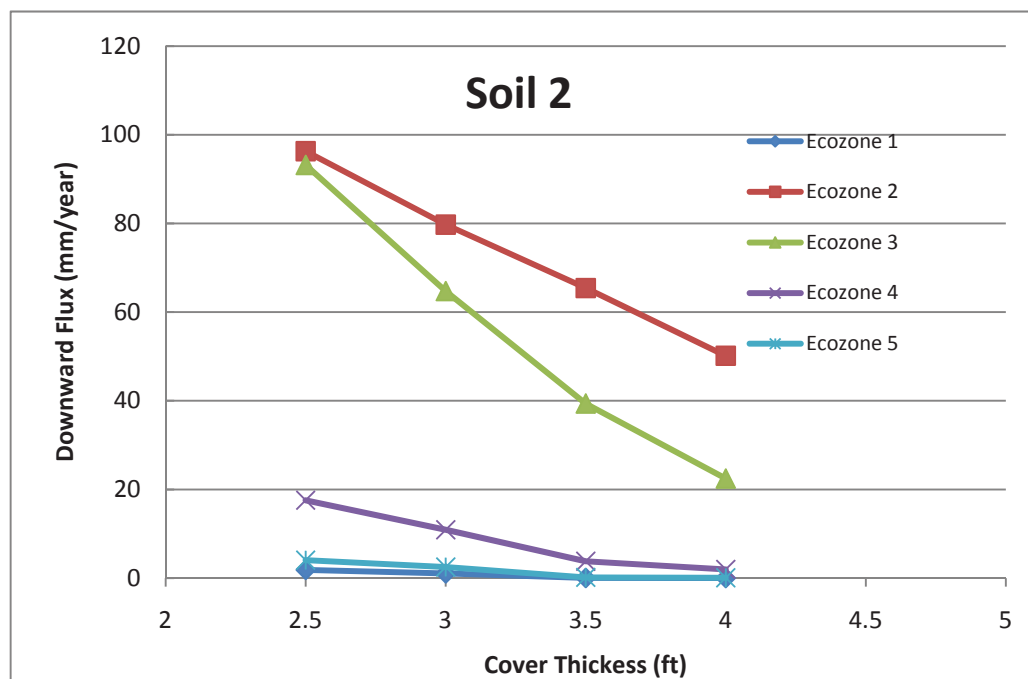
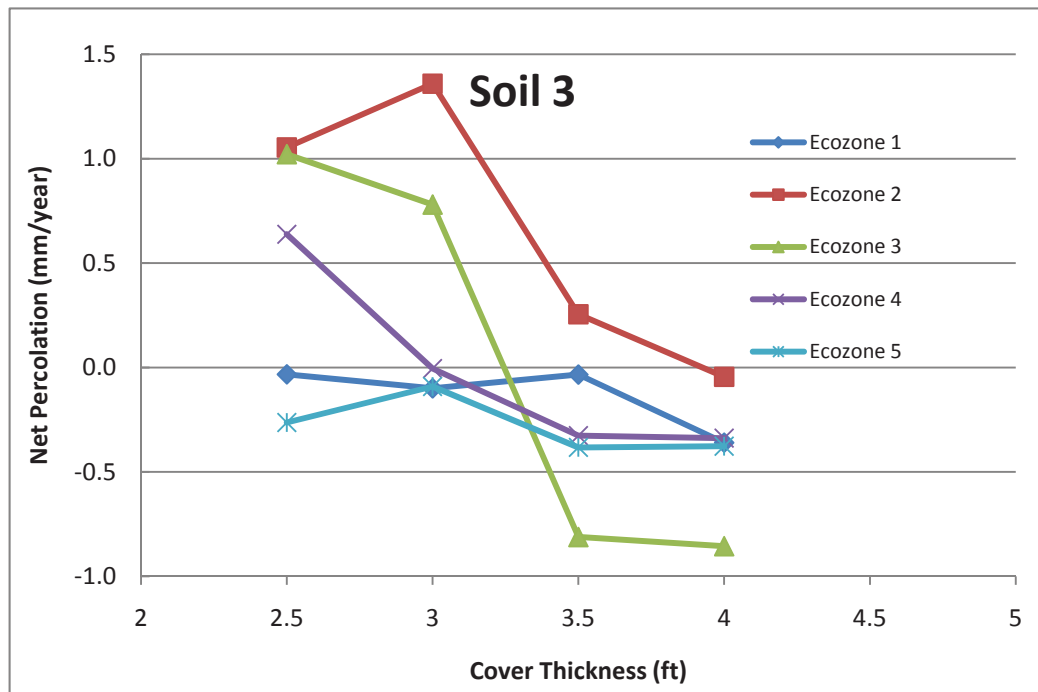


Figure 23. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 2

(a)



(b)

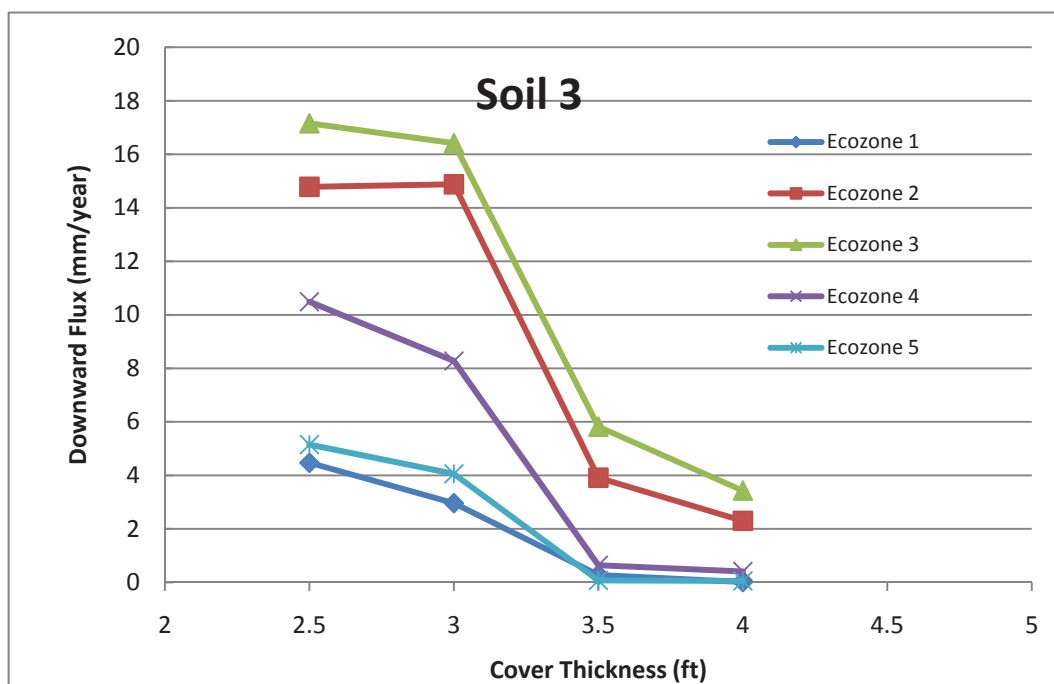
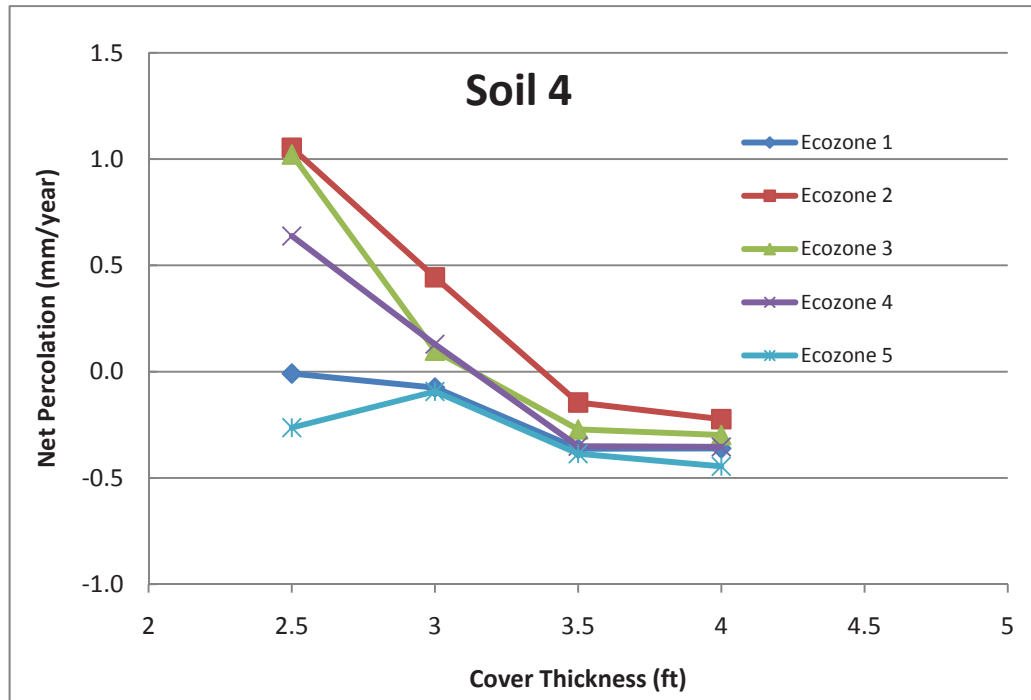


Figure 24. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 3

(a)



(b)

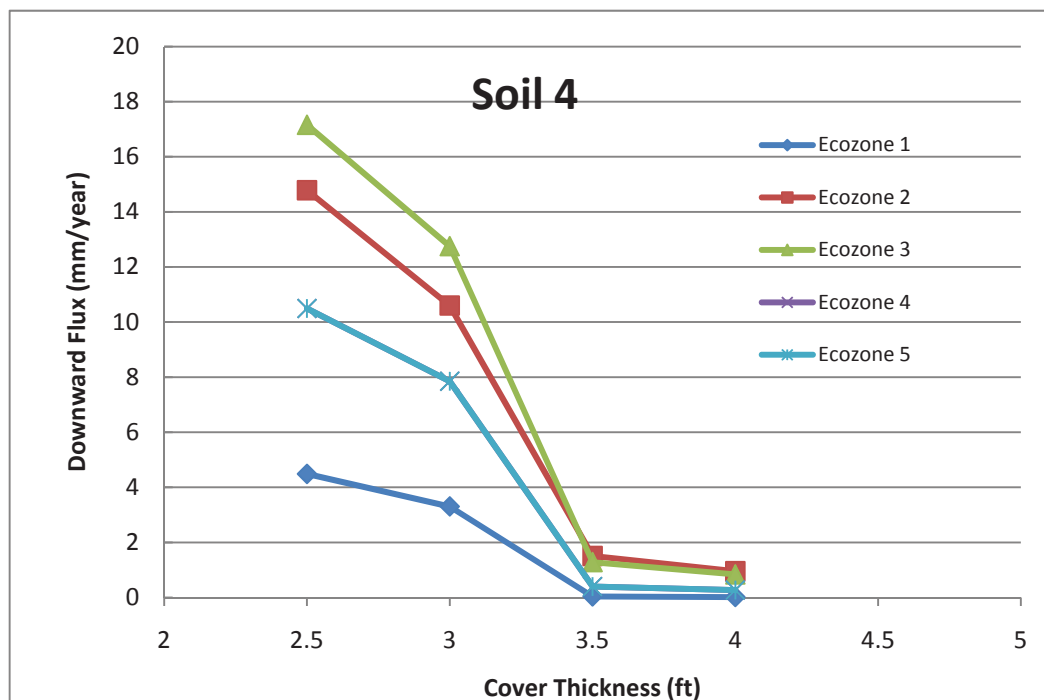
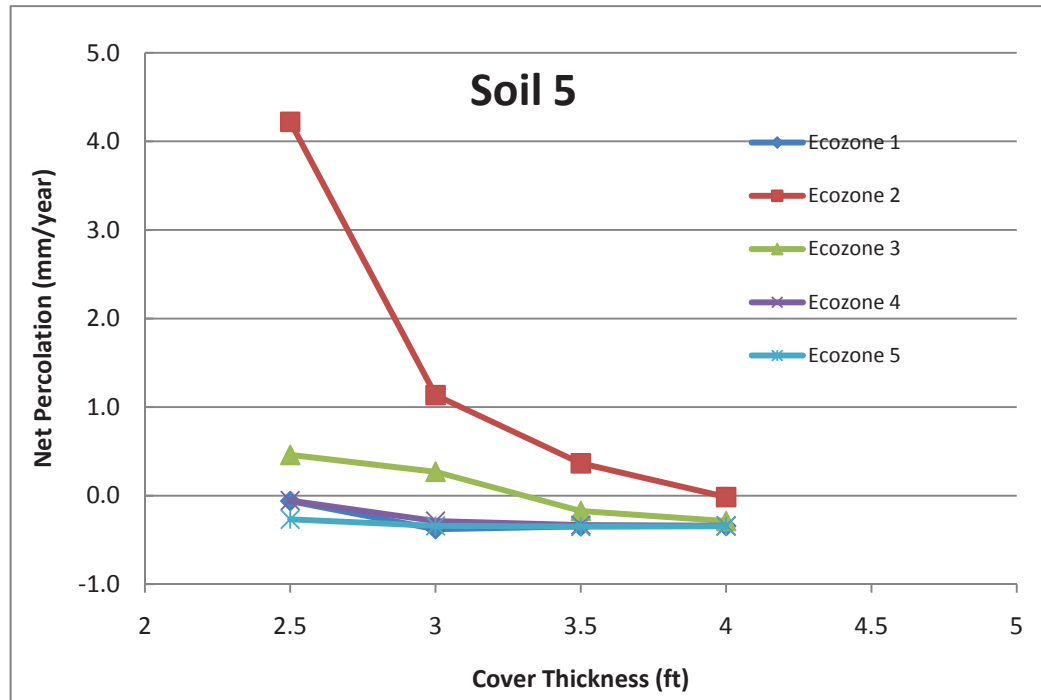


Figure 25. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 4

(a)



(b)

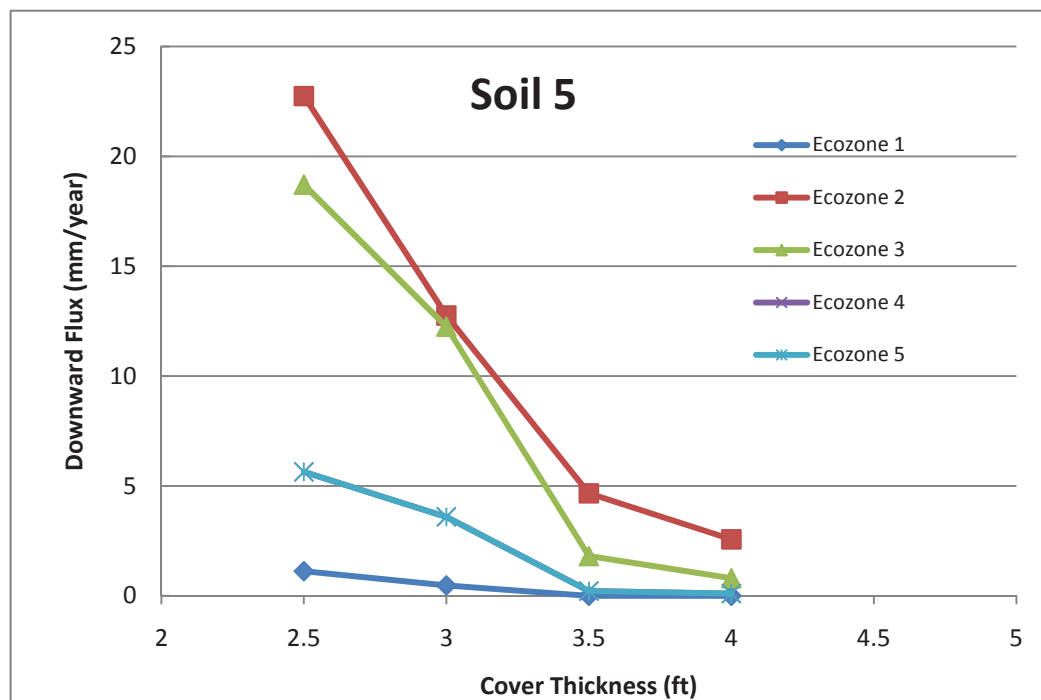
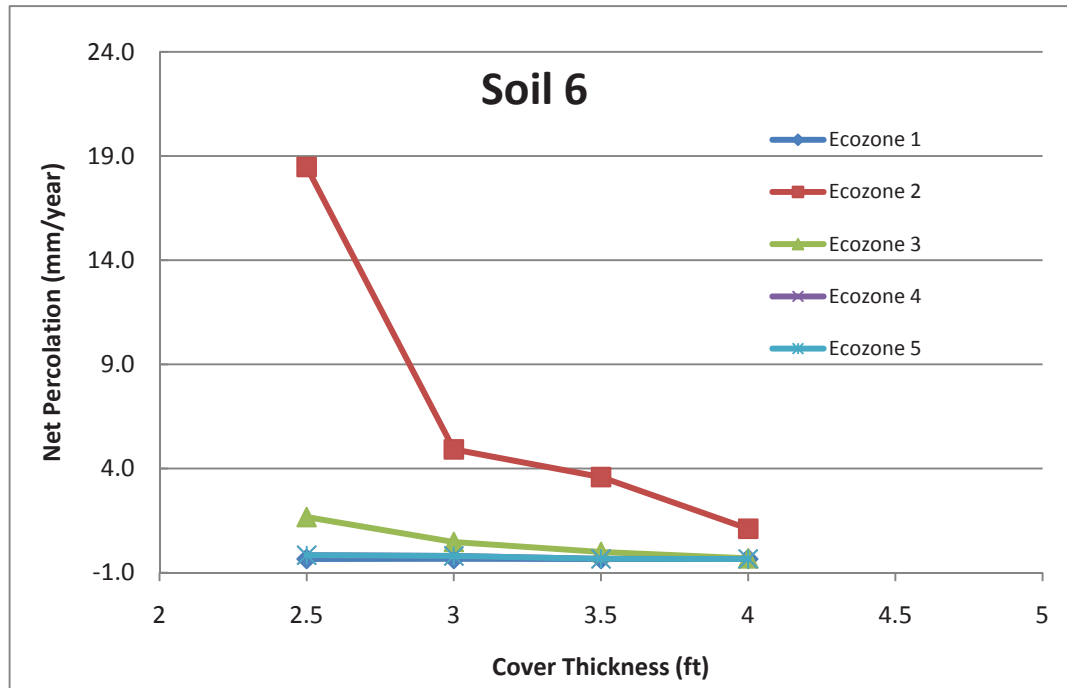


Figure 26. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 5

(a)



(b)

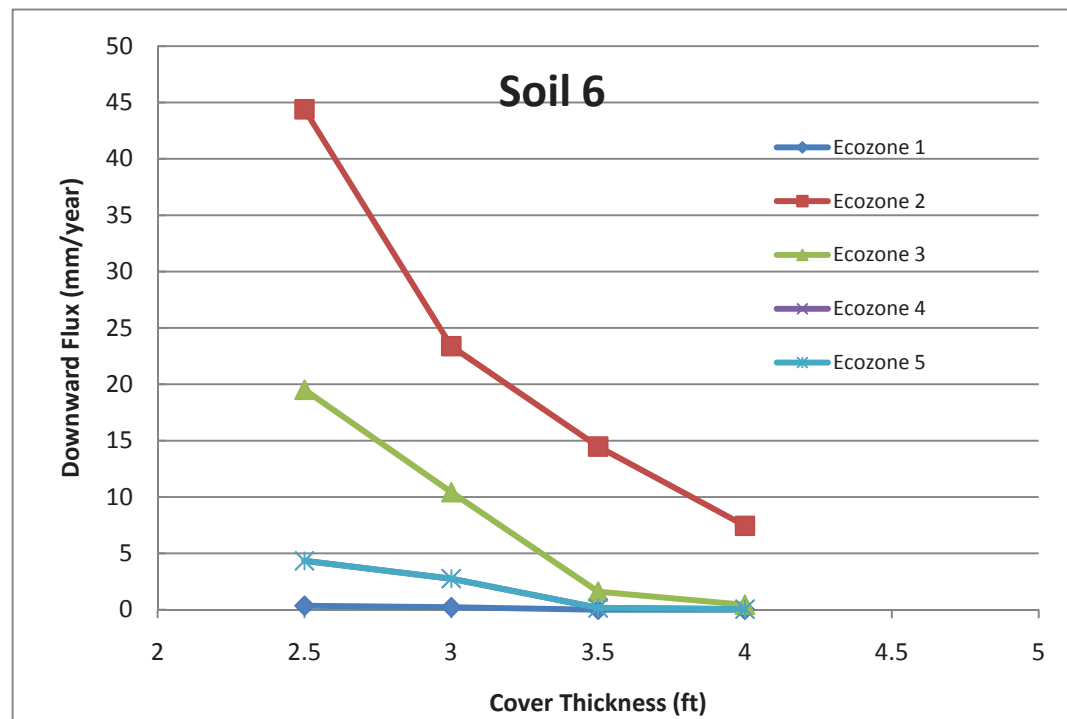
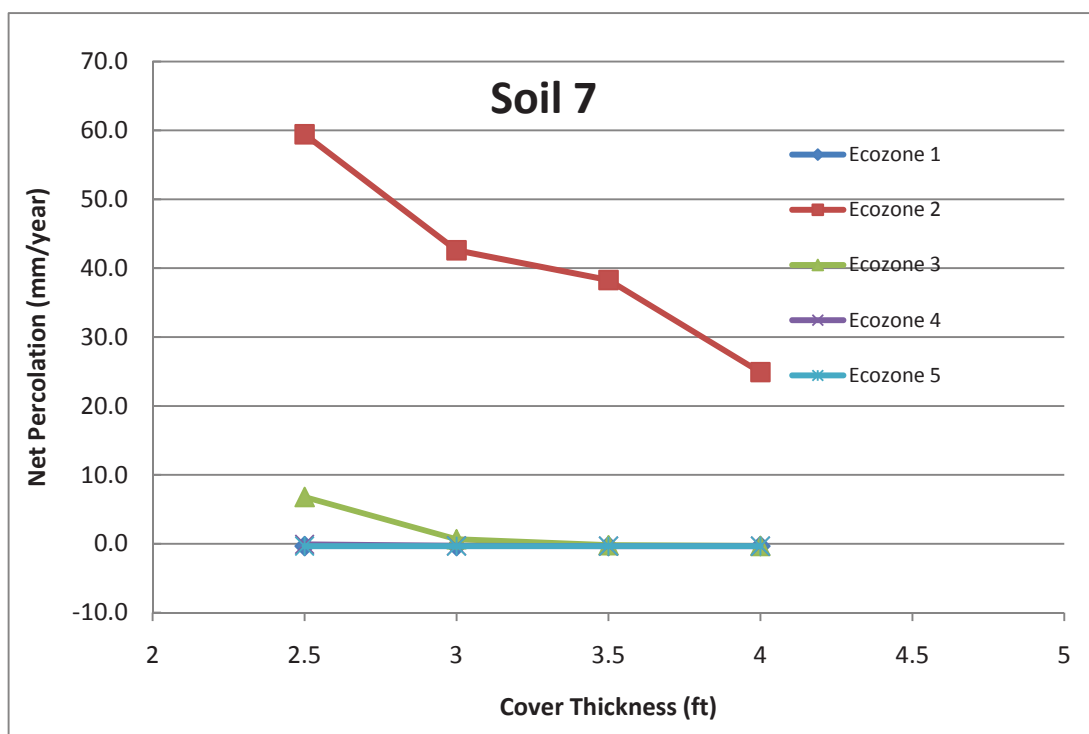


Figure 27. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 6

(a)



(b)

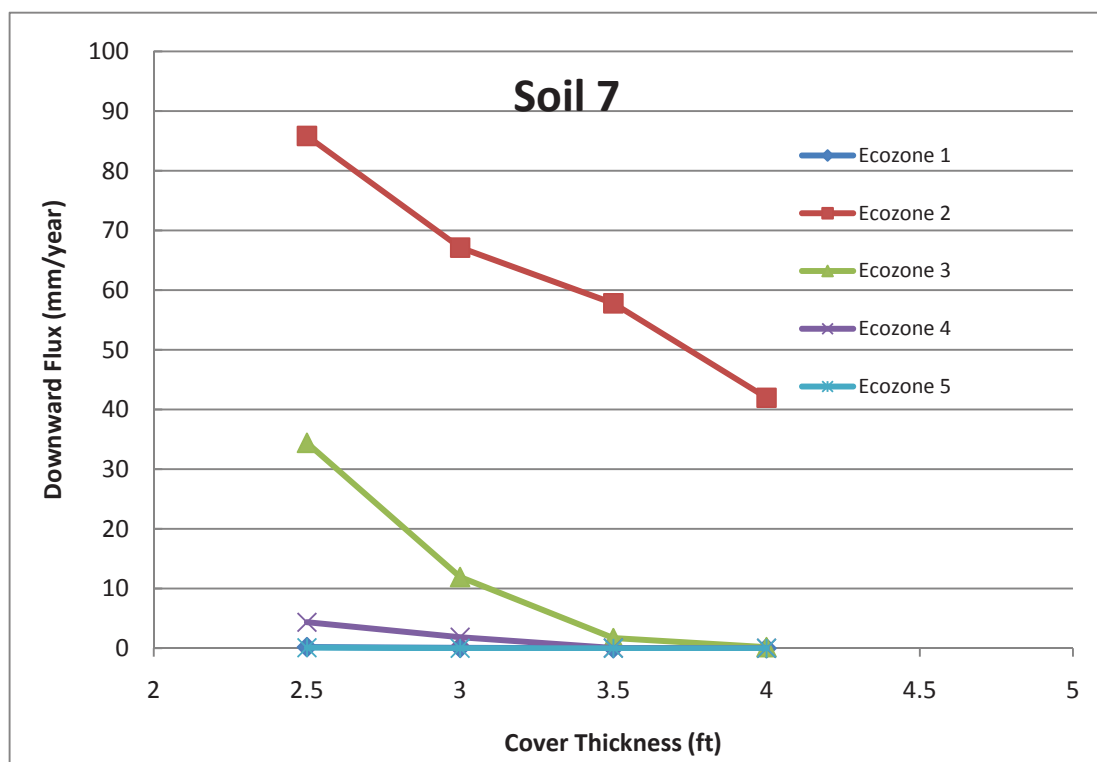


Figure 28. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 7

3.12 Sensitivity Analysis

3.12.1 Effects of Climate and Soil Type (S_r and Soil Water Storage Capacity)

The sensitivity of modeled percolation and downward flux was considered relative to two main types of input parameters: total soil water storage capacity (soil type and thickness), and climate conditions. These inputs are the backbone of water balance cover design. Of these two parameter types, climatic factors govern the quantity of water that must be stored to prevent percolation into the underlying waste. The quantity of water to be stored is often represented as “ S_r ” (Albright et al., 2010). The concept of S_r was developed using an extensive set of field data obtained during EPA’s Alternative Covers Assessment Program (ACAP). The ACAP data show that the variability in S_r is related to the variability in climatic conditions among locations.

The second parameter that governs the performance of a water balance cover is water storage capacity. After assessing S_r , the next step in the design process is to choose a thickness and a soil type that are capable of storing this volume of water. The total water storage capacity of a soil cover is the product of the soil unit water storage capacity multiplied by the cover thickness. Variability in soil properties can greatly impact the water storage capacity of a cover.

Modeling was performed using different values of S_r for each ecozone and different soil water storage capacities. Plots of the net percolation rate and the downward flux versus the calculated total water storage capacity of each cover are shown in Figures 31 and 32. These graphs show how net percolation and downward flux vary with ecozone (or S_r) and total soil water storage capacity for the cover. Regression equations, using the form below, were developed for downward flux and net percolation rate for each ecozone. Parameter values for correlations are presented in Table 13. Note that ecozones 2 and 3 exhibited an exponential response.

$$\text{Downward Flux} = m (\text{Unit Storage Capacity} * \text{Thickness}) + b, R^2$$

$$\text{Net Percolation} = n (\text{Unit Storage Capacity} * \text{Thickness}) + c, R^2$$

Given a known unit soil water storage capacity and a cover thickness, these correlations can be used to provide an estimate of net percolation rate and downward flux from each ecozone. Note that these estimates are applicable only within the range of soil parameters, cover thicknesses, and climatic conditions that were modeled as part of this effort. Vegetation schemes similar to those described in this report are also assumed.

Table 13. Values for parameters in downward flux and net percolation correlations

Ecozone	Downward Flux			Net Percolation		
	m	b	R^2	n	c	R^2
1	-0.664	1.118	0.006	-0.031	- 0.257	0.001
2	$730.72e^{-7.9}$	0	0.899	-112.66	70.704	0.668
3	$310.1e^{-7.9}$	0	0.583	-37.02	21.41	0.45
4	-16.01	11.56	0.300	-1.357	0.579	0.308
5	-4.056	2.940	0.191	-0.257	- 0.182	0.165

The sensitivity of percolation values to the input parameters varies across ecozones. In ecozones 1 and 5, the regression lines are nearly horizontal. The interpretation of this slope is that

percolation is insensitive to cover design. The values of S_r in ecozones 1 and 5 are 8.4 and 7.11 cm, respectively, which are relatively low values. This results in a wider range of feasible soil types and cover thicknesses in these zones. In ecozone 4, percolation fluxes are slightly more sensitive to cover design, due primarily to increased S_r . In ecozones 2 and 3, cover performance is much more dependent on cover design parameters due to increased S_r . In ecozone 2, lower PET and a shorter growing season also increase the importance of cover design parameters. In ecozones 2 and 3, thicker covers with finer-textured soils are needed to minimize percolation.

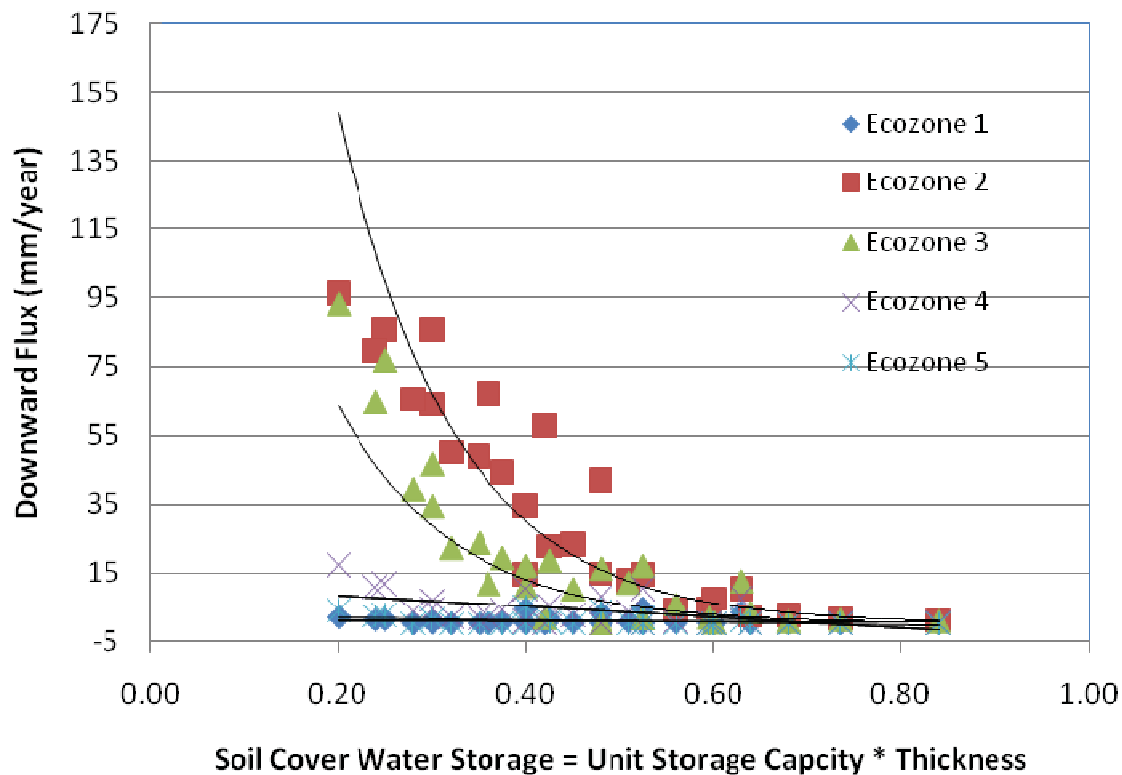


Figure 29. Downward flux versus total water storage capacity

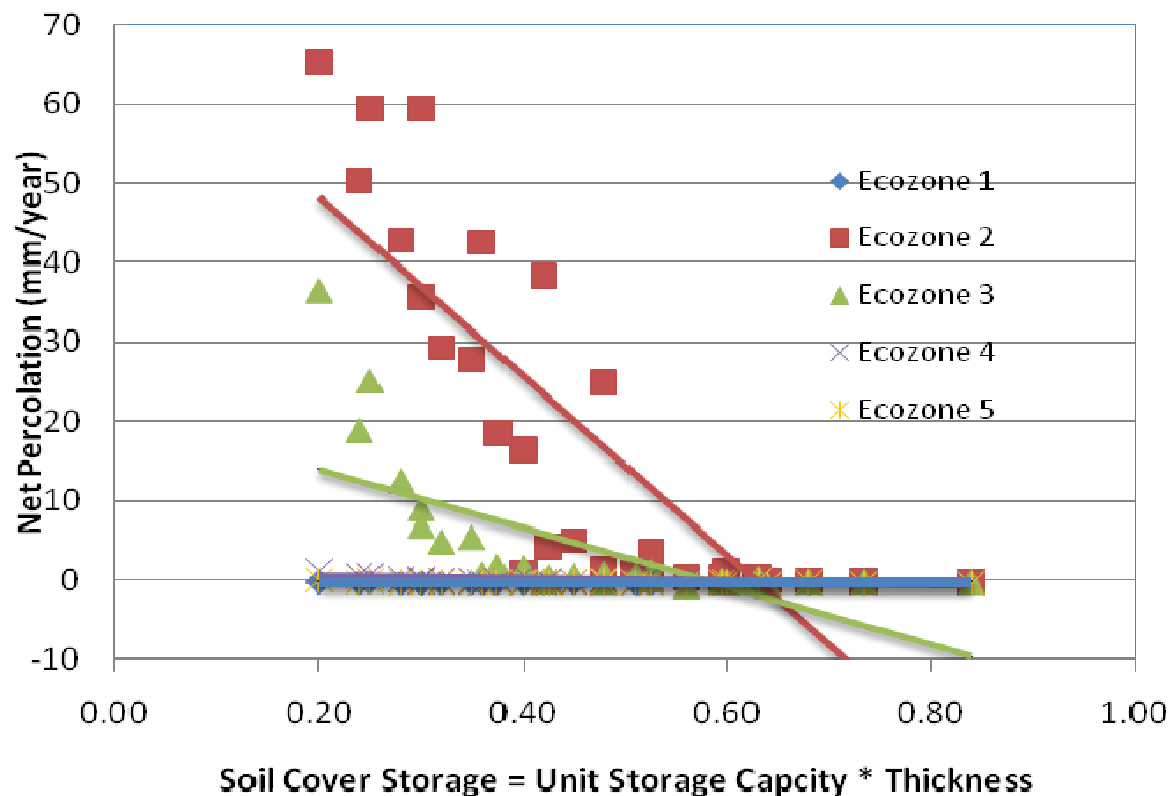


Figure 30. Net Percolation versus total water storage capacity

3.12.2 Effect of Length of Growing Season

Simulations for ecozone 2 were performed using two growing season lengths. One set of simulations was performed using the same growing season as the other ecozones (March 15th to November 15th). The other set of simulations was performed using a growing season from May 15th to September 15th, which is believed to be a more realistic growing season length in this mountainous ecozone (Sievering et al., 1992). Table 14 shows the modeled percolation values for both sets of simulations for ecozone 2 using cover thicknesses of 4 ft. and 3.5 ft.

The net percolation rates for the longer growing season are significantly lower for Soil 1, Soil 2, and Soil 7. These soils have the lowest soil water storage capacity. The difference in percolation between the two growing season lengths is somewhat significant for Soil 6, and less significant for Soils 3-5. This analysis suggests that percolation results for some soil types in ecozone 2 are sensitive to the growing season length used in the model. A precise estimate of growing season length may be critical to understanding how a given soil type may perform in a water balance cover within ecozone 2.

Table 14. Summary of Results for Ecozone 2 Using Short and Long Growing Season

Ecozone 2 Long Growing Season														
DEPTH	SOIL1		SOIL2		SOIL 3		SOIL 4		SOIL 5		SOIL 6		SOIL 7	
ft	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET
4	3.4	0.1	8.1	1.3	0.4	-0.3	0.2	-0.3	0.3	-0.3	0.6	-0.3	2.0	0.0
3.5	5.3	0.5	0.0	-9.8	0.6	-0.3	0.3	-0.3	0.5	-0.3	0.9	-0.3	2.8	0.1
Ecozone 2 Short Growing Season														
DEPTH	SOIL1		SOIL2		SOIL 3		SOIL 4		SOIL 5		SOIL 6		SOIL 7	
ft	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET	DOWN	NET
4	34.7	16.4	50.2	29.3	2.3	0.0	1.0	-0.2	2.6	0.0	7.4	1.1	42.0	24.9
3.5	49.0	27.8	65.4	42.8	3.9	0.3	1.5	-0.1	4.7	0.4	14.5	3.6	57.8	38.3

4. Discussion

Developing general water balance covers for a state with a diverse climate and landscape is challenging. The following list presents the challenges faced during this study, discusses the decisions made and the rationale for these decisions, and provides potential alternatives that may be explored during future research efforts.

Ecozone Delineation: The delineation of ecozones was an iterative process, as a number of factors were used to determine the appropriate boundary lines. The EPA Level III ecoregion boundaries were used as a starting point for ecozone delineation due to their general adherence to variation in Colorado's physical geography and climate. The boundaries were refined to reflect patterns in P and PET data and to enhance future implementation efforts. Other factors that may be considered in future delineation efforts include the locations of landfills and population distributions.

Representative stations: Representative stations were selected based on the availability of data for parameters that drive the performance of water balance covers, including average annual P and average P in the wettest month. Furthermore, the location of the station within the ecozone was considered, and a centrally-located station was chosen when practicable. In addition, the length of the period of record was considered, and stations with longer periods of data were selected. Alternative approaches to the selection of representative stations merit exploration, including selection based on additional climate parameters and proximity to existing or proposed landfills.

Evapotranspiration: PET was calculated using the theoretical Blaney-Criddle equation, using the average monthly temperature for each of the representative stations. The Blaney-Criddle method is relatively simple; it provides only a coarse estimate because it does not account for many of the factors that may influence evapotranspiration such as wind speed, relative humidity, and solar radiation. The Food and Agriculture Organization (FAO) reports that under "extreme" climatic conditions, the Blaney-Criddle method may underestimate PET by up to 60% in windy, dry, sunny areas, and overestimate by up to 40% in calm, humid, cloudy areas. Limited data availability for these additional climate measures necessitated the use of the Blaney-Criddle method for this study. If additional climatic data are available, the Penman-Monteith equation (or variations thereof) may provide more accurate estimates of PET. Sammis et al. (2011) presented a methodology that may allow Blaney-Criddle data to be translated into Penman-Monteith equivalents. If both Blaney-Criddle and Penman-Monteith datasets are available, regressions between Blaney-Criddle PET values and Penman-Monteith values may be used to determine a multiplier. In this study, we did not apply these data because Penman-Monteith PET values were only available for highly agricultural areas, which may have biased the results. Another alternative is to use measured pan evaporation data to provide estimates of PET.

Growing season: For simplicity, an extended growing season was used in this study (March 15 – November 15) and applied to all ecozones except ecozone 2. Some regions within Colorado (i.e. mountain areas) may experience shorter growing periods. The growing season is influenced by factors such as elevation, temperature, precipitation, and sunlight hours. It may vary from year to year, making it difficult to determine an average growing season for a large region.

Section 3.12.2 demonstrates the effect of the length of the growing season in the mountainous regions (ecozone 2) of Colorado. Local data on the growing season may result in improved percolation estimates at specific sites.

Snow: Total precipitation data provided by NCDC, which include rain and snow water equivalent data, were used for this study. As a result, all precipitation in the model is assumed to be liquid water. It may be beneficial to separate rain and snow data. In mountainous regions (e.g. ecozone 2), snow accumulates throughout the winter and then rapidly melts during spring runoff. There is a potential for higher levels of infiltration during the spring due to rapid melt-off of the snowpack. A method that accurately models the effects of winter accumulation and spring snowmelt, taking into consideration such phenomena as sublimation, wind transfer, and rapid melting, may result in new insights into the predicted performance of water balance covers.

LAI: Average LAI values were used for transforming PET into PT and PE in this study. Alternatively, maximum LAI values could be used. Using the average values avoids overestimating the amount of transpiration that is taking place because the canopy has its maximum leaf area for only a brief time during the growing season. At the beginning of the growing season, water is lost primarily from soil evaporation. As the growing season progresses and the soil is less bare, water is lost primarily to plant transpiration.

Waste parameters: Because MSW can be coarse-grained compared to overlying soil, it may act as a capillary barrier. This effect arises when fine grained material overlies coarser material. When the pressure heads are equal across the boundary, the fine grained soil may be much wetter than the coarse material. The $K(\theta)$ for the drier coarse-grained material may be orders of magnitude lower than the fine grained soil above, and it will not allow the flow of appreciable amounts of water until the coarse-grained material can wet up further (through an accumulation of water above the barrier). In general, the effect is magnified by very low moisture content at field capacity in the coarse-grained material, along with a low K_s . The saturated hydraulic conductivity of waste from previous laboratory studies ranged from 1×10^{-8} m/s (0.086 cm/d) (Bleiker et. al., 1993) to 1.3×10^{-3} m/s (1.1×10^4 cm/d) (Chen and Chynoweth, 1995). Literature values for van Genuchten water retention curve (WRC) parameters for waste also vary considerably. Parameters for van Genuchten water retention curve (WRC) measured by Kazimoglu et al. (2006) produced an intermediate percolation rate and were used in this modeling study. These variations in waste properties and their effect on predicted percolation values must be considered when developing detailed water balance cover designs.

Wilting Point: Simulated percolation rates may be sensitive to the assumed values of the wilting point. Some soils will not store much more water with an increased suction at the wilting point (e.g., Soil 2), but other soils (e.g., soils 3 and 6) gain storage with a higher wilting point. Higher wilting points decrease percolation rates substantially and should be considered during the development of detailed water balance cover designs.

Design Year Determination: For this study, the maximum P/PET ratio was used to determine the design year. As reported in Albright et al. (2010), a study by Apiwantragoon (2007) showed that the P/PET ratio is the best metric for determining when water will accumulate in the soil. Using the maximum P/PET ratio is a conservative approach because the conditions modeled

represent the highest potential quantity of water accumulation. Other studies have chosen design years based solely on precipitation including the wettest 10 year period, wettest year on record, and average year. The selected design year was used for 20 consecutive years in the model to diminish the effects of the initial conditions.

5. Summary

This report presents percolation results for generic monolithic water balance covers for seven different soil types within five distinct Colorado ecozones. The tasks completed to reach the project objective included acquiring climate and soil data, delineating ecozones to represent regions with similar physical and climate characteristics, modeling water balance landfill covers for seven soil types in five ecozones using the HYDRUS-1D model, and summarizing the modeled downward, upward, and net percolation estimates. The results of this study indicate that water balance landfill covers constructed in Colorado with suitable soils will result in minimal net percolation rates and downward fluxes. Higher rates of percolation are predicted with thinner (2.5ft and 3ft) cover thicknesses and some soil types (e.g. Soils 1 & 2). Ecozones 1 and 5 appear to be best suited for water balance covers, with all modeled soils and thicknesses resulting in low net percolation and downward fluxes. Ecozones 2, 3, and 4 may also be suitable, although percolation rates are more sensitive to the selected soil type and cover thickness.

This study provides general percolation estimates using representative climate data intended to be applicable to large regions within Colorado. The results may inform landfill owners and operators on the potential for developing water balance covers at specific sites where the climate (precipitation and evapotranspiration) is similar to the climate at the selected monitoring stations, and if the parameters of proposed cover soils fall within ranges used for modeling water balance covers in this study. In locations within or beyond Colorado, where climate and soils data vary from those modeled in this study, percolation values may be substantially different and additional site-specific modeling may be necessary to design appropriate landfill covers.

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APPENDIX B

**METHODS TO EVALUATE
LONG-TERM VEGETATIVE SUCCESS**

As discussed in Guidance Document Section 2.3.5.1 – Suggested Techniques for Conducting Evaluations, there are a number of generally accepted methods to be used. This appendix provides more detail on those methods.

Methods that may be used to evaluate long-term vegetative success are listed below.

- 1) Stand Height Measurement Method – Measure the stand height of the newly established vegetation and compare that against natural growth stands in the reference area (see also Section 2.3.4: Soil Amendments and Revegetation Establishment).
- 2) Biomass Measurement Method – Measure the biomass of the newly established vegetation by removing a specific amount (e.g., vegetation over a 1 foot by 1 foot area), dry the biomass, and weigh the biomass. Compare this sample against a sample processed in a similar manner and collected from a similar 1 foot by 1 foot area of natural growth stands in the reference area. The weight of the dried biomasses should be similar.
- 3) Soil Moisture Measurement Method – Measure the soil moisture content of the upper WBC soils against the soil moisture content of natural soils in the reference area. The soil moisture content of the upper WBC soils should be similar to that of the soil in the reference area.
- 4) Small Area Evaluation Method – Evaluate 3 foot by 3 foot square areas (9 square feet) on the WBC as appropriate for the size of the WBC and compare plant density (species type and coverage) with a similar 3 foot by 3 foot area of the reference area. Alternatively, simply count the “clumps” of grass within the 9 square feet area on the WBC against a 9 square feet area of the reference area. Visually assess the density of the species of plants, or the count of the clumps of grass. The density or count on the WBC should be approximately similar to that of the natural growth in the reference area.
- 5) Transect Liner Intercept Method – Plot/Quadrat locations, starting points within the plots/quadrats, and transect angles will be selected randomly prior to the inspections. Transects will be 100 feet long with a determination of cover made at 1-foot intervals. Live vegetative cover will be recorded by species, along with litter cover. This will produce 100 points of data per transect. The transects will be continued until statistical adequacy is met. Sample size will be determined statistically adequate using the Snedecor-Cochran sample adequacy formula, as shown below:

$$N_{\min} = (t^2 s^2) / (dX)^2$$

Where:

- $N_{\min}$ = the minimum number of transects needed;
- t = 1.833 (the t-table value for a two-tailed t-test [n-1] degrees of freedom at the 90 percent confidence level);
- s^2 = the sample variance;
- d = 0.1 (level of precision for estimate of the mean to be within 10 percent of the actual mean); and
- X = the sample mean.

Vegetation success monitoring will continue until the success criteria outlined below are met. Comparison to the criteria below will begin two years after the initial seeding. At this point, if the appropriate live vegetation and/or percent cover have not passed the success criteria, additional measures will be implemented to achieve successful revegetation of the site.

Vegetative cover will be measured against the following standards beginning two years following initial seeding. The applicable standards are:

- Total live vegetation cover of perennial species in the seed mix or other appropriate live perennial vegetative species (excluding noxious weeds/vegetation) in any year starting two years after initial seeding > 25%;
- Two-year running average for percent cover starting two years after initial seeding > 50%; and
- Three-year running average for percent cover starting two years after initial seeding > 67%.

With percent cover defined as:

- Percent cover = 100 – percent bare ground = Percent live vegetation of perennial species in seed mix (i.e., Blue Grama, Buffalo Grass, Thickspike Wheatgrass, Western Wheatgrass, Prairie Clover, Sandberg Blue Grass, Needle and Thread) + Percent appropriate live perennial vegetation by species not in seed mix + Percent inappropriate live vegetation by species (e.g., noxious weeds/vegetation) + Percent standing dead vegetation + Percent rock + Percent litter + Percent cryptogams.

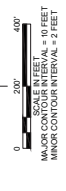
Also, a single live perennial species in the seed mix or other appropriate live perennial species may not comprise more than 60 percent of the vegetative growth of live perennial species. Areas having insufficient vegetation success two years after initial seeding will be repaired and reseeded as necessary as per procedures provided to the Department in the annual vegetation success monitoring report. If the vegetative cover standards are not achieved at five (5) calendar years after initial seeding, the existing vegetation activities shall be revisited and additional remedial procedures shall be submitted to the local governing authority and Department for review and approval within ninety (90) calendar days following such a determination.

APPENDIX B – CCR LANDFILL DESIGN DRAWINGS

rev	date	by	chkd	description
0	7/27	MG	JL	DESIGN DRAWINGS

NOTE:

1. DETENTION POND 2 OUTLET STRUCTURE SHALL BE MODIFIED TO INCLUDE ROW OF FOUR 0.5-INCH HOLES AT ELEVATION EQUAL TO POND BOTTOM TO ALLOW FOR FULL DRAINAGE OF POND.



9785 Maroon Circle, Suite 400
Colorado Springs, CO 80902
303.771-9282

date	designed	checked	approved
JULY 2018	J LEE	M GONZALES	B COLEMAN



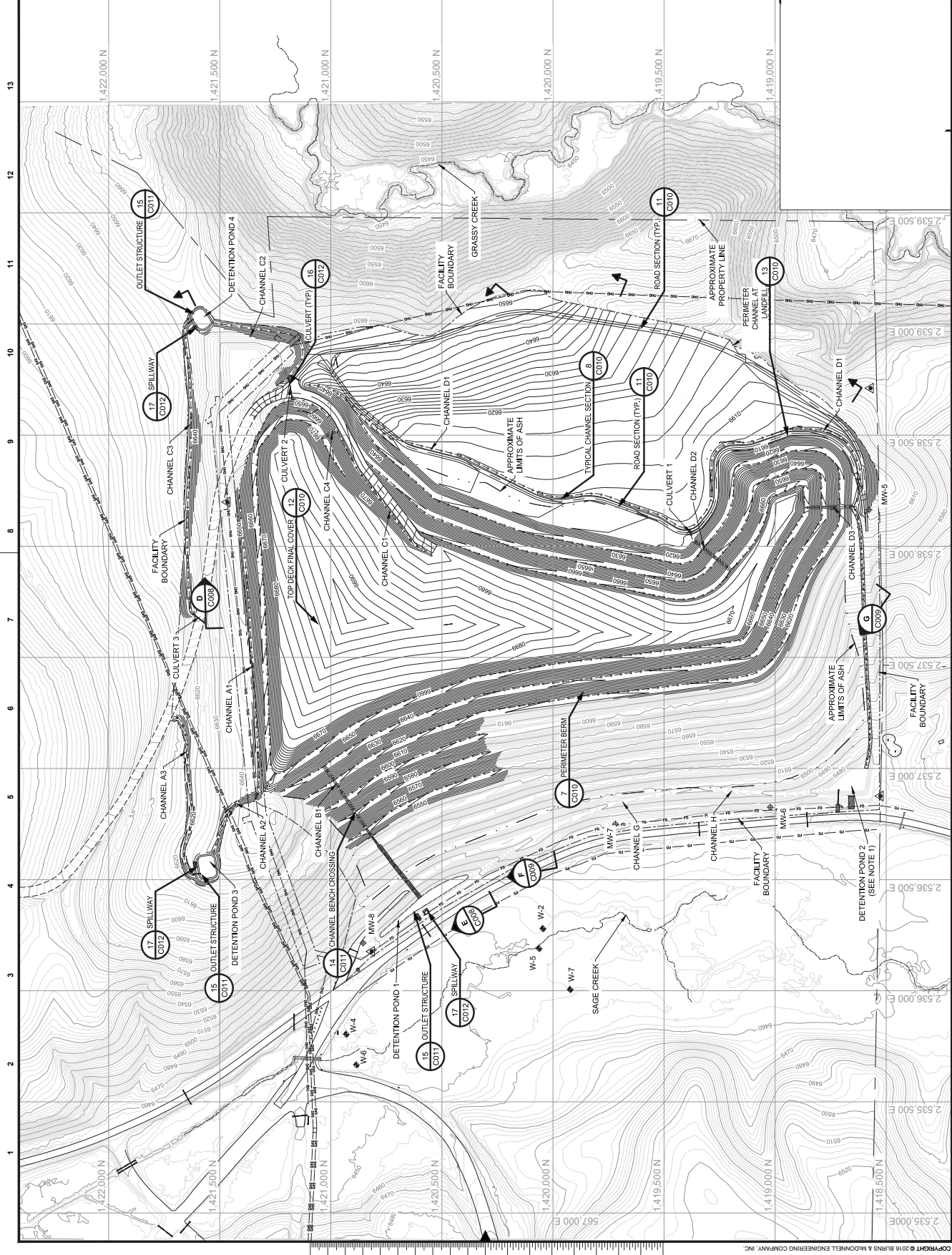
HAYDEN, COLORADO
HAYDEN STATION DISPOSAL FACILITY
DESIGN DRAWINGS

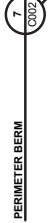
FINAL COVER GRADING PLAN

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drawing	sheet	of	14	sheets
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9785 Maroon Circle, Suite 400
Centennial, CO 80112
303-721-9292

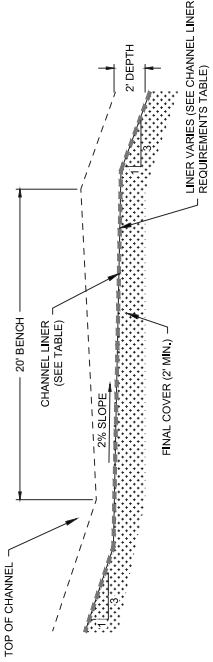
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DETAILS 1

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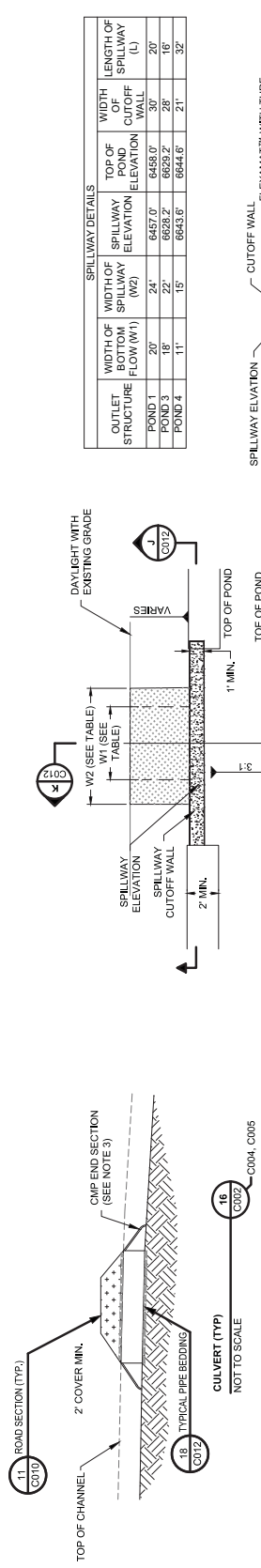
- 8 TYPICAL CHANNEL SECTION
C010



NOT TO SCALE

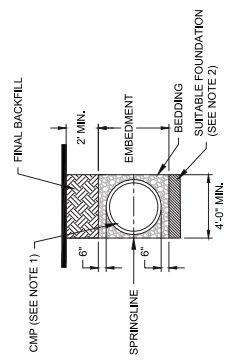
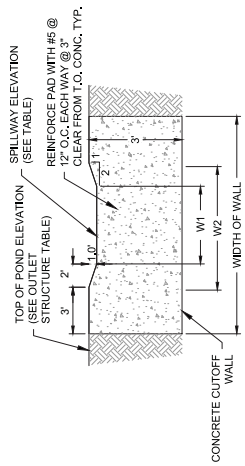


OUTLET STRUCTURE DETAILS



CULVERT DETAILS					
NAME	INVERT IN	INVERT OUT	TYPE	LENGTH	QUANTITY
CULVERT 1	6608.9'	6608.6'	CMP	30.0'	3
CULVERT 2	6645.9'	6644.9'	CMP	100.0'	1
CULVERT 3	6627.2'	6626.2'	CMP	63.0'	1
					24' Ø

- NOTES:
- ALL PIPES SHALL BE INSTALLED IN ACCORDANCE WITH CDOT SPECIFICATIONS.
 - CONTRACTOR SHALL EXCAVATE UNSUITABLE MATERIAL AND REPLACE WITH MATERIAL AS SPECIFIED BY THE ENGINEER AS AN ALTERNATIVE AND THE TRENCH BOTTOM MAY BE STABILIZED USING A GEOTEXTILE MATERIAL.
 - CMP END SECTION SHALL BE A STANDARD TACKON APPROX THAT WILL FIT THE SPECIFIED PIPE DIAMETER MATERIAL DIMENSIONS, AND INSTALLATIONS SHALL MEET CDOT SPECIFICATIONS.



TYPICAL PIPE BEDDING
NOT TO SCALE
C012

SPILLWAY - SECTION
NOT TO SCALE
C012

SPILLWAY - SECTION
NOT TO SCALE
C012

BURNS MEDONNELL
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date	JULY 2018	designed	J LEE
checked	M GONZALES	checked	B COLEMAN



HAYDEN, COLORADO
HAYDEN STATION DISPOSAL FACILITY
DESIGN DRAWINGS

project	98286	contract	62417
drawing	C012	rev.	0

sheet	14	of	14
drawn			

file 98286C012DET3.DWG

APPENDIX C – CLIMATE DATA CALCULATIONS

Hayden Ash Landfill Climate Data Calculations



PROJECT	Hayden Ash Landfill
SUBJECT	Colorado Guidance Climate Zone
PROJECT NUMBER	98286
DATE	07/10/17

Page 1 of 3

Purpose: This calculation package will analyze precipitation and potential evapotranspiration data for the Xcel Hayden Ash Landfill site to evaluate which ecozone the area most closely represents.

Background: Xcel's Hayden Ash Landfill (Landfill) requires an update to its engineering, design and operations plan (EDOP). As part of the EDOP, an evaluation of the final cover will be performed. The final cover will consist of a water balance cover as defined in Reference 1, *Final Guidance Document for Water Balance Covers in Colorado* (Guidance Document), and will meet the storage layer thickness design criteria or the associated ecozone. The landfill site is located on the boundary of Ecozone 1 and Ecozone 2 shown in the Guidance Document. The distinction between the two ecozones is important because landfills in Ecozone 1 follows the procedures outlined in the Guidance Document, whereas landfills in Ecozone 2 require site specific modeling to evaluate a final cover thickness.

Methodology: Using the equations and procedures from the Guidance Document, a ratio of annual average precipitation to annual average potential evapotranspiration (PET) will be calculated based on data obtained for the Hayden, Colorado weather station near the Landfill. The ratio calculated will then be compared to the ratios for the other ecozones. Data was obtained from the National Oceanic & Atmospheric Administration (NOAA) National Centers for Environmental Information (formerly the National Climatic Data Center) (Reference 2) to match the time period used in the original evaluation, 1980-2010. The data was obtained in pdf and tabular format and the calculations were performed using the tabular data. Attachment 2 consists of the first page of the pdf showing the station meta data and format of the obtained data. The full pdf and tabular data are available upon request.

Precipitation

Daily precipitation data was summed for each year and annual precipitation quantities are shown on page 3.

PET

The mean daily temperature was calculated from daily high and low temperatures for use in the following PET equation. Daily calculated PET data was summed for each year and annual quantities are shown on page 3.

Equation 1 $PET = p * (0.46 * T_{mean} + 8)$

where:

PET = Potential Evapotranspiration

p = Monthly Percentage of Daytime Hours of the Year (Reference 3)

T_{mean} = Mean Temperature

Hayden Ash Landfill Climate Data Calculations



PROJECT	Hayden Ash Landfill		
SUBJECT	Colorado Guidance Climate Zone		
PROJECT NUMBER	98286		
DATE	07/10/17	Page <u>2</u> of <u>3</u>	

References: 1. Guidance Document. "Final Guidance Document Water Balance Covers in Colorado". Colorado Department of Public Health and Environment. **(Attachment 1)**
2. Page of data from Data Tools: Hayden Station. National Oceanic & Atmospheric Administration. <https://www.ncdc.noaa.gov/cdo-web/datatools/findstation> **(Attachment 2)**
3. "Determining Consumptive Use and Irrigation Water Requirement". United States Department of Agriculture. **(Attachment 3)**

Conclusions: The Hayden Landfill has an average P/PET ratio of 0.40 from 1980-2010. This value more closely corresponds to Ecozone 1 (0.30) than Ecozone 2 (0.53). Therefore the final cover design for the upper deck will use the Ecozone 1 design criteria from the Guidance Document.

Prepared By: Mark Gonzales, PE Date: 7/10/2017

Checked By: Joshua Lee, PE Date: 7/10/2017

Approved By: Bradley A. Coleman Date: 7/21/2017

Digitally signed by Bradley A. Coleman
DN: C=US,
E=bacoleman@burnsmcd.com,
O=Burns & McDonnell,
OU=Environmental Services,
CN=Bradley A. Coleman
Date: 2018.12.20 18:33:25-07'00'

Hayden Ash Landfill Climate Data Calculations

Prepared By: Mark Gonzales, PE
Checked By: Joshua Lee, PE

Date: 7/10/2017
Date: 7/10/2017

Yearly P/PET Calculations

Year	Annual Precipitation, P	Annual PET	Annual P/PET
	(mm)	(mm)	
1980	328	1,191	0.28
1981	550	1,243	0.44
1982	457	1,141	0.40
1983	607	1,166	0.52
1984	544	1,115	0.49
1985	539	1,114	0.48
1986	515	1,193	0.43
1987	378	1,178	0.32
1988	400	1,169	0.34
1989	412	1,160	0.36
1990	424	1,178	0.36
1991	416	1,138	0.37
1992	467	1,167	0.40
1993	431	1,121	0.38
1994	306	1,191	0.26
1995	527	1,178	0.45
1996	490	1,168	0.42
1997	671	1,158	0.58
1998	404	1,198	0.34
1999	460	1,200	0.38
2000	450	1,216	0.37
2001	361	1,209	0.30
2002	340	1,184	0.29
2003	514	1,216	0.42
2004	425	1,186	0.36
2005	574	1,209	0.48
2006	485	1,187	0.41
2007	512	1,213	0.42
2008	445	1,144	0.39
2009	506	1,148	0.44
2010	526	1,154	0.46
Average	467	1,175	0.40

Final Guidance Document Water Balance Covers in Colorado

Guidelines for Design, Construction, and Development of Water Balance Covers
According to the Regulations Pertaining to Solid Waste Sites and Facilities
6 CCR 1007-2, Part 1



Colorado Department Public Health and Environment
Hazardous Materials and Waste Management Division
Solid Waste and Materials Management Program

March 2013

.2.2.1 Precipitation

Monthly precipitation and snowfall data for all Colorado stations (n=354) were downloaded for the years 1980-2010 and imported into Microsoft Excel. Years with incomplete data were deleted. In addition, all stations with less than 10 years of complete data were removed from the dataset with the exception of those located near a new station in the same local area (e.g., Station Delta [COOP ID 52192] collected data from 1980-1999, and Delta 3E [COOP ID 52196] collected data from 2000-2010).

For the remaining stations (n=239), average annual precipitation and average annual snowfall were calculated. In addition, “typical years” at each station were defined as years within ½ standard deviation of the average annual P. For each typical year, the wettest month was calculated as the month with the highest percentage of the total annual rainfall. The average wettest month (in terms of P [mm] and percent contribution to total annual P) was calculated for the typical years.

The values calculated at each station for average annual P, wettest month P, and average annual snowfall were used to interpolate precipitation data for Colorado. Interpolation was conducted with the ArcGIS v.10 and Spatial Analyst geographic information system (GIS) software applications. Interpolation was performed through Kriging, using a variable search distance (12 points) and a spherical semivariogram model. Interpolated results for average annual P, wettest month P, and average annual snowfall are shown in Figures 4, 5, and 6 respectively.

Following the interpolation of snowfall and P, the ratio of snow/P was calculated using the Raster Calculator in ArcGIS. This calculation assumed equivalent water content in the snow across all snow events. These results are shown in Figure 7.

2.2.2 Evapotranspiration (PET)

Temperature data from NCDC were downloaded for 294 stations in Colorado. Average annual reference evapotranspiration (ET_0 , hereafter referred to as PET)¹ values were calculated for 188 stations that had at least 10 complete years of temperature data. The Blaney-Criddle (B-C) equation was used to calculate PET using available temperature data from NCDC (Blaney and Criddle, 1950). The B-C formula used in this study (calculated for grass that is 8-15 cm high and receiving adequate water), is:

$$PET = p (0.46 T_{\text{mean}} + 8)$$

Where:

PET = Reference crop evapotranspiration (mm/day) as an average for a period of 1 month

T_{mean} = mean daily temperature (°C)

p = mean daily percentage of annual daytime hours

¹ ET_0 and potential evapotranspiration (PET) are terms which are often used interchangeably, although PET is a more general term and does not specify a particular crop type. The definition of ET_0 in this study is the rate of ET calculated for green grass, with an assumed height of 0.12 m, which is well watered and completely shades the ground as the reference crop (Allen et al., 1998). The term PET is used throughout this report to refer to ET_0 .

Elev: 6467 ft [Lat: 40.493° N, Lon: 107.255° W]

Station: HAYDEN, CO US GHCND:USC00053867

Observation Time Temperature: 1800 Observation Time Precipitation: 1800

P r e l i m i n a r y	Y e a r	M o n t h	D a y	Temperature (F)		Precipitation				Evaporation		Soil Temperature (F)			
				24 hrs. ending at observation time		24 Hour Amounts ending at observation time				At Obs Time		4 in depth			
				Max.	Min.	Rain, melted snow, etc. (in)	F l a g	Snow, ice pellets, hail (in)	F l a g	Snow, ice pellets, hail, ice on ground (in)	24 Hour Wind Move ment (mi)	Amount of Evap. (in)	Ground Cover (see *)	Max.	Min.
	1980	1	1	36	7	0.02		0.5		11.0					
	1980	1	2	31	23	0.20		3.0		13.0					
	1980	1	3	28	10	0.00		0.0		13.0					
	1980	1	4	33	21	0.15		2.0		14.0					
	1980	1	5	38	17	0.00		0.0		13.0					
	1980	1	6	37	-11	T		T		13.0					
	1980	1	7	27	0	0.02		0.5		13.0					
	1980	1	8	28	7	0.30		7.0		19.0					
	1980	1	9	39	18	T		0.2		17.0					
	1980	1	10	40	18	0.15		5.0		15.0					
	1980	1	11	19	-4	0.00		0.0		15.0					
	1980	1	12	38	16	0.47		3.5		17.0					
	1980	1	13	44	34	0.00		0.0		14.0					
	1980	1	14	43	33	0.40		2.0		14.0					
	1980	1	15	40	27	0.00		0.0		13.0					
	1980	1	16	34	23	0.06		0.5		13.0					
	1980	1	17	38	21	0.01		T		13.0					
	1980	1	18	39	22	0.03		1.0		13.0					
	1980	1	19	34	17	0.00		0.0		13.0					
	1980	1	20	24	15	T		T		13.0					
	1980	1	21	30	8	T		T		13.0					
	1980	1	22	24	1	0.00		0.0		13.0					
	1980	1	23	25	-4	0.00		0.0		13.0					
	1980	1	24	32	3	0.00		0.0		13.0					
	1980	1	25	34	4	0.03		1.0		14.0					
	1980	1	26	20	0	0.11		3.0		17.0					
	1980	1	27	18	-7	0.13		2.0		19.0					
	1980	1	28	15	11	0.85		11.0		26.0					
	1980	1	29	33	11	0.47		8.0		29.0					
	1980	1	30	24	-9	T		T		27.0					
	1980	1	31	22	-11	0.00		0.0		26.0					
			Summary	31	10	3.40		50.2							

The "*" flags in Preliminary indicate the data have not completed processing and quality control and may not be identical to the original observation

Empty, or blank, cells indicate that a data observation was not reported.

*Ground Cover: 1=Grass; 2=Fallow; 3=Bare Ground; 4=Brome grass; 5=Sod; 6=Straw mulch; 7=Grass mulch; 8=Bare muck; 9=Unknown

"s" This data value failed one of NCDC's quality control tests.

"T" values in the Precipitation category above indicate a TRACE value was recorded.

"A" values in the Precipitation Flag or the Snow Flag column indicate a multiday total, accumulated since last measurement, is being used.

Data value inconsistency may be present due to rounding calculations during the conversion process from SI metric units to standard imperial units.

**Determining Consumptive Use
and
Irrigation Water Requirements**

Technical Bulletin No. 1275

**Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE
in cooperation with
The Office of Utah State Engineer**

CONSUMPTIVE USE AND WATER REQUIREMENTS

43

TABLE 16.—*Monthly percentage of daytime hours of the year*¹

FOR LATITUDES 0° TO 65° NORTH OF THE EQUATOR

Latitude North	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
65°	3.45	5.14	7.90	9.92	12.65	14.12	13.66	11.25	8.55	6.60	4.12	2.64
64°	3.75	5.30	7.93	9.87	12.42	13.60	13.31	11.15	8.58	6.70	4.35	3.04
63°	4.01	5.40	7.95	9.83	12.22	13.22	13.02	11.04	8.60	6.79	4.55	3.37
62°	4.25	5.52	7.99	9.75	12.03	12.91	12.79	10.92	8.50	6.86	4.72	3.67
61°	4.46	5.61	8.01	9.71	11.88	12.63	12.55	10.84	8.55	6.94	4.89	3.93
60°	4.67	5.70	8.05	9.66	11.72	12.39	12.33	10.72	8.57	7.00	5.04	4.15
59°	4.81	5.78	8.05	9.60	11.61	12.23	12.21	10.60	8.56	7.07	5.09	4.31
58°	4.99	5.85	8.06	9.55	11.44	12.00	12.00	10.56	8.56	7.13	5.13	4.55
57°	5.14	5.93	8.07	9.51	11.32	11.77	11.87	10.47	8.54	7.19	5.27	4.69
56°	5.29	6.00	8.10	9.45	11.20	11.67	11.69	10.40	8.52	7.25	5.54	4.89
55°	5.39	6.06	8.12	9.41	11.11	11.53	11.59	10.32	8.51	7.30	5.62	5.01
54°	5.53	6.12	8.15	9.36	11.00	11.40	11.43	10.27	8.50	7.33	5.74	5.17
53°	5.64	6.19	8.16	9.32	10.88	11.31	11.34	10.19	8.52	7.38	5.83	5.31
52°	5.75	6.23	8.17	9.28	10.81	11.13	11.22	10.15	8.49	7.40	5.94	5.43
51°	5.87	6.25	8.21	9.26	10.76	11.07	11.13	10.05	8.48	7.41	5.97	5.46
50°	5.98	6.32	8.25	9.25	10.69	10.93	10.99	10.00	8.44	7.43	6.07	5.65
48°	6.13	6.42	8.22	9.15	10.50	10.72	10.83	9.92	8.45	7.56	6.24	5.86
46°	6.30	6.50	8.24	9.09	10.37	10.54	10.66	9.82	8.44	7.61	6.38	6.05
44°	6.45	6.59	8.25	9.04	10.22	10.38	10.50	9.73	8.43	7.67	6.51	6.23
42°	6.60	6.66	8.28	8.97	10.10	10.21	10.37	9.64	8.42	7.73	6.63	6.30
40°	6.73	6.73	8.30	8.92	9.99	10.08	10.34	9.56	8.41	7.78	6.73	6.53
38°	6.87	6.79	8.34	8.90	9.92	9.95	10.10	9.47	8.38	7.80	6.82	6.66
36°	6.99	6.86	8.35	8.85	9.31	9.83	9.99	9.40	8.36	7.85	6.92	6.79
34°	7.10	6.91	8.36	8.80	9.72	9.70	9.88	9.33	8.36	7.90	7.02	6.92
32°	7.20	6.97	8.37	8.72	9.63	9.60	9.77	9.28	8.34	7.93	7.11	7.05
30°	7.30	7.03	8.38	8.72	9.53	9.49	9.67	9.22	8.34	7.99	7.19	7.14
28°	7.40	7.02	8.39	8.68	9.46	9.38	9.58	9.16	8.32	8.02	7.27	7.27
26°	7.49	7.12	8.40	8.64	9.37	9.30	9.49	9.10	8.32	8.06	7.36	7.35
24°	7.58	7.17	8.40	8.60	9.30	9.19	9.41	9.05	8.31	8.10	7.43	7.46
22°	7.76	7.22	8.41	8.57	9.22	9.12	9.31	9.00	8.30	8.13	7.50	7.56
20°	7.73	7.26	8.20	8.52	9.14	9.02	9.25	8.95	8.30	8.19	7.58	7.88
18°	7.88	7.26	8.40	8.46	9.06	8.99	9.20	8.81	8.29	8.24	7.67	7.89
16°	7.94	7.30	8.42	8.45	8.98	8.98	9.07	8.80	8.28	8.24	7.72	7.90
14°	7.08	7.39	8.43	8.44	8.90	8.73	8.99	8.79	8.28	8.28	7.85	8.04
12°	8.08	7.40	8.44	8.43	8.84	8.64	8.90	8.78	8.27	8.28	7.85	8.05
10°	8.11	7.40	8.44	8.43	8.81	8.57	8.84	8.74	8.26	8.29	7.89	8.08
8°	8.13	7.41	8.45	8.39	8.75	8.51	8.77	8.70	8.25	8.31	7.89	8.11
6°	8.19	7.49	8.45	8.39	8.73	8.48	8.75	8.69	8.25	8.41	7.95	8.19
4°	8.20	7.58	8.46	8.33	8.65	8.40	8.67	8.63	8.21	8.43	7.95	8.20
2°	8.43	7.62	8.47	8.22	8.51	8.25	8.52	8.50	8.20	8.45	8.16	8.42
0°	8.49	7.67	8.49	8.22	8.49	8.22	8.49	8.49	8.19	8.49	8.22	8.49

FOR LATITUDES 0° TO 50° SOUTH OF THE EQUATOR

Latitude South	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0°	8.49	7.67	8.49	8.22	8.49	8.22	8.49	8.49	8.19	8.49	8.22	8.49
2°	8.55	7.71	8.49	8.19	8.44	8.17	8.43	8.44	8.19	8.52	8.27	8.55
4°	8.64	7.76	8.50	8.17	8.39	8.08	8.20	8.41	8.19	8.56	8.33	8.65
6°	8.71	7.81	8.50	8.12	8.30	8.00	8.19	8.37	8.18	8.59	8.38	8.74
8°	8.79	7.84	8.51	8.11	8.24	7.91	8.13	8.32	8.18	8.62	8.47	8.84
10°	8.85	7.86	8.52	8.09	8.18	7.84	8.11	8.28	8.18	8.65	8.52	8.90
12°	8.91	7.91	8.53	8.06	8.15	7.79	8.08	8.26	8.17	8.67	8.58	8.95
14°	8.97	7.97	8.54	8.03	8.07	7.70	7.08	8.19	8.16	8.69	8.65	9.01
16°	9.09	8.02	8.56	7.98	7.96	7.57	7.94	8.14	8.14	8.76	8.72	9.17
18°	9.18	8.06	8.57	7.93	7.99	7.50	7.88	8.90	8.14	8.80	8.80	9.24
20°	9.25	8.09	8.58	7.92	7.83	7.41	7.73	8.05	8.13	8.83	8.85	9.32
22°	9.36	8.12	8.58	7.89	7.74	7.30	7.76	8.03	8.13	8.86	8.90	9.38
24°	9.44	8.17	8.59	7.87	7.60	7.24	7.58	7.99	8.12	8.89	8.96	9.47
26°	9.52	8.28	8.00	7.81	7.56	7.07	7.49	7.87	8.11	8.94	9.10	9.61
28°	9.61	8.31	8.61	7.79	7.49	6.99	7.40	7.85	8.10	8.97	9.19	9.74
30°	9.69	8.33	8.63	7.75	7.43	6.94	7.30	7.80	8.09	9.00	9.24	9.80
32°	9.76	8.36	8.64	7.70	7.39	6.85	7.20	7.73	8.08	9.04	9.31	9.87
34°	9.88	8.41	8.65	7.68	7.30	6.73	7.10	7.69	8.06	9.07	9.38	9.99
36°	10.06	8.53	8.67	7.61	7.10	6.59	6.99	7.59	8.06	9.15	9.51	10.21
38°	10.14	8.61	8.68	7.59	7.03	6.46	6.87	7.51	8.05	9.19	9.60	10.34
40°	10.24	8.65	8.70	7.54	6.96	6.33	6.73	7.46	8.04	9.23	9.69	10.42
42°	10.39	8.72	8.71	7.49	6.85	6.20	6.60	7.39	8.01	9.27	9.79	10.57
44°	10.52	8.81	8.72	7.44	6.73	6.04	6.45	7.30	8.00	9.34	9.91	10.72
46°	10.68	8.88	8.73	7.39	6.61	5.87	6.30	7.21	7.98	9.41	10.03	10.90
48°	10.85	8.98	8.76	7.32	6.45	5.69	6.13	7.12	7.96	9.47	10.17	11.09
50°	11.03	9.06	8.77	7.25	6.31	5.48	5.98	7.03	7.95	9.53	10.32	11.30

¹ From references (34, table 171) and (48).



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