# 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.*

# Table of Contents

# Tables



# Figures

# Appendices

# 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 x $10^{-5}$ 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 materials[1].

### 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 | ≥ 80% and ≤ 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.

# 3.0 REFERENCES

Albright, W.H.; Benson, C.H.; Waugh, W.J. (2010). "Water Balance Covers for Waste Containment, Principles and Practice," ASCE Press, Reston, VA.

Buckner, D.L. (1985). "Point Intercept Sampling in Revegetation Studies: Maximizing Objectivity and Repeatability," Paper Presented at the American Society for Surface Mining and Reclamation Conference, Denver, Colorado, October 1985.

Buckner, D.L. (2000). "Sampling Protocol – Basin A Vegetation Monitoring, Rocky Mountain Arsenal, RCRA-Equivalent, 2 and 3-foot Covers, Long-Term Care Plan." Third Revision.

Buckner, D.L. (2012). Electronic Mail Correspondence, dated June 18, 2012.

Colorado Natural Areas Program (1998) Native Plant Revegetation Guide for Colorado. Colorado State Parks and Colorado Department of Natural Resources, Caring for the Land Series, Volume III. p. 258.

Cadmus Group, Inc., The (2011). "Modeling Water Balance Covers for Colorado Ecozones," prepared for the Office of Research and Development Engineering Technical Support Center National Risk Management Research Laboratory, United States Environmental Protection Agency.

Corser, P. and Cranston, M. (1991). "Observation on Long-Term Performance of Composite Clay Liners and Covers," *Proceedings, Geosynthetic Design and Performance,* Vancouver Geotechnical Society, Vancouver, BC.

Corser, P.; Pellicer, J.; and Cranston, M. (1992). "Observation on Long-Term Performance of Composite Clay Liners and Covers," *Geotechnical Fabrics Report,* Vol. 10, No. 8, Industrial Fabrics Association International, St. Paul, MN, pp. 6-16.

Doesken, Nolan J. (2010). "Questions and Answers," Colorado Climate Center, Department of Atmospheric Science, Colorado State University, http://ccc.atmos.colostate.edu/questions.php.

Environmental Protection Agency (1993). "Technical Guidance Document for Quality Assurance and Quality Control for Waste Containment Facilities," EPA/600/R-93/182.

Golder Associates Inc. (2012). "Denver Regional Landfill (South) Closure/Post-Closure Plan," April 5, 2012 (Revision 3), Prepared for Waste Connections, Inc., pp. 8-9

Goldsmith, W.; Silva, M.; and Fischenich, C. (2001). "Determining Optimal Degree of Soil Compaction for Balancing Mechanical Stability and Plant Growth Capacity," ERDCTN EMRRP-SR-26), United States Army Engineer Research and Development Center, Vicksburg, MS, http://acwc.sdp.sirsi.net/client/search/asset/1004296.

Khire, M.V.; Benson, C.H.; and Bosscher, P.J. (1997). "Water Balance Modeling of Earthen Final Covers," *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 123, No. 8, pp. 744-754.

Khire, M.V.; Benson, C.H.; and Bosscher, P.J. (1999). "Field Data from a Capillary Barrier and Model Predictions with UNSAT-H," *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 123, No. 6, pp. 518-527.

Kiel, R.; Chadwick, D.G.; Lowrey, J; Mackey, C.; Greer, L. (2002). "Design of Evapotranspirative (ET) Covers at the Rocky Mountain Arsenal."

Maine Bureau of Remediation and Waste Management (1997). "An Assessment of Landfill Cover System Barrier Layer Hydraulic Performance," Augusta, ME.

Melchior, S.; Berger, K.; Vielhaver, B.; and Miehlich, G. (1994). "Multilayered Landfill Covers: Field Data on the Water Balance and Liner Performance," *In-Situ Remediation: Scientific Basis for Current and Future Technologies,* Gee, G.W., and Wing, N.R. (eds.), Battelle Press, Columbus, OH, Part 1, pp. 411-425.

Melchior, S. (1997a). "In-situ Studies of the Performance of Landfill Caps (Compacted Soil Liners, Geomembranes, Geosynthetic Clay Liners, Capillary Barriers)," *Proceedings, International Containment Technology Conference,* St. Petersburg, FL, pp. 365-373.

Melchior, S. (1997b). "In-situ Studies of the Performance of Landfill Caps (Compacted Soil Liners, Geomembranes, Geosynthetic Clay Liners, Capillary Barriers)," *Land Contamination and Reclamation,* Vol. 5, No. 3, pp. 209-216.

Montgomery, R.J. and Parsons, L.J. (1989). "The Omega Hills Final Cover Test Plot Study: Three-Year Data Summary," presented at the Annual Meeting of the National Solid Waste Management Association, Washington, DC.

Montgomery, R.J. and Parsons, L.J. (1990). "The Omega Hills Final Cover Test Plot Study: Three-Year Data Summary," presented at the 22nd Mid-Atlantic Industrial Waste Conference, Drexel University, Philadelphia, PA.

National Resources Conservation Service (2011). "Big Sagebrush Plant Guide." May 21, 2011.

Schenk, H. J. and Jackson, R. B. (2002). "Rooting depths, lateral root spreads and below ground/above-ground allometries of plants in water-limited ecosystems," *Journal of Ecology*, Vol. 90, pp. 480-494.

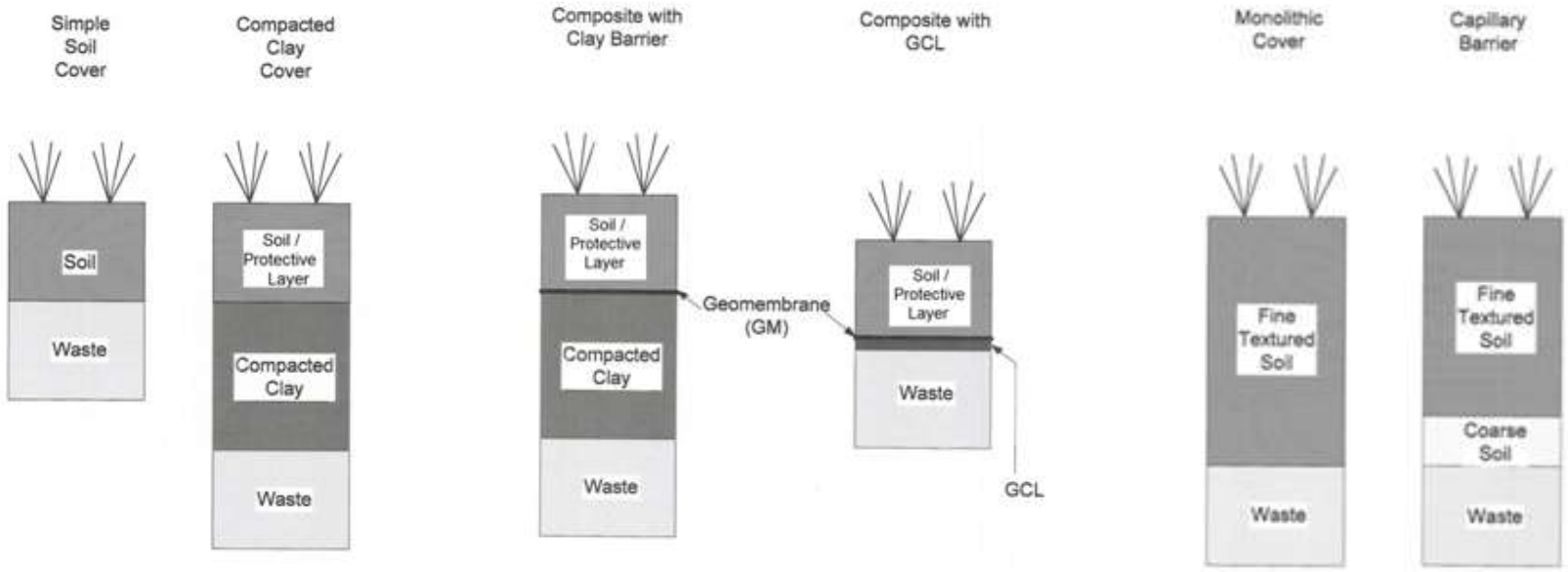
Self, J. R. (2012). Personal Interview. Director, Colorado State University Soil, Water, and Plant Testing Laboratory. May 22, 2012.

# F I G U R E S

**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




Conventional Covers with Earthen Barriers

Conventional Covers with Composite Barriers

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.

**Reference**: "Alternative Covers for Landfills, Waste Repositories, and Mine Wastes Workshop," by C.H. Benson (Denver, Colorado, November 28-30, 2006).

**FIGURE 2.2.1-1**

**COLORADO ECOZONES AND**
**ACTIVE MUNICIPAL SOLID WASTE LANDFILLS**

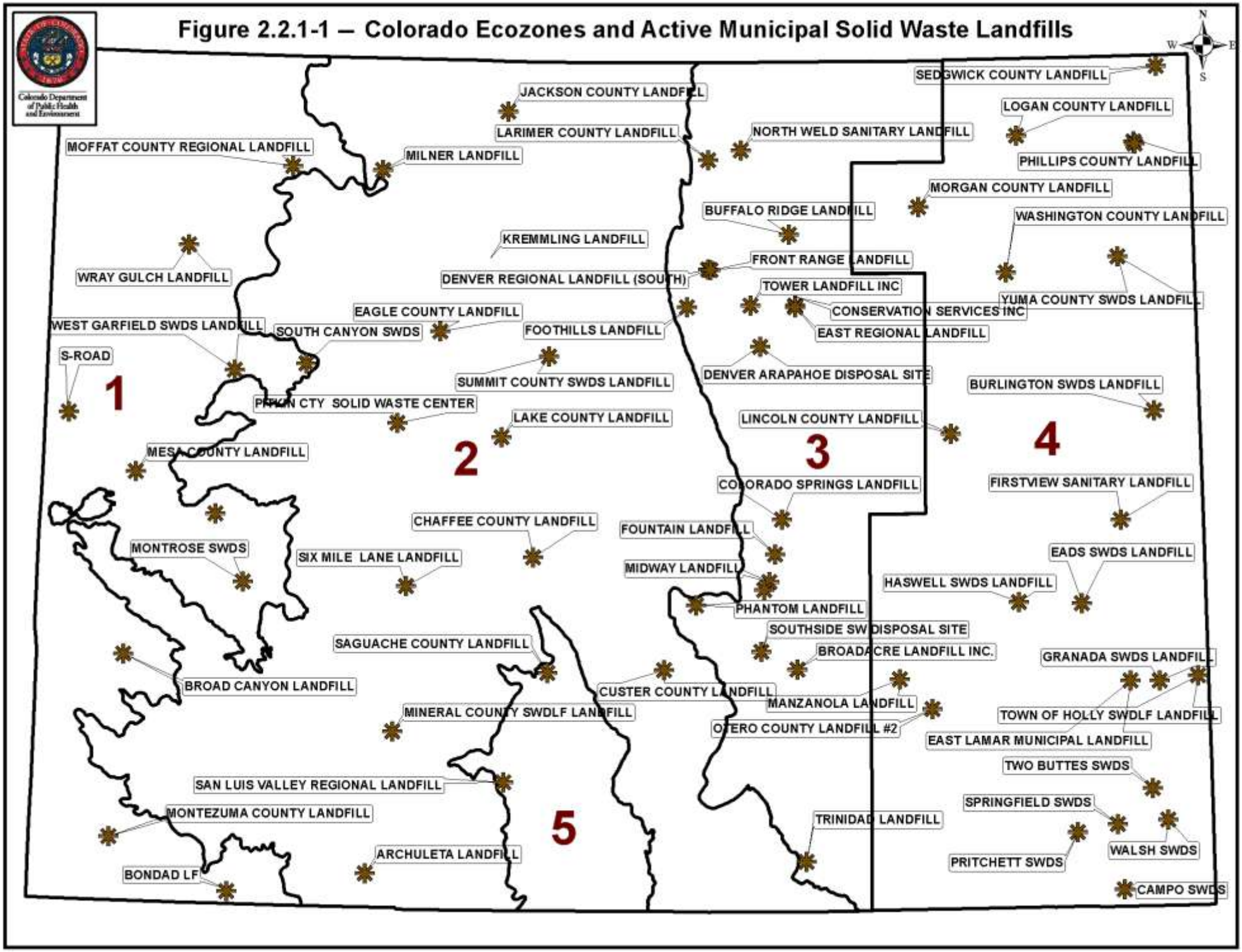
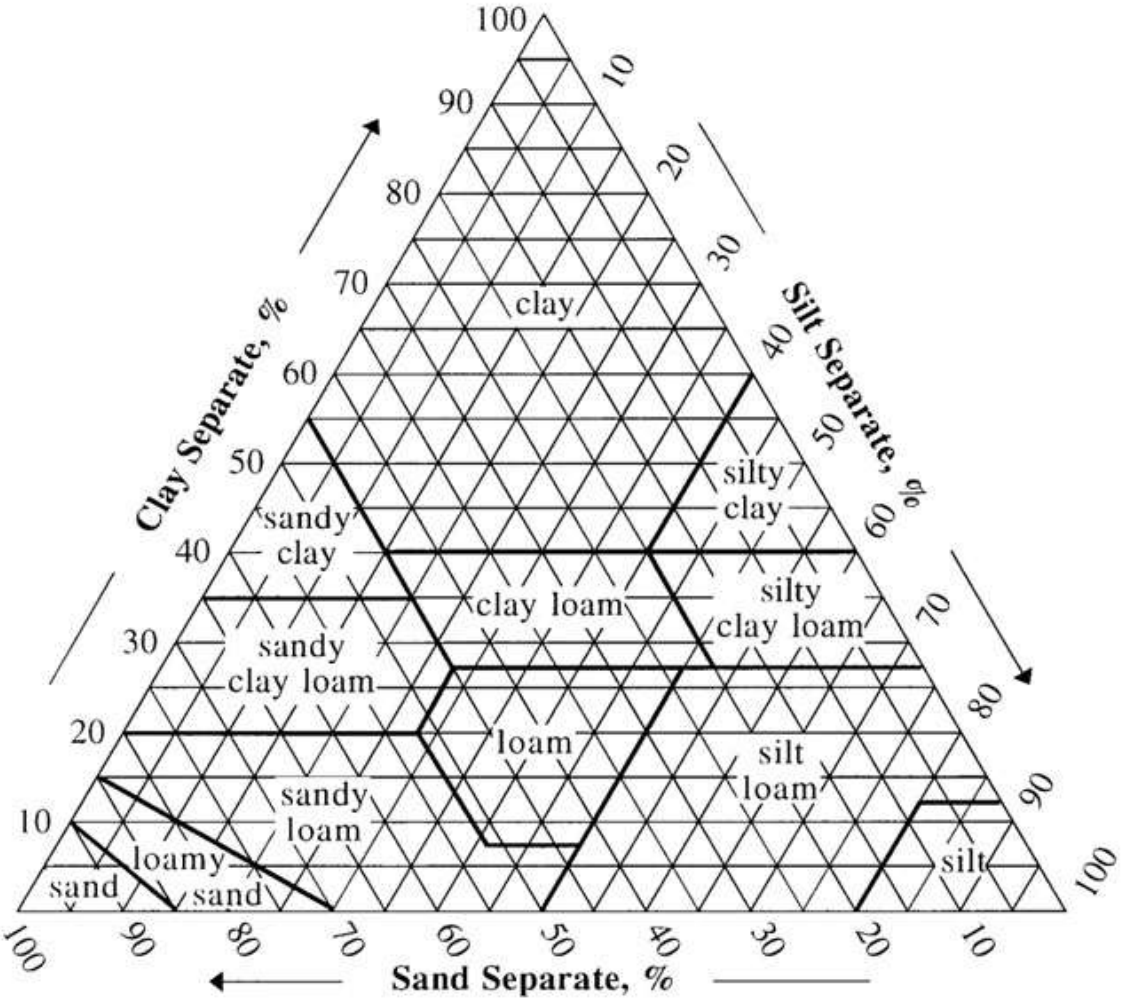


Figure 2.2.1-1 – Colorado Ecozones and Active Municipal Solid Waste Landfills
Colorado Department of Public Health and Environment
N
W
E
S
SEDGWICK COUNTY LANDFILL
JACKSON COUNTY LANDFILL
LOGAN COUNTY LANDFILL
LARIMER COUNTY LANDFILL
NORTH WELD SANITARY LANDFILL
MOFFAT COUNTY REGIONAL LANDFILL
MILNER LANDFILL
PHILLIPS COUNTY LANDFILL
MORGAN COUNTY LANDFILL
BUFFALO RIDGE LANDFILL
WASHINGTON COUNTY LANDFILL
KREMMLING LANDFILL
WRAY GULCH LANDFILL
FRONT RANGE LANDFILL
DENVER REGIONAL LANDFILL (SOUTH)
TOWER LANDFILL INC
YUMA COUNTY SWDS LANDFILL
CONSERVATION SERVICES INC
EAGLE COUNTY LANDFILL
WEST GARFIELD SWDS LANDFILL
SOUTH CANYON SWDS
FOOTHILLS LANDFILL
EAST REGIONAL LANDFILL
S-ROAD
DENVER ARAPAHOE DISPOSAL SITE
BURLINGTON SWDS LANDFILL
SUMMIT COUNTY SWDS LANDFILL
1
PITKIN CTY SOLID WASTE CENTER
LAKE COUNTY LANDFILL
LINCOLN COUNTY LANDFILL
2
3
4
MESA COUNTY LANDFILL
COLORADO SPRINGS LANDFILL
FIRSTVIEW SANITARY LANDFILL
CHAFFEE COUNTY LANDFILL
FOUNTAIN LANDFILL
MONTROSE SWDS
SIX MILE LANE LANDFILL
EADS SWDS LANDFILL
MIDWAY LANDFILL
HASWELL SWDS LANDFILL
PHANTOM LANDFILL
SOUTHSIDE SW DISPOSAL SITE
SAGUACHE COUNTY LANDFILL
BROADACRE LANDFILL INC.
GRANADA SWDS LANDFILL
BROAD CANYON LANDFILL
CUSTER COUNTY LANDFILL
MANZANOLA LANDFILL
TOWN OF HOLLY SWDLF LANDFILL
MINERAL COUNTY SWDLF LANDFILL
OTERO COUNTY LANDFILL #2
EAST LAMAR MUNICIPAL LANDFILL
TWO BUTTES SWDS
SAN LUIS VALLEY REGIONAL LANDFILL
SPRINGFIELD SWDS
MONTEZUMA COUNTY LANDFILL
TRINIDAD LANDFILL
5
WALSH SWDS
PRITCHETT SWDS
ARCHULETA LANDFILL
BONDAD LF
CAMPO SWDS

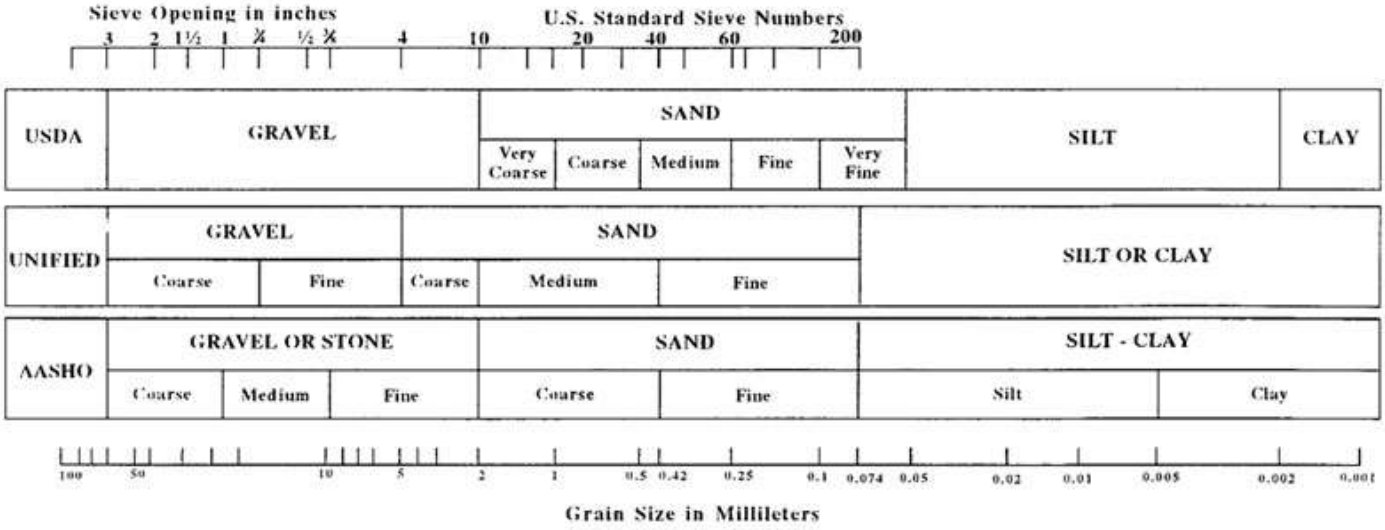
**FIGURE 2.2.1-2**

**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**

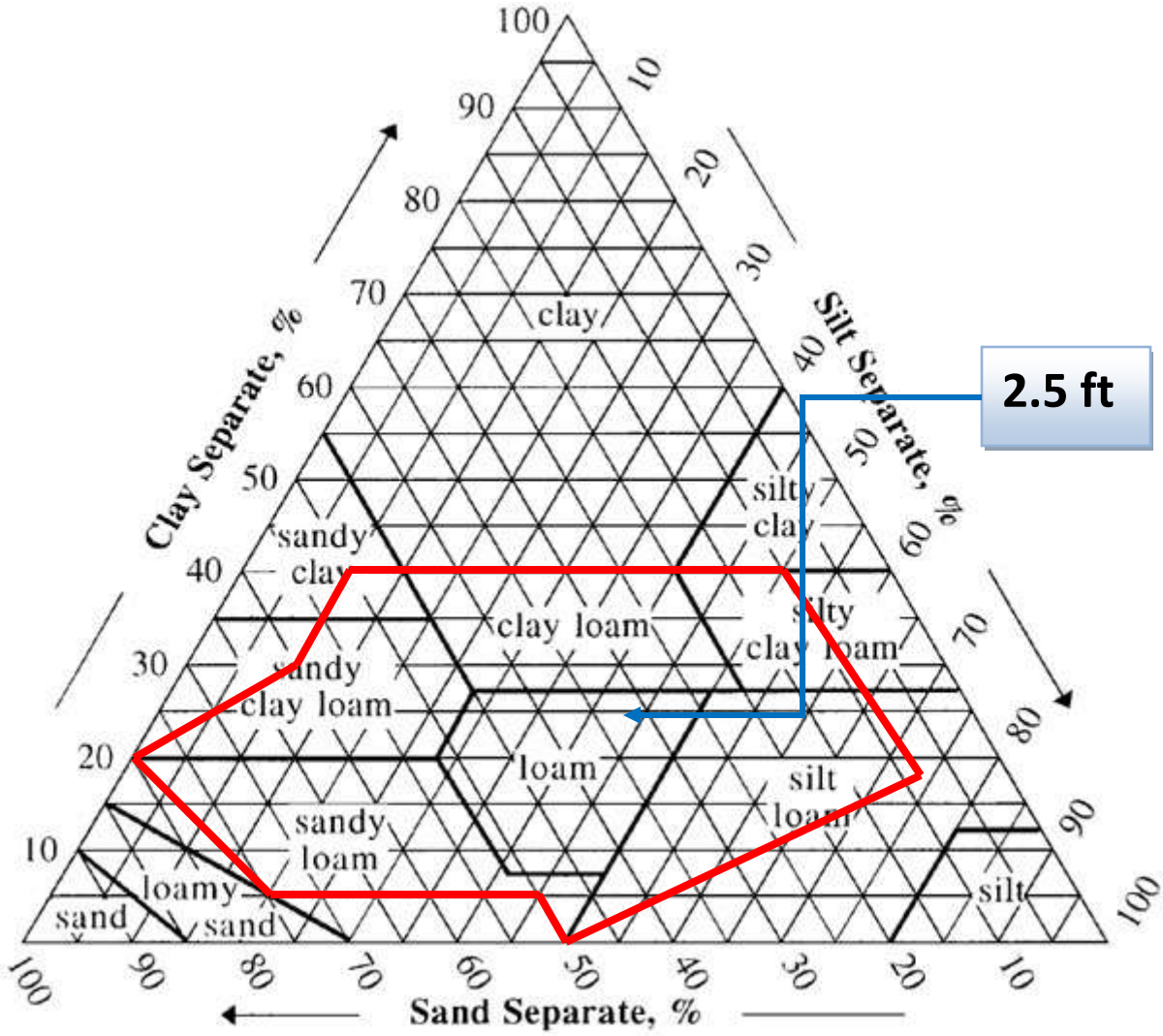


**FIGURE 2.2.1-4**

**WATER STORAGE LAYER THICKNESSES FOR ECOZONE 3**

**Figure 2.2.1-4**
**Water Storage Layer Thicknesses for**
**Ecozone 3**

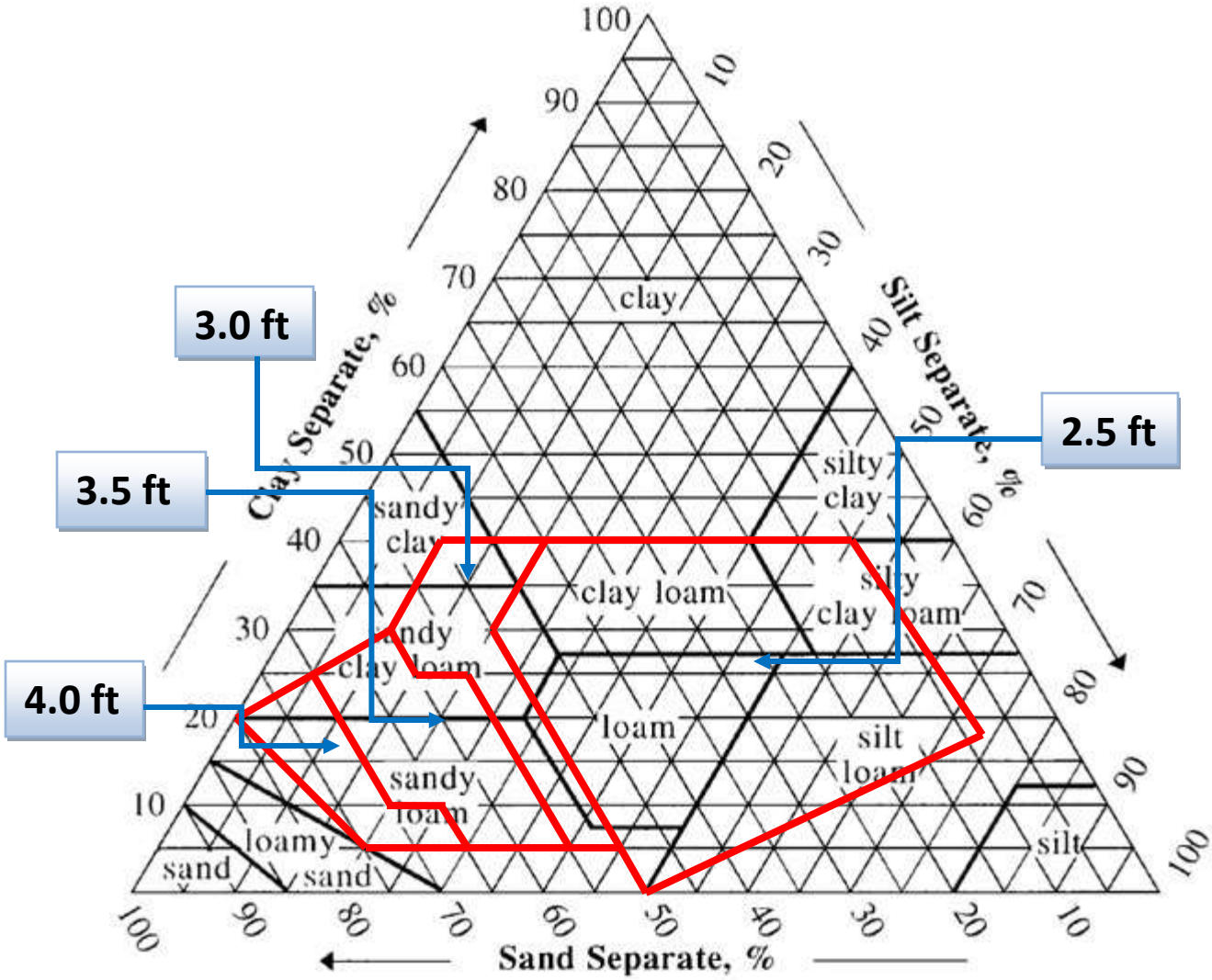
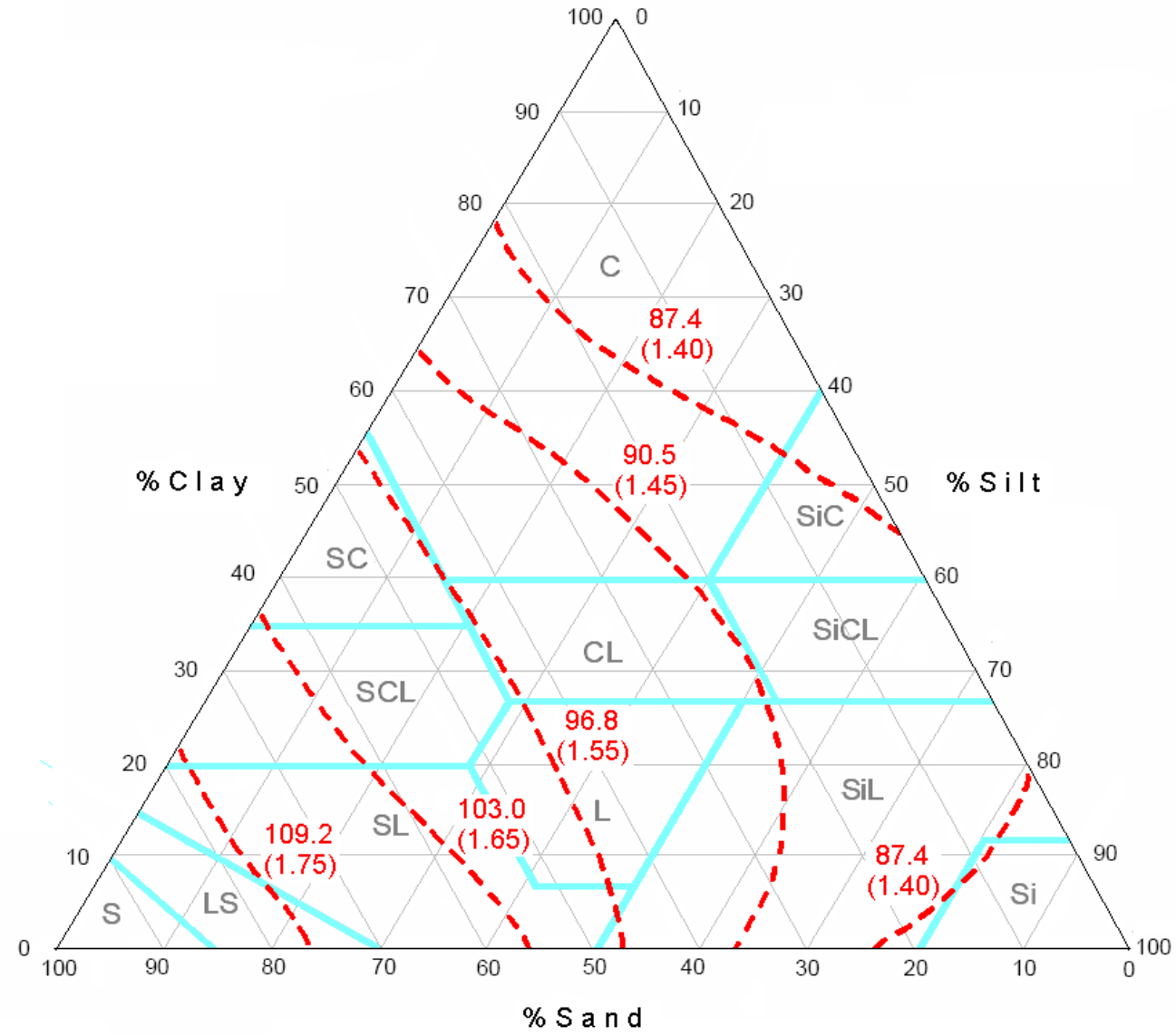


**FIGURE 2.2.3-1**

**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).

# A P P E N D I C E S

# 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:*
The Cadmus Group, Inc.
57 Water St,
Watertown, MA 02472

This page intentionally left blank.

# Authors

Tarek Abichou, Ph.D. — Florida State University

David Benson, Ph.D. — Colorado School of Mines
Mengistu Geza, Ph.D. — Colorado School of Mines

Katy Beggs, Ph.D. — The Cadmus Group, Inc.
Jeff Maxted
Nupur Hiremath
Daniel Mahr

This page intentionally left blank.

# Table of Contents

# List of Figures

# List of Tables

# 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 |

This page intentionally left blank.

# 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 ($\Delta S_w$) 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.

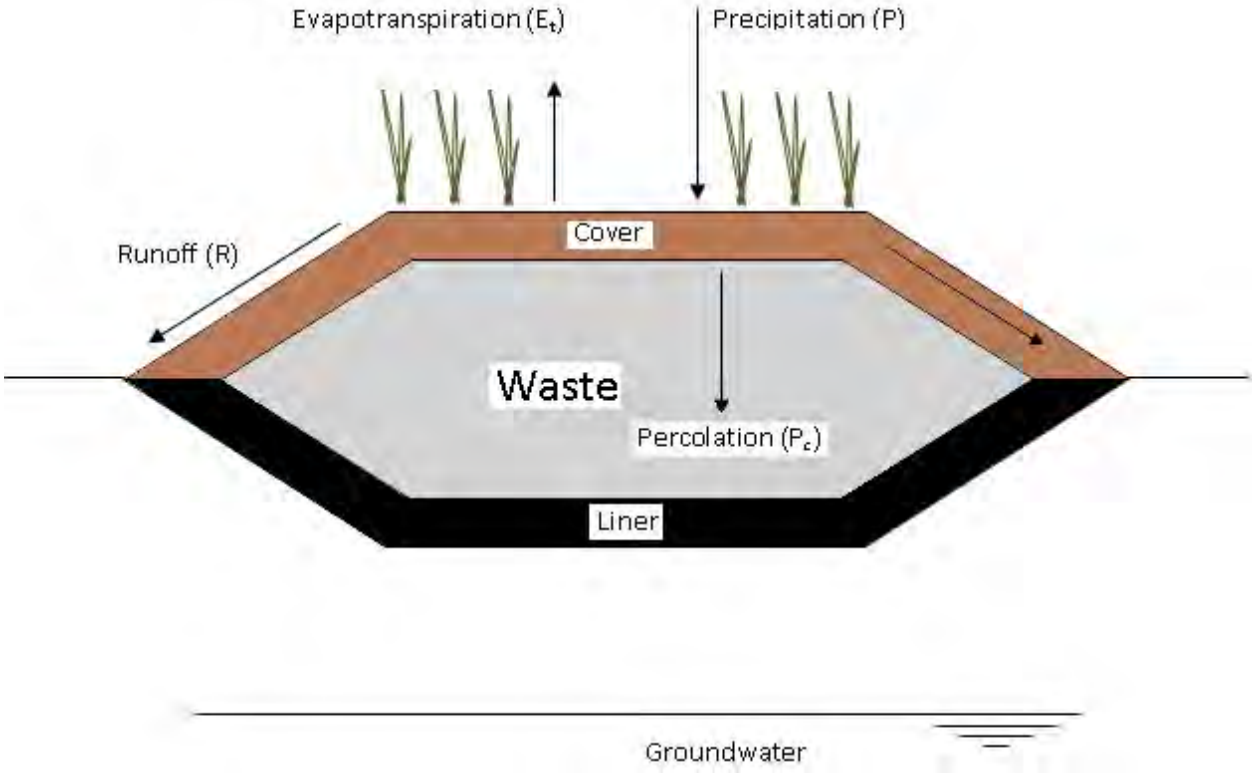



**Figure 1. Schematic of a Monolithic Water Balance Landfill Cover**

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.

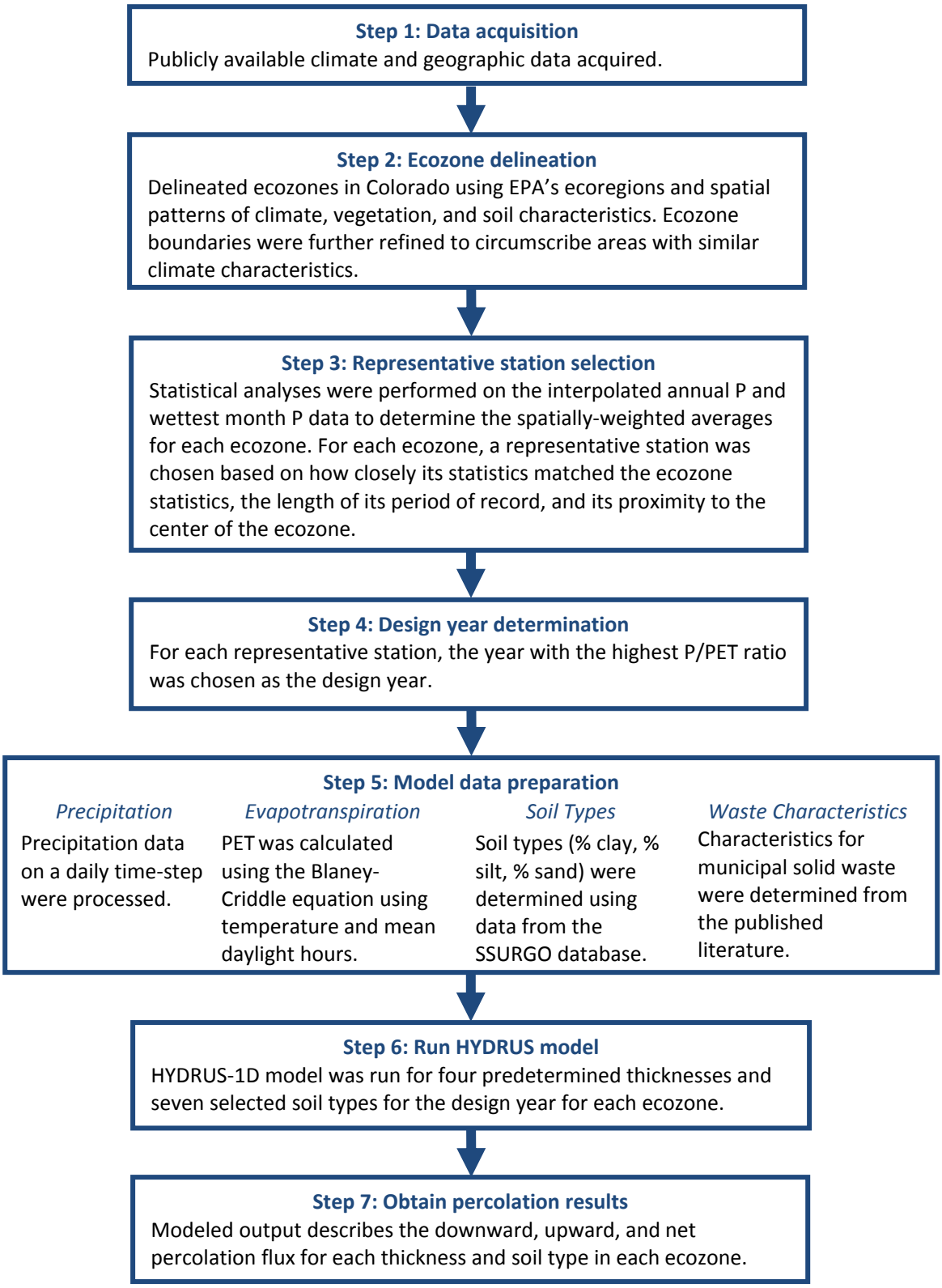



**Figure 2. Overview of Methodology for Modeling Water Balance Covers in Ecozones**

# 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).

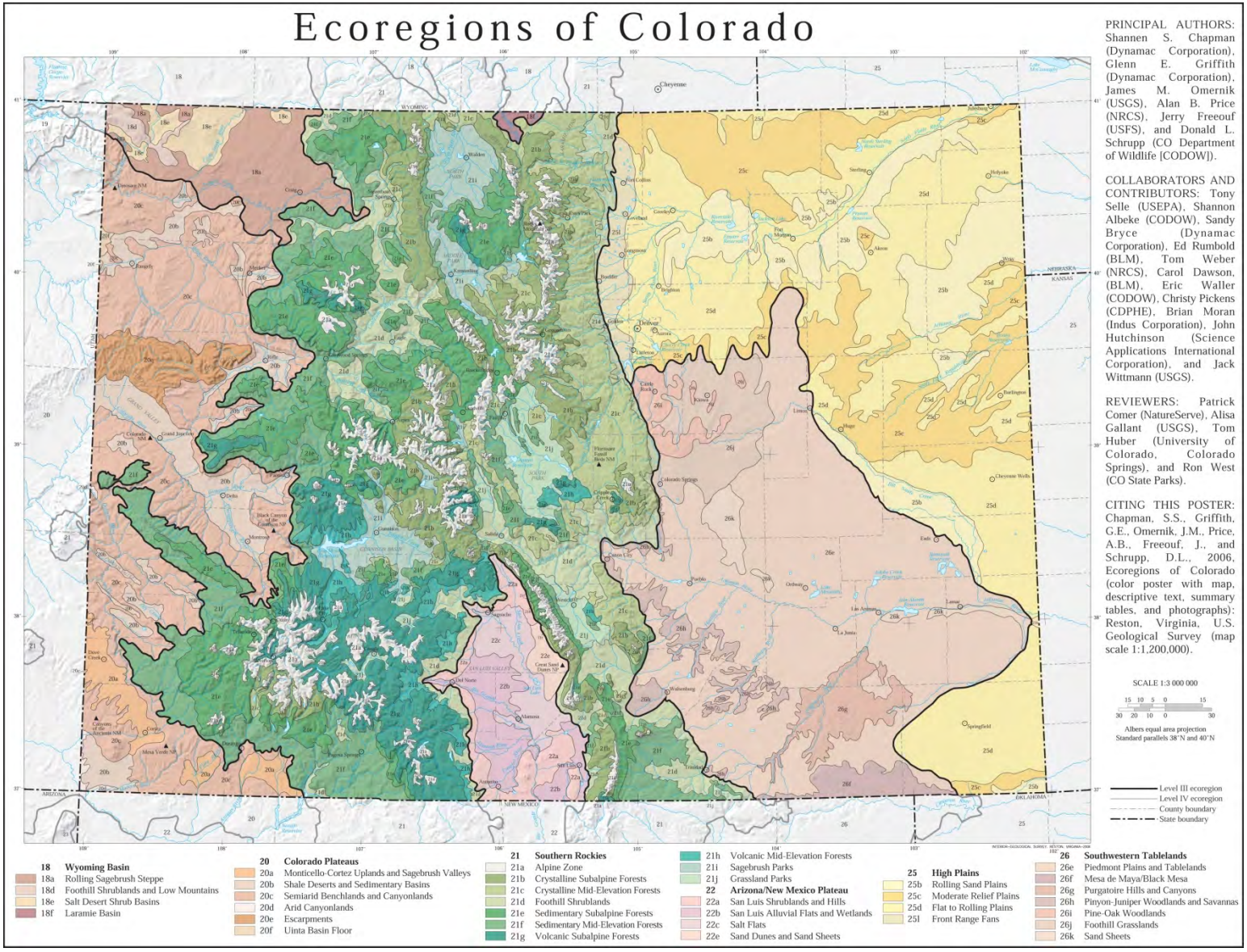



**Figure 3. Ecoregions of Colorado**
*Source: Chapman et al., 2006*

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.govhttp://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:

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

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] $ET_o$ and potential evapotranspiration (PET) are terms which are often used interchangeably, although PET is a more general term and does that specify a particular crop type. The definition of $ET_o$ 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 $ET_o$.

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.

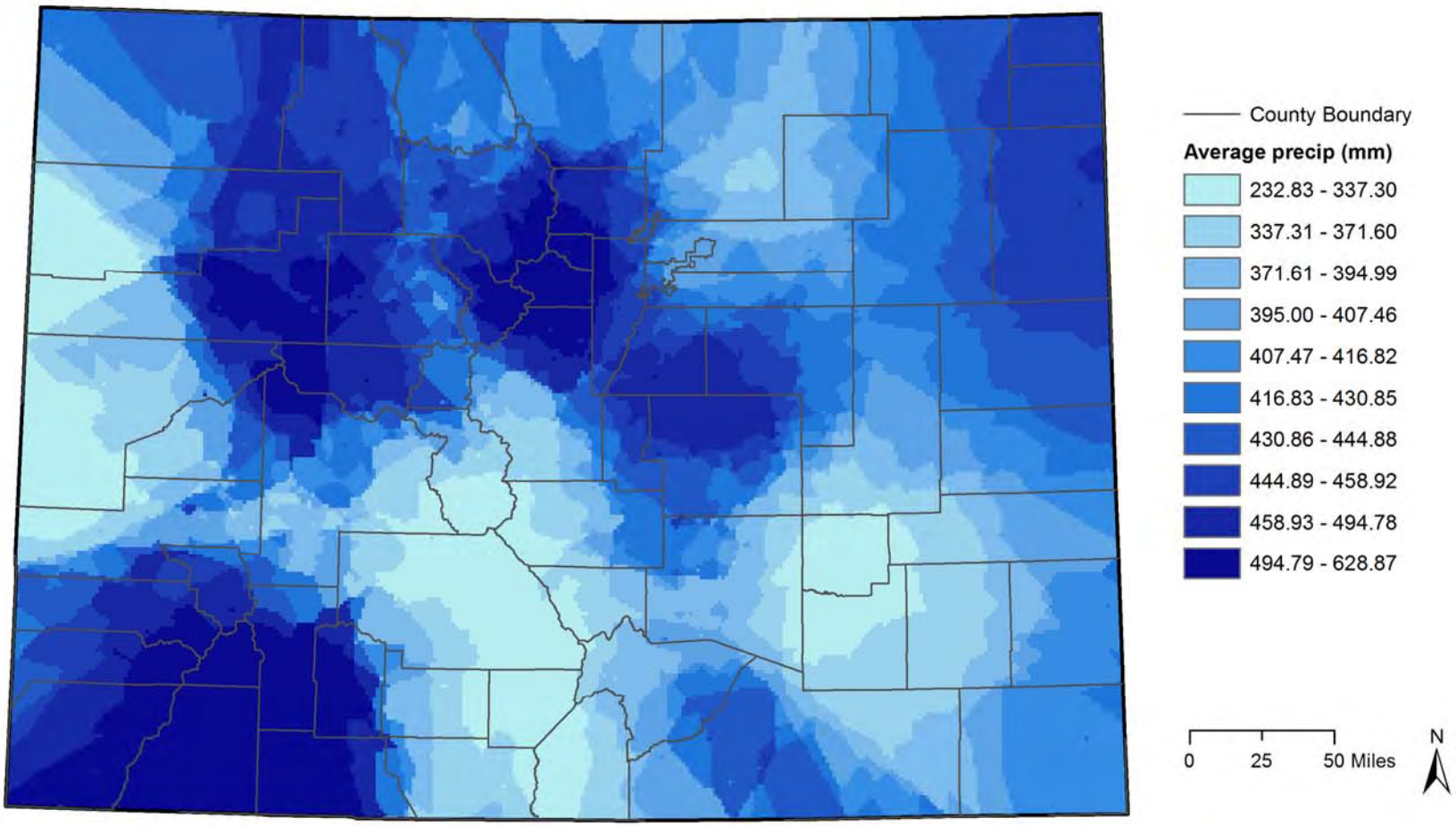



**Figure 4. Average Annual Precipitation in Colorado (in mm of water and snow water equivalent)**

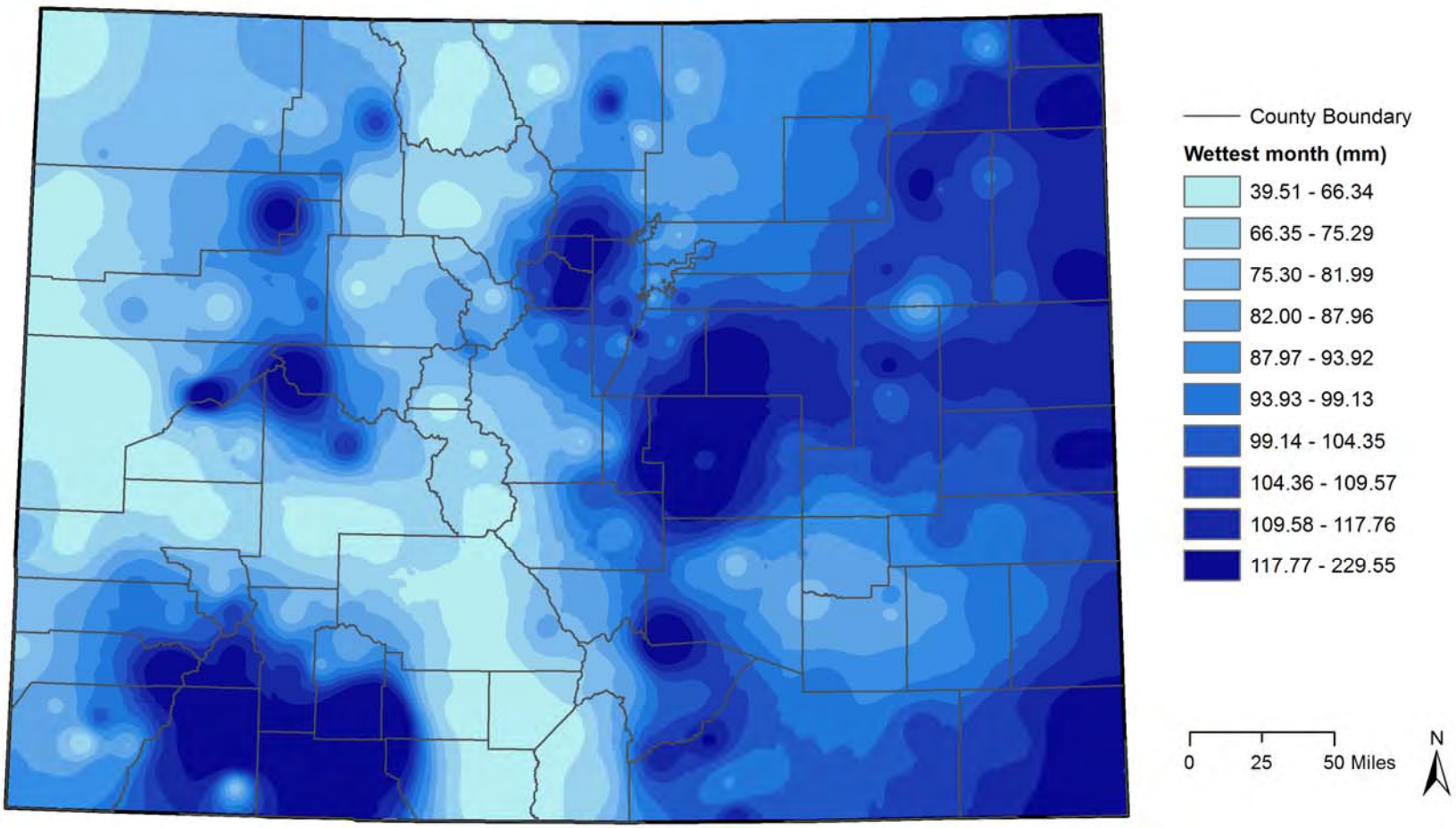



**Figure 5. Average Annual Precipitation in Colorado in the Wettest Month of the Year (in mm)**

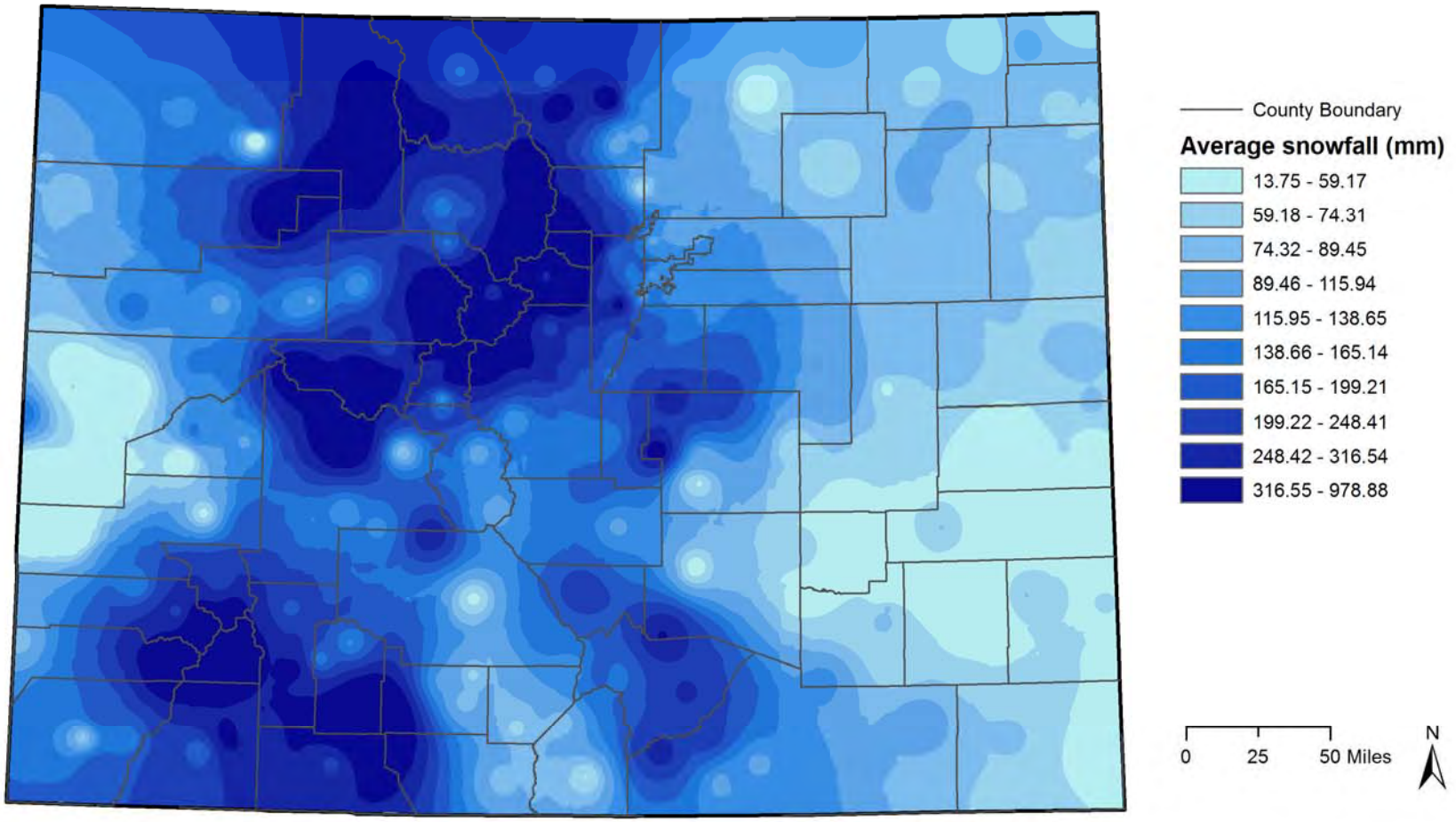



**Figure 6. Average Annual Snowfall in Colorado (mm of snow)**

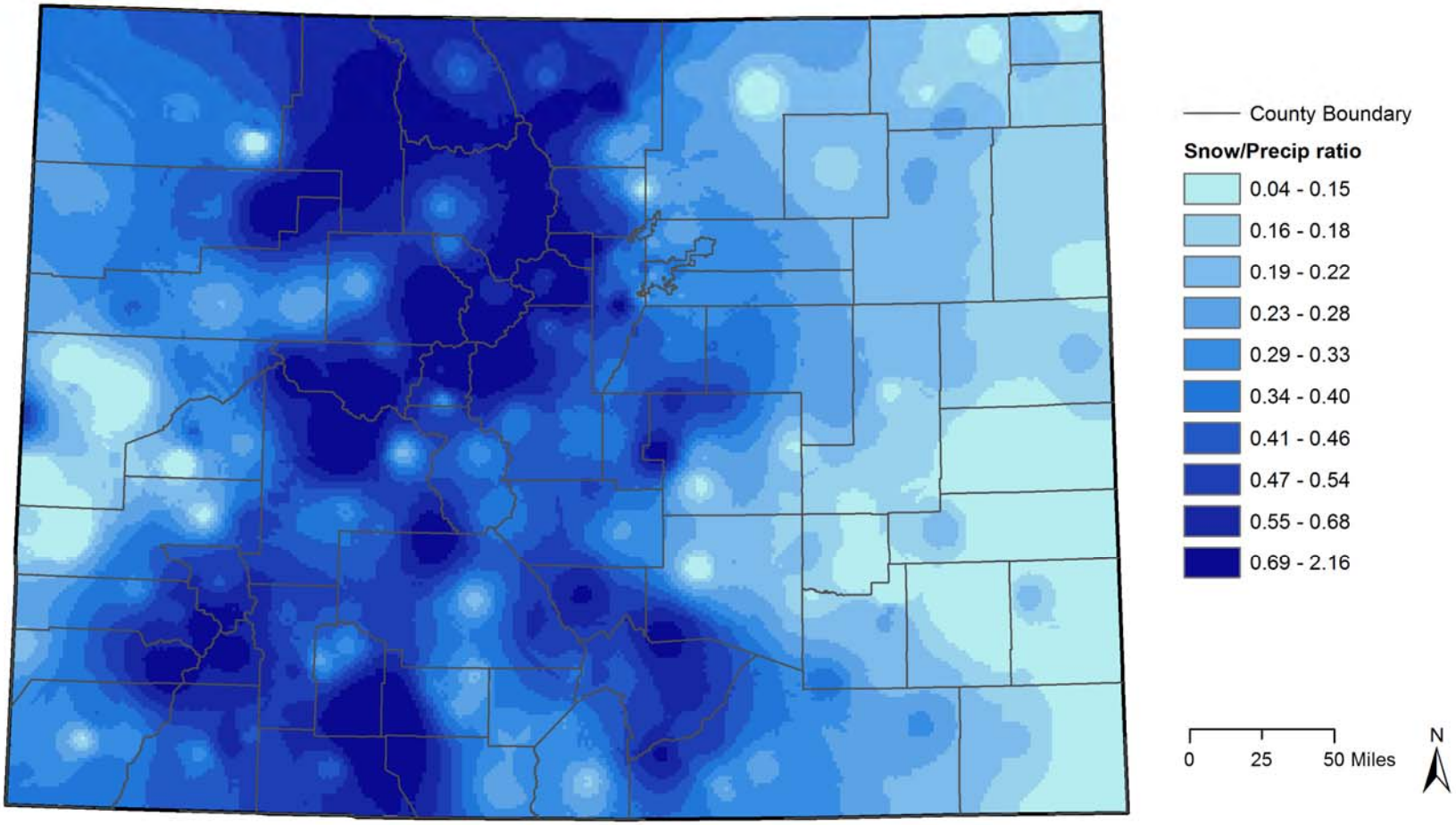



**Figure 7. Ratio of Average Annual Snow (in mm) to Average Annual Precipitation (in mm) in Colorado**

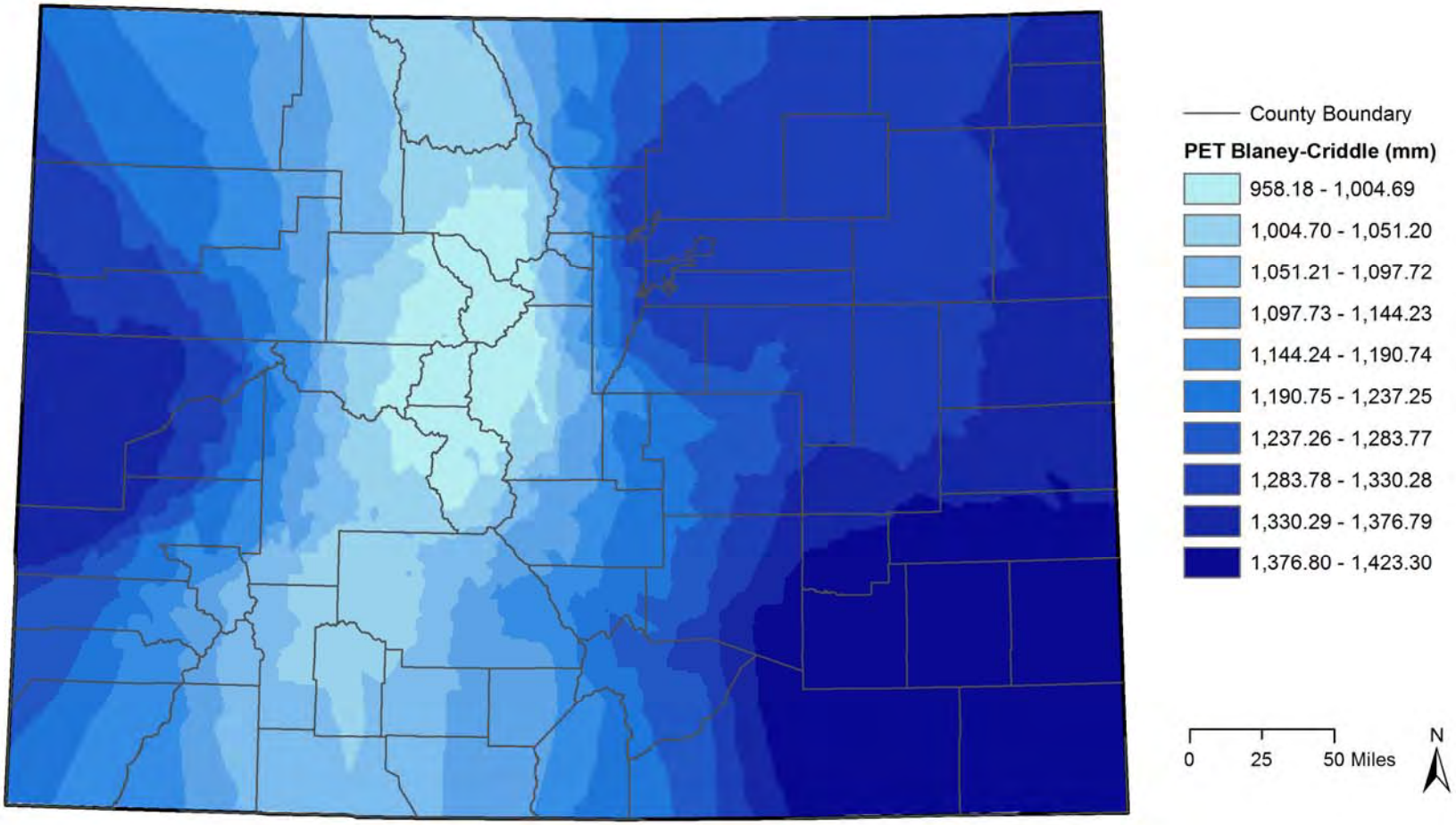



**Figure 8. Average Annual Potential Evapotranspiration (Blaney-Criddle) in Colorado (in mm)**
*Evapotranspiration was calculated using measured temperature data from NCDC stations in the Blaney-Criddle Equation for calculating reference ET.*

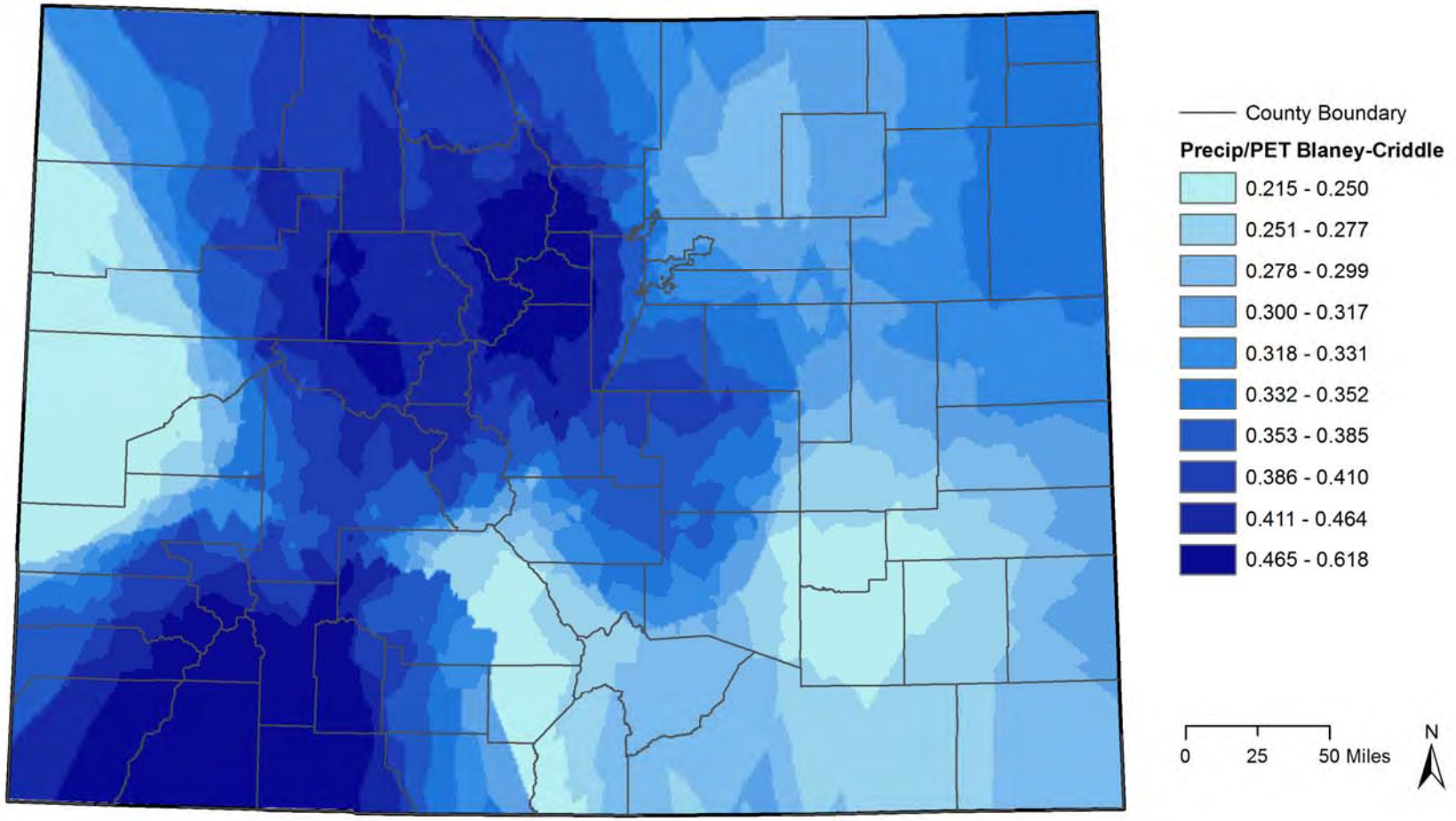



**Figure 9. Ratio of Average Annual Precipitation to Average Annual Potential Evapotranspiration (Blaney-Criddle) in Colorado**

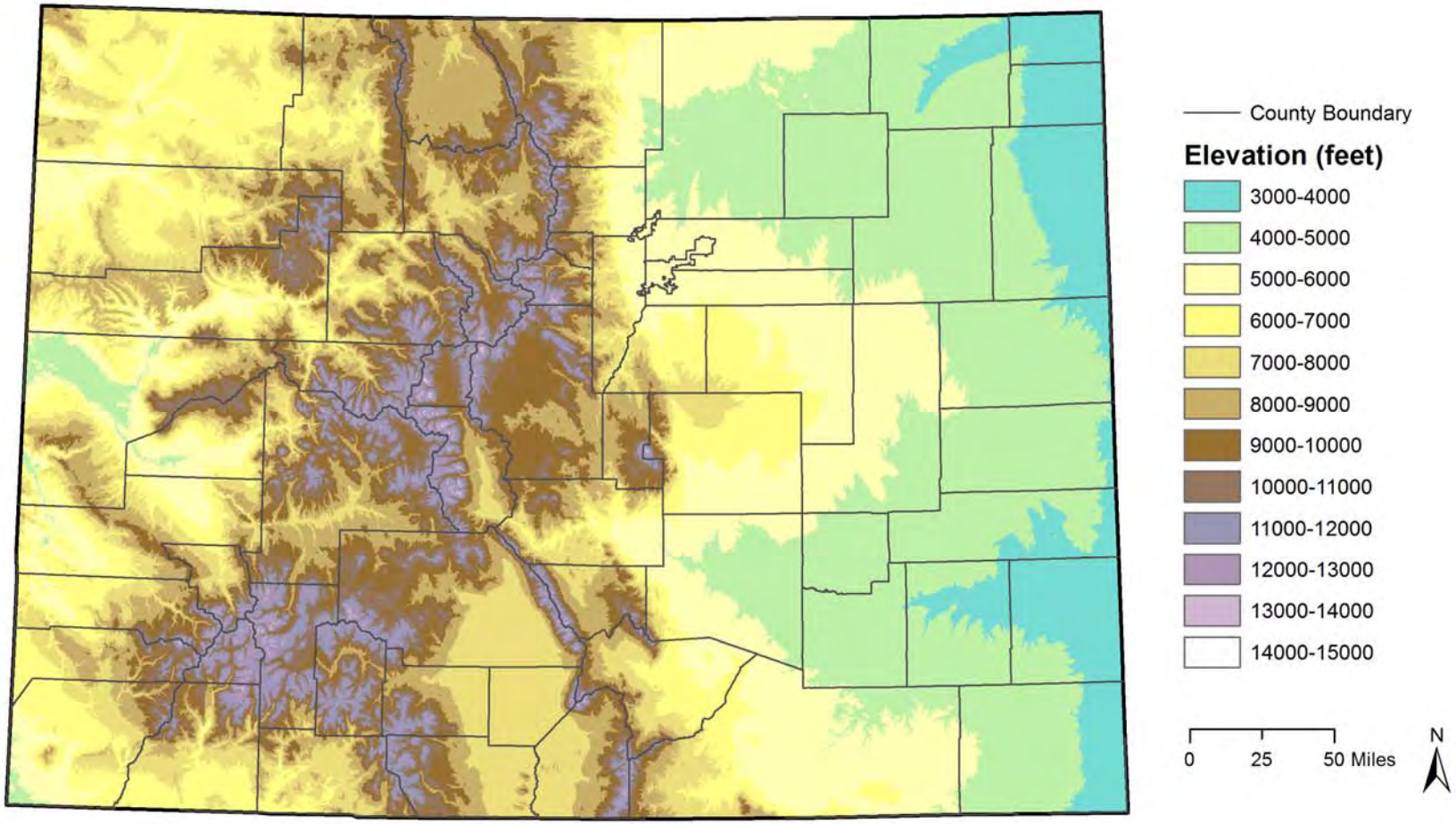



**Figure 10. Elevation in Colorado (feet above mean sea level)**

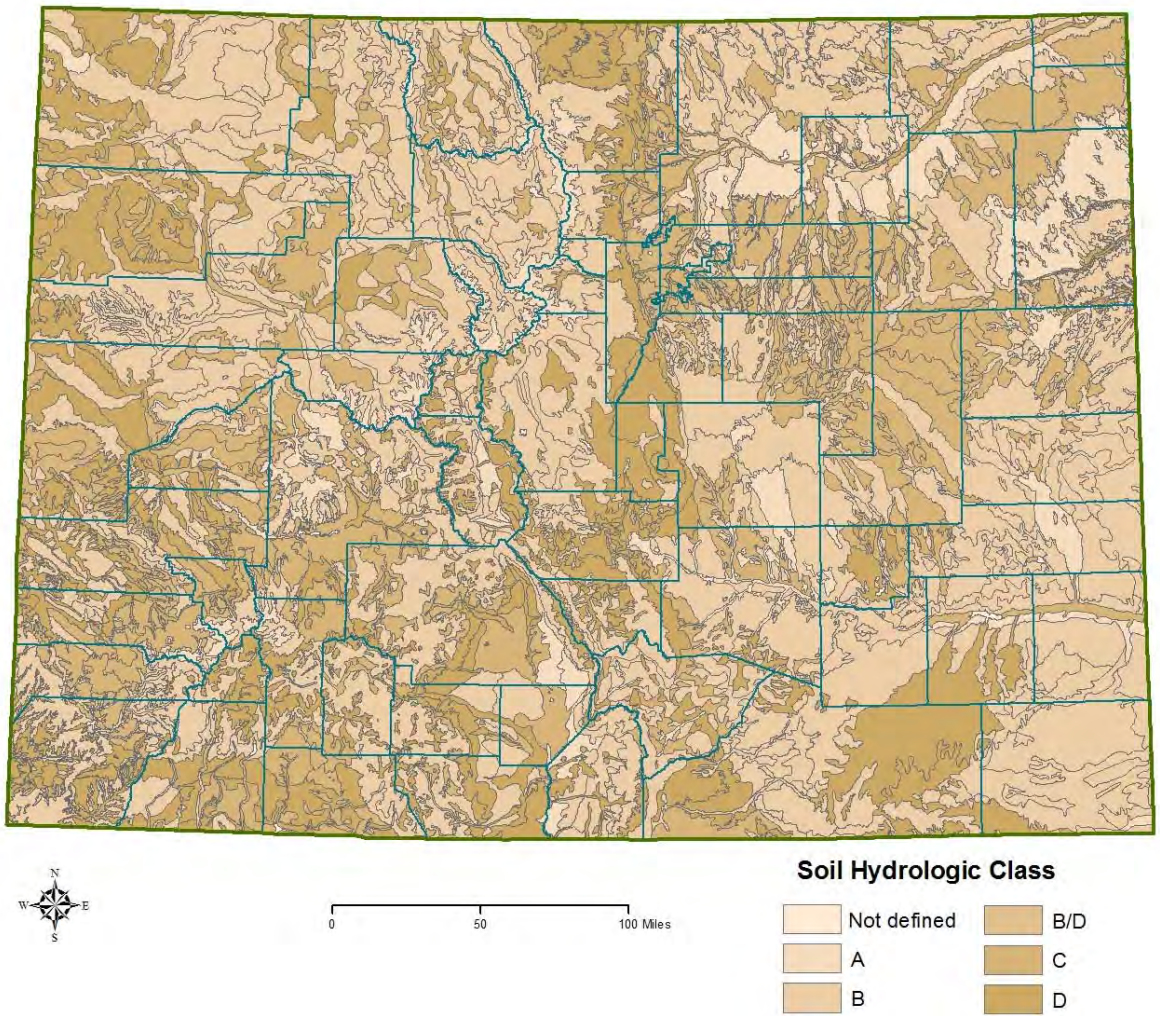



**Figure 11. Soil Cover in Colorado**
*Hydrologic soil groups are a classification system used by the U.S. Natural Resources Conservation Service to describe soil infiltration rates. The soil classes include Category A (high infiltration rate), Category B (moderate infiltration rates), Category C (low infiltration rates), and Category D (very low infiltration rates). The classes shown on the map represent the predominant surficial soil characteristics.*

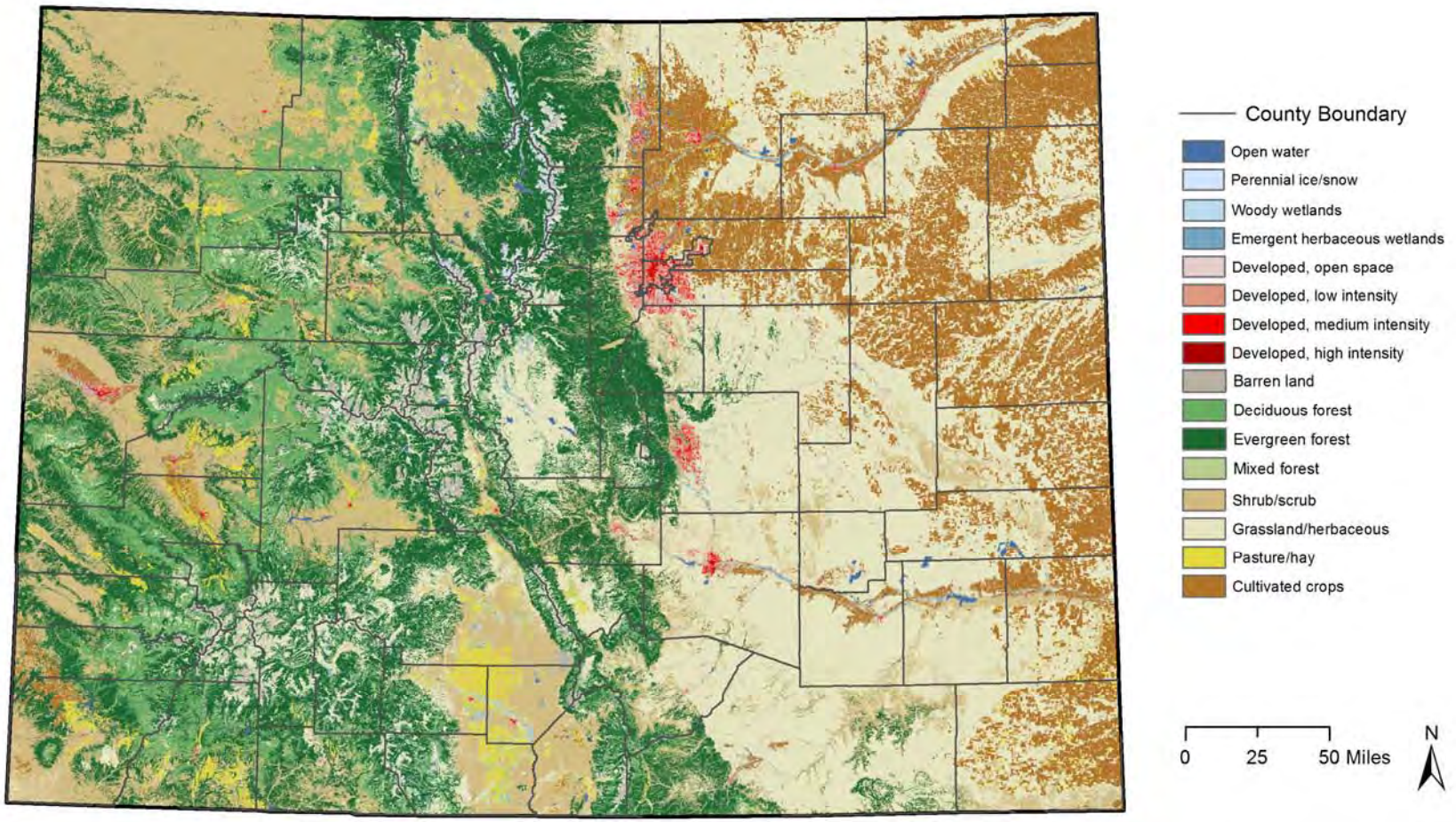



**Figure 12. Land Cover in Colorado**

## 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.

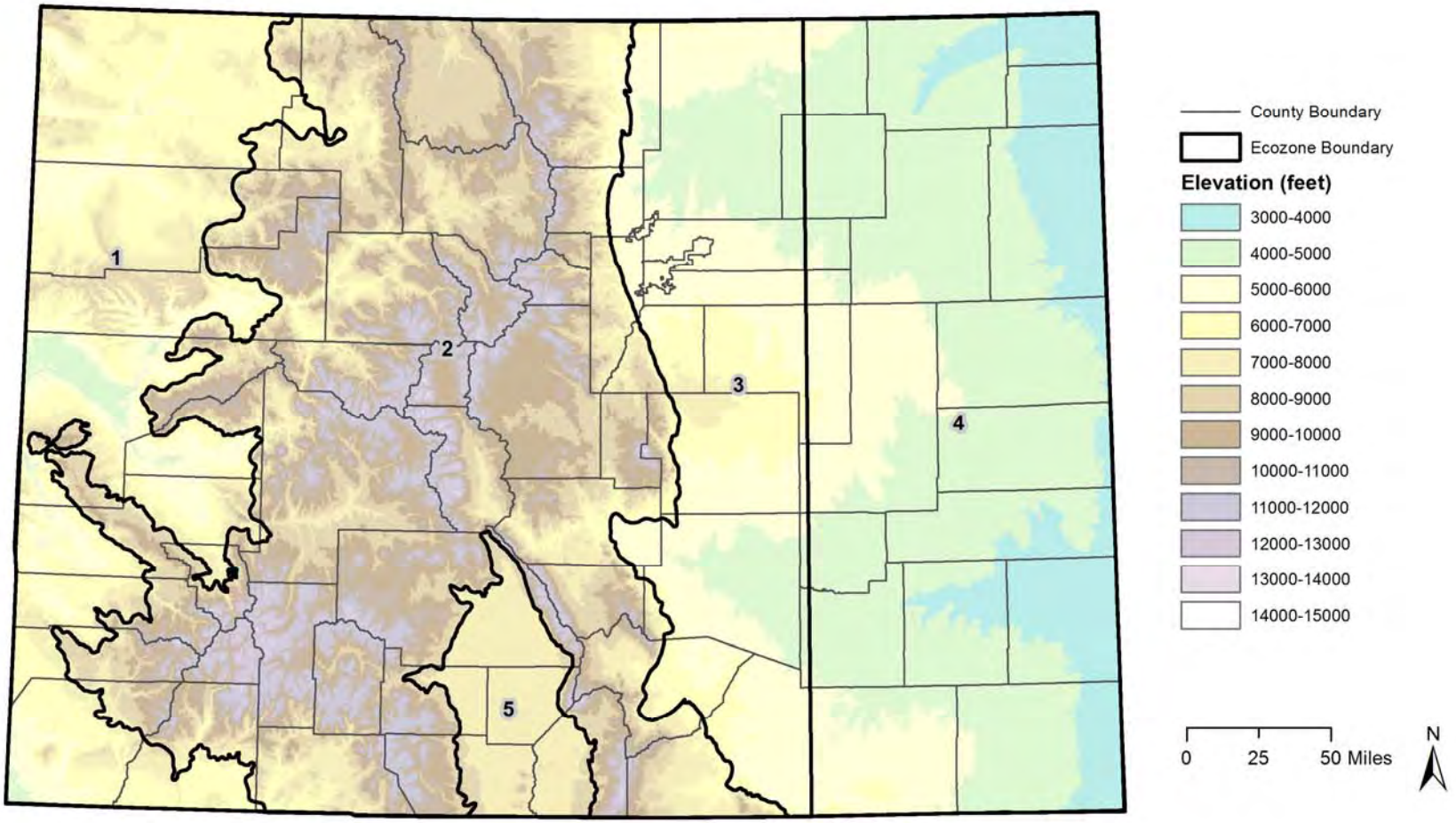



**Figure 13. Final Colorado Ecozone Boundaries with Elevation**

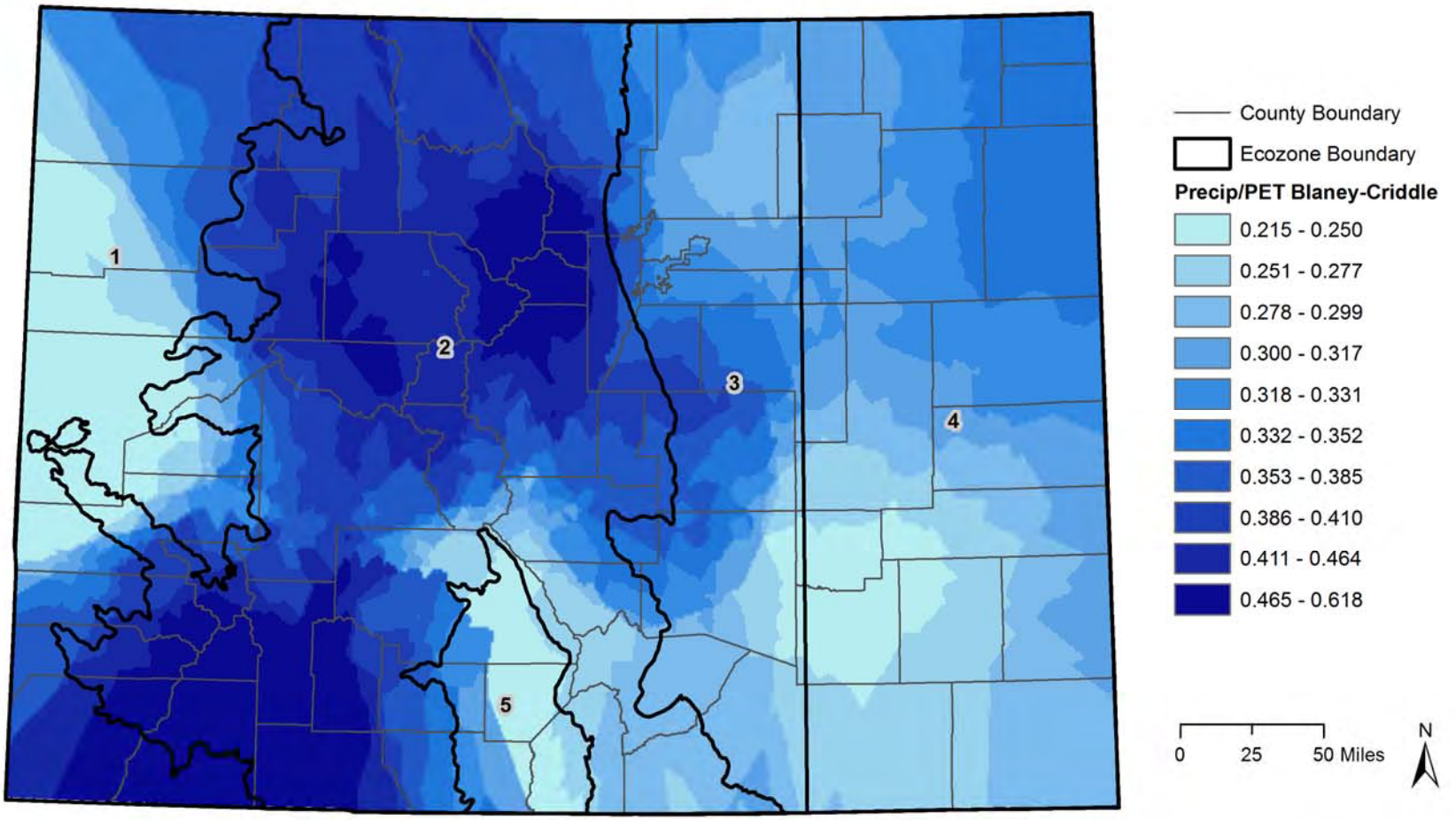



**Figure 14. Ratio of Average Annual Precipitation to Average Annual PET in Colorado Ecozones**

# 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].

[2]Model available online at: http://www.flinders.edu.au/science_engineering/environment/our-school/staff-postgrads/academic-staff/hutson-john/leachm.cfm
[3] Model available online at: http://hydrology.pnl.gov
[4] Model available online at: http://www.geo-slope.com
[5] Model available online at: www.soilvision.com
[6] Model 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 ½ 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.

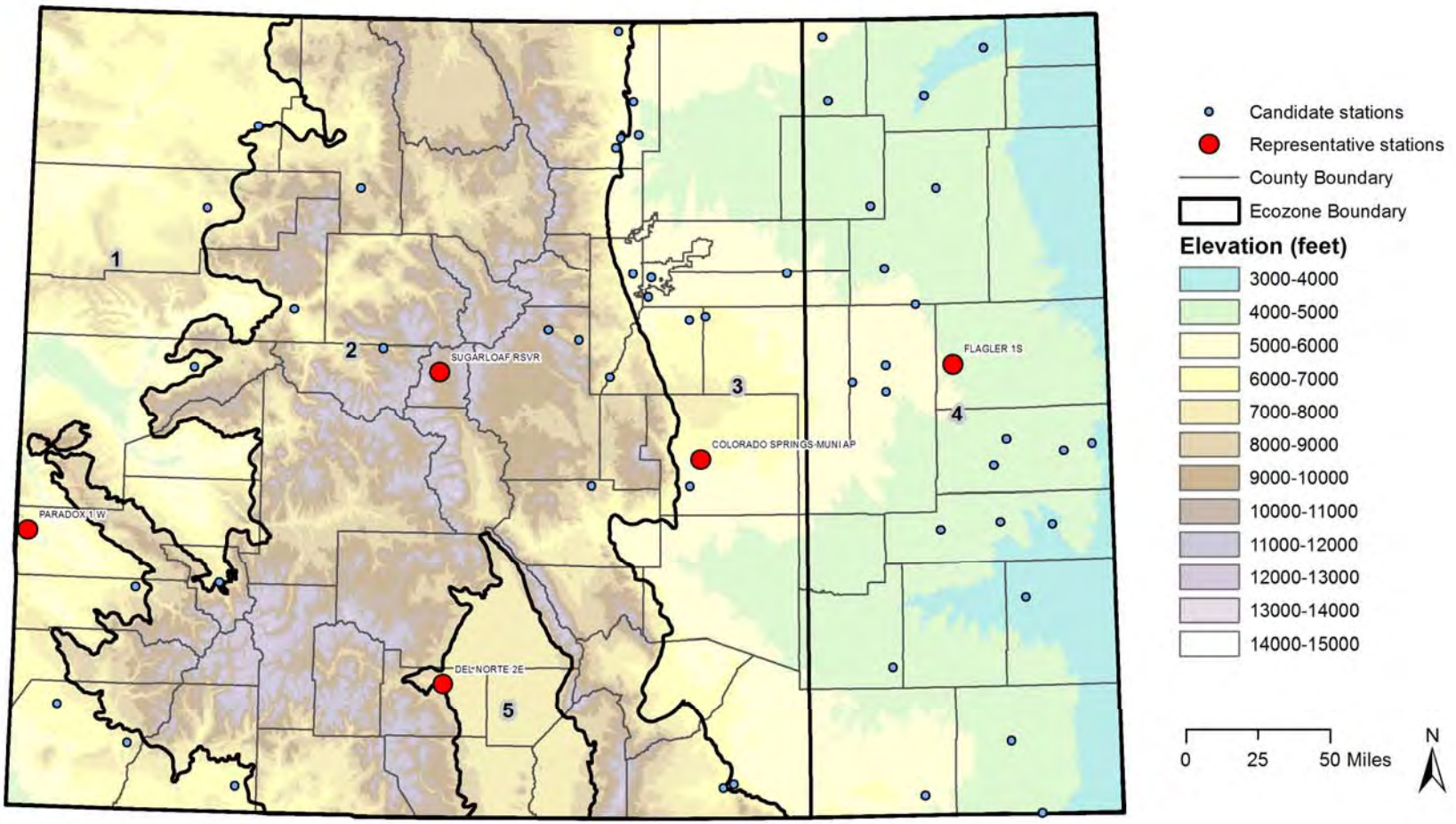



**Figure 13. Map of Representative Stations**
*Candidate stations had an average annual precipitation value within 25.4 mm (or 1 inch) of the ecozone average (shown in Table 2).*

## 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:

$$\mathbf{S_r} = \underbrace{\sum_{m=1}^{6}\{(\boldsymbol{P_m} - \boldsymbol{\beta_{FW}}\boldsymbol{PET_m}) - \boldsymbol{\Lambda_{FW}}\}}_{\text{Fall-Winter Months}} + \underbrace{\sum_{m=1}^{6}\{(\boldsymbol{P_m} - \boldsymbol{\beta_{FW}}\boldsymbol{PET_m}) - \boldsymbol{\Lambda_{SS}}\}}_{\text{Spring-Summer Months}}$$

Where:

$P_m$ = monthly precipitation
$PET_m$ = monthly PET
$\beta_{FW}$ = ET/PET in fall-winter
$\beta_{SS}$ = ET/PET in spring-summer
$\Lambda_{FW}$ = runoff & other losses in fall-winter
$\Lambda_{SS}$ = 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 20$^{th}$ 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 ($\theta_r$), saturated water content ($\theta_s$) (equivalent to soil porosity), and a series of parameters ($\alpha$, *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; $\alpha$ 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.

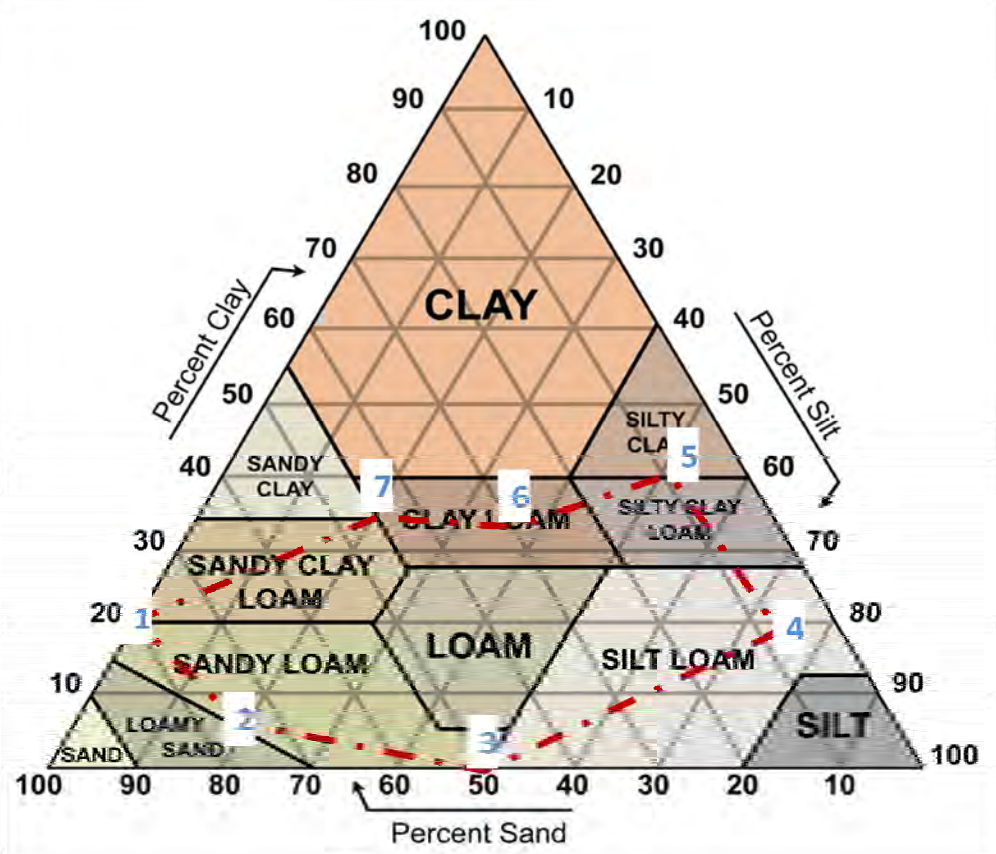



**Figure 14. Summary of Location of the Seven Selected Soils on USDA Chart**

**Table 8. Summary of Rosetta Estimated Soil Parameters**

| Soil Type | % clay | % sand | % silt | $\theta_r$ | $\theta_s$ | $\alpha$ | 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 | 0.011 | 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:

$\theta_r$ = residual water content
$\theta_s$ = saturated water content
$\alpha$ = Curve fitting parameter related to air entry suction
$\psi$ = 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 $cm^3$ of water per $cm^3$ of soil), and Soil 4 has the highest (0.20 $cm^3$ of water per $cm^3$ 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** $cm^3water/cm^3soil$ | **Wilting Point** $cm^3water/cm^3soil$ | **Unit Storage Capacity** $cm^3water/cm^3soil$ |
|---|---|---|---|
| **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 ($1 \times 10^{-3}$ 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**

| | $\theta_r$ | $\theta_s$ | $\alpha$ | 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 15$^{th}$ to November 15$^{th}$. LAI was assumed to increase linearly from zero on March 15$^{th}$ to a maximum value of 1.8 on May 15$^{th}$. LAI then remains constant for four months (until September 15$^{th}$), before decreasing linearly to reach zero on November 15$^{th}$. For mountainous ecozone 2, the growing season is shorter because of more extreme climatic conditions, and was determined to start May 15$^{th}$ to September 15$^{th}$ (Sievering et al., 1992). LAI for ecozone 2 is assumed to reach the maximum of 1.8 on June 15$^{th}$ (Figure 17). LAI remains at 1.8 until August 15$^{th}$, and then decreases linearly to zero on September 15$^{th}$. 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.

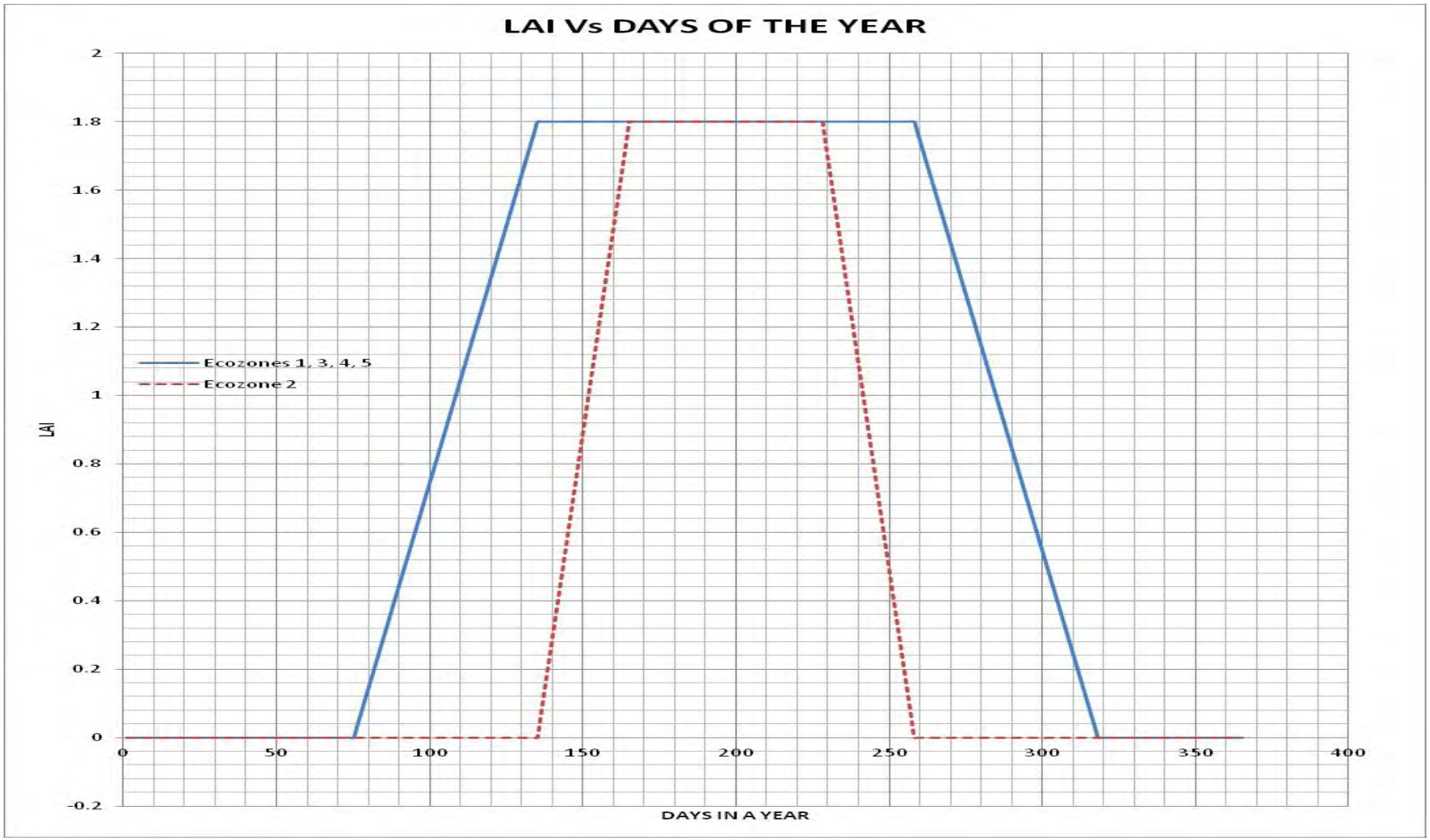



**Figure 15. Daily Variation of LAI During an Example Design Year for Ecozones 1, 2, 3, 4, and 5**

## 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, *h1*). Root water uptake is also zero for pressure heads less than the Wilting Point (*h4*). Water uptake is considered optimal between pressure heads *h2* and *h3* (Figure 18a), whereas for pressure heads between *h3*and *h4* (or *h1* and *h2*) 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.

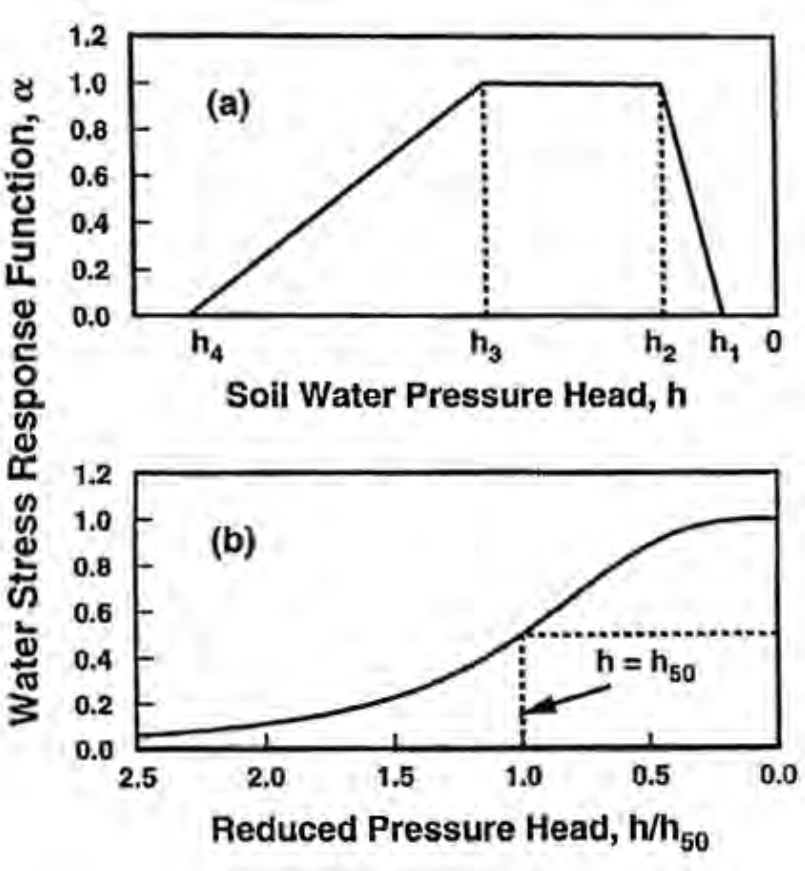



**Figure 16. Schematic of the plant water stress response function, α, as used by a) Feddes et al. (1978) and b) van Genuchten (1985).**

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

| Symbol | Definition | Grass Value |
|---|---|---|
| *h1* | Value of the soil water pressure head below which roots start to extract water from the soil. | -10 cm |

| Symbol | Definition | Grass Value |
|---|---|---|
| *h2* | Value of the soil water pressure head below which roots extract water at the maximum possible rate. | -25 cm |
| *h3H* | 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 *r2H*). | -300 cm |
| *h3L* | As above, but for a potential transpiration rate of *r2L*. | -1000 cm |
| *h4* | 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 *h3* 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 15$^{th}$ to November 15$^{th}$.
- The growing season for ecozone 2 was assumed to start on May 15$^{th}$ and end on September 15$^{th}$.
- 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.

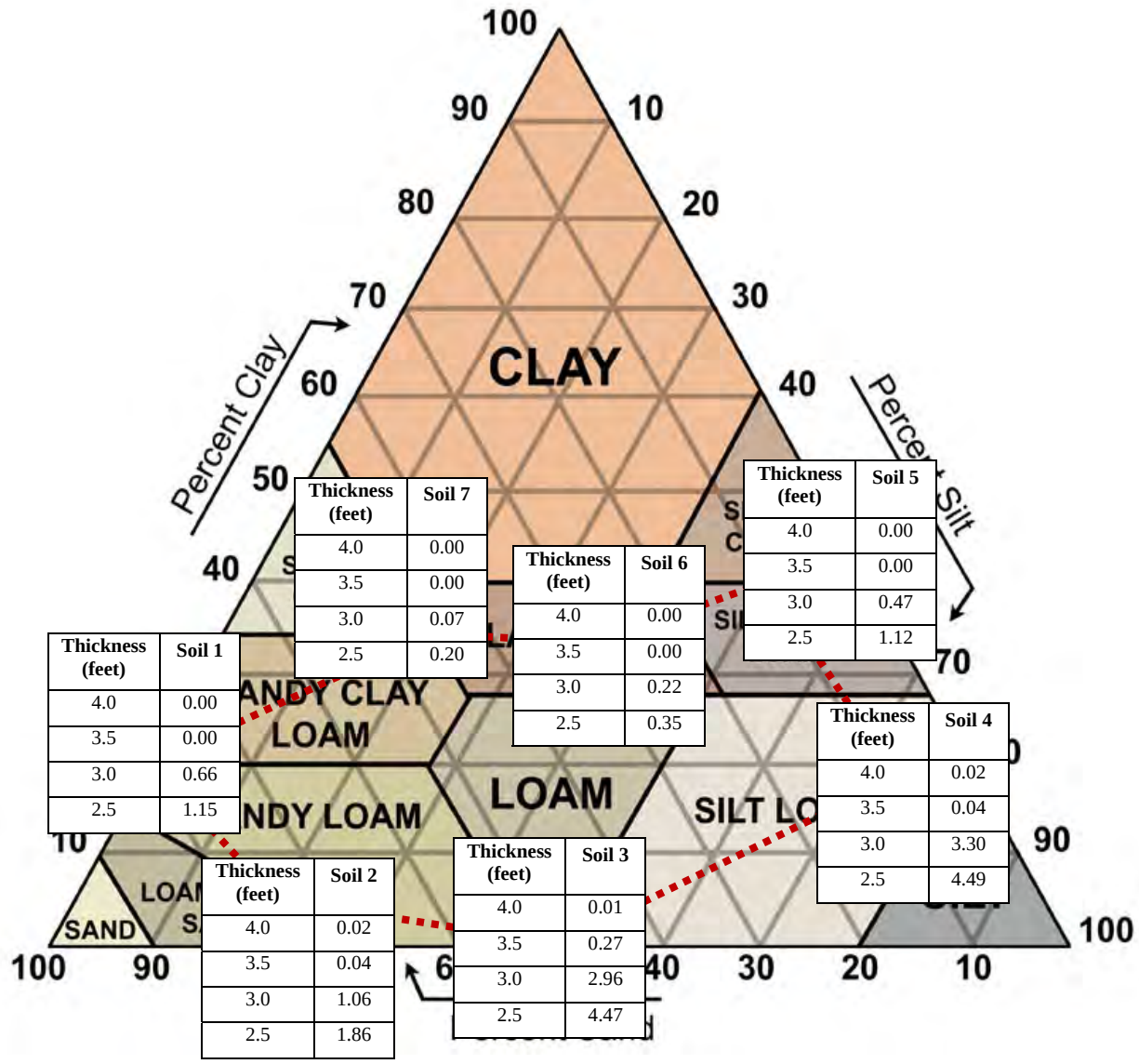
However, looking only at downward flux values provides a slightly different perspective. Water balance covers that are 4 and 3.5 ft thick have low downward flux values (less than 1 mm/year) when modeled with Soils 3, 4, 5, 6, and 7. A cover modeled with Soil 1 has downward flux values of 0.81 mm/year 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** | | | **SOIL 3** | | | **SOIL 4** | | | **SOIL 5** | | | **SOIL 6** | | | **SOIL 7** | | |
| **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 |
| **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 |
| **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 |
| **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 |
| **Ecozone 2** | | | | | | | | | | | | | | | | | | | | | |
| **DEPTH** | **SOIL1** | | | **SOIL2** | | | **SOIL 3** | | | **SOIL 4** | | | **SOIL 5** | | | **SOIL 6** | | | **SOIL 7** | | |
| **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 |
| **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 |
| **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 |
| **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 |
| **Ecozone 3** | | | | | | | | | | | | | | | | | | | | | |
| **DEPTH** | **SOIL1** | | | **SOIL2** | | | **SOIL 3** | | | **SOIL 4** | | | **SOIL 5** | | | **SOIL 6** | | | **SOIL 7** | | |
| **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 |
| **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 |
| **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 |
| **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 |
| **Ecozone 4** | | | | | | | | | | | | | | | | | | | | | |
| **DEPTH** | **SOIL1** | | | **SOIL2** | | | **SOIL 3** | | | **SOIL 4** | | | **SOIL 5** | | | **SOIL 6** | | | **SOIL 7** | | |
| **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 |
| **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 |
| **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 |
| **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 |
| **Ecozone 5** | | | | | | | | | | | | | | | | | | | | | |
| **DEPTH** | **SOIL1** | | | **SOIL2** | | | **SOIL 3** | | | **SOIL 4** | | | **SOIL 5** | | | **SOIL 6** | | | **SOIL 7** | | |
| **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 |
| **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 |
| **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 |
| **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 |




| Thickness (feet) | Soil 1 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 0.66 |
| 2.5 | 1.15 |

| Thickness (feet) | Soil 2 |
|---|---|
| 4.0 | 0.02 |
| 3.5 | 0.04 |
| 3.0 | 1.06 |
| 2.5 | 1.86 |

| Thickness (feet) | Soil 3 |
|---|---|
| 4.0 | 0.01 |
| 3.5 | 0.27 |
| 3.0 | 2.96 |
| 2.5 | 4.47 |

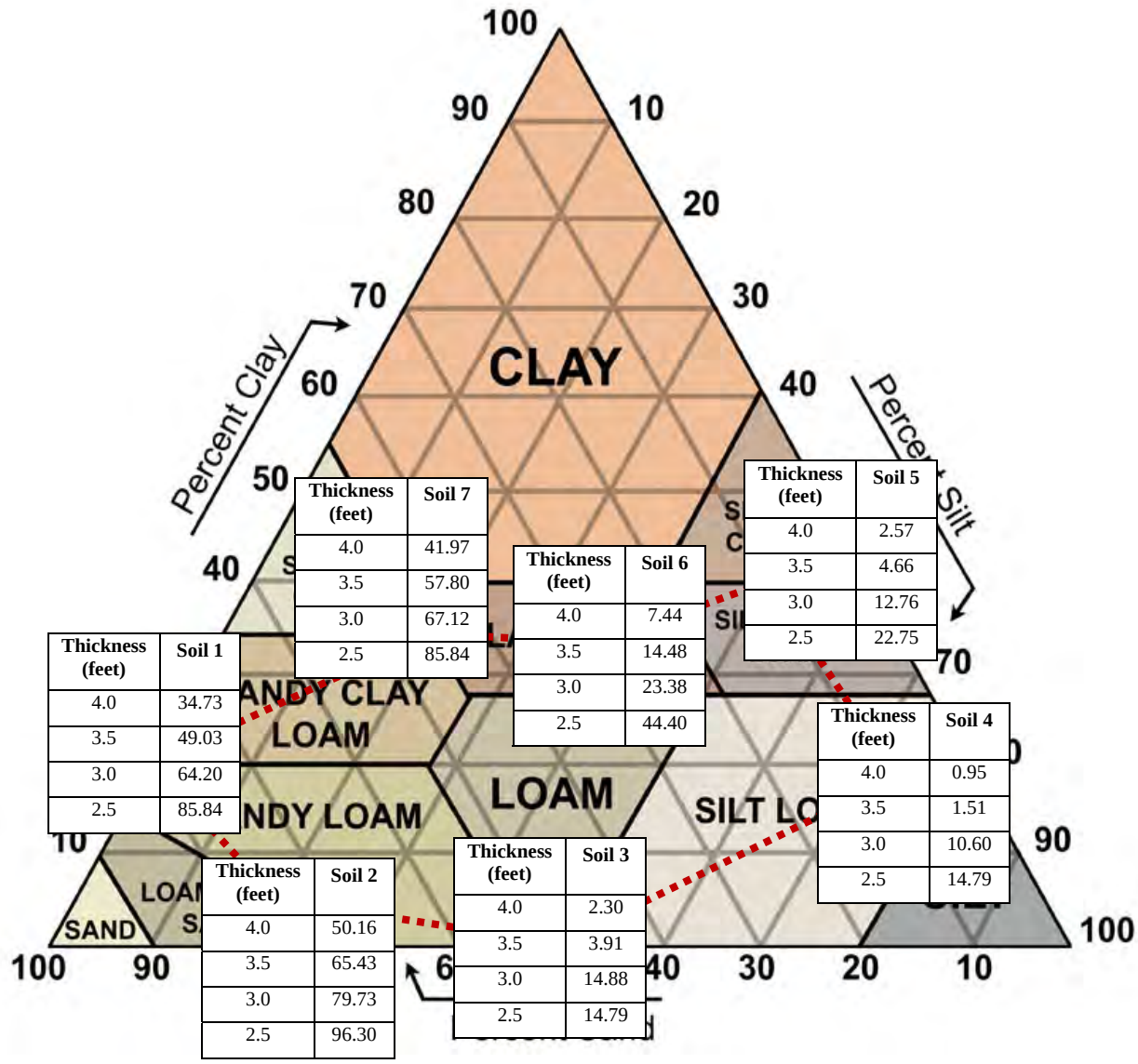
| Thickness (feet) | Soil 4 |
|---|---|
| 4.0 | 0.02 |
| 3.5 | 0.04 |
| 3.0 | 3.30 |
| 2.5 | 4.49 |

| Thickness (feet) | Soil 5 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 0.47 |
| 2.5 | 1.12 |

| Thickness (feet) | Soil 6 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 0.22 |
| 2.5 | 0.35 |

| Thickness (feet) | Soil 7 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 0.07 |
| 2.5 | 0.20 |

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




| Thickness (feet) | Soil 1 |
|---|---|
| 4.0 | 34.73 |
| 3.5 | 49.03 |
| 3.0 | 64.20 |
| 2.5 | 85.84 |

| Thickness (feet) | Soil 2 |
|---|---|
| 4.0 | 50.16 |
| 3.5 | 65.43 |
| 3.0 | 79.73 |
| 2.5 | 96.30 |

| Thickness (feet) | Soil 3 |
|---|---|
| 4.0 | 2.30 |
| 3.5 | 3.91 |
| 3.0 | 14.88 |
| 2.5 | 14.79 |

| Thickness (feet) | Soil 4 |
|---|---|
| 4.0 | 0.95 |
| 3.5 | 1.51 |
| 3.0 | 10.60 |
| 2.5 | 14.79 |

| Thickness (feet) | Soil 5 |
|---|---|
| 4.0 | 2.57 |
| 3.5 | 4.66 |
| 3.0 | 12.76 |
| 2.5 | 22.75 |

| Thickness (feet) | Soil 6 |
|---|---|
| 4.0 | 7.44 |
| 3.5 | 14.48 |
| 3.0 | 23.38 |
| 2.5 | 44.40 |

| Thickness (feet) | Soil 7 |
|---|---|
| 4.0 | 41.97 |
| 3.5 | 57.80 |
| 3.0 | 67.12 |
| 2.5 | 85.84 |

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

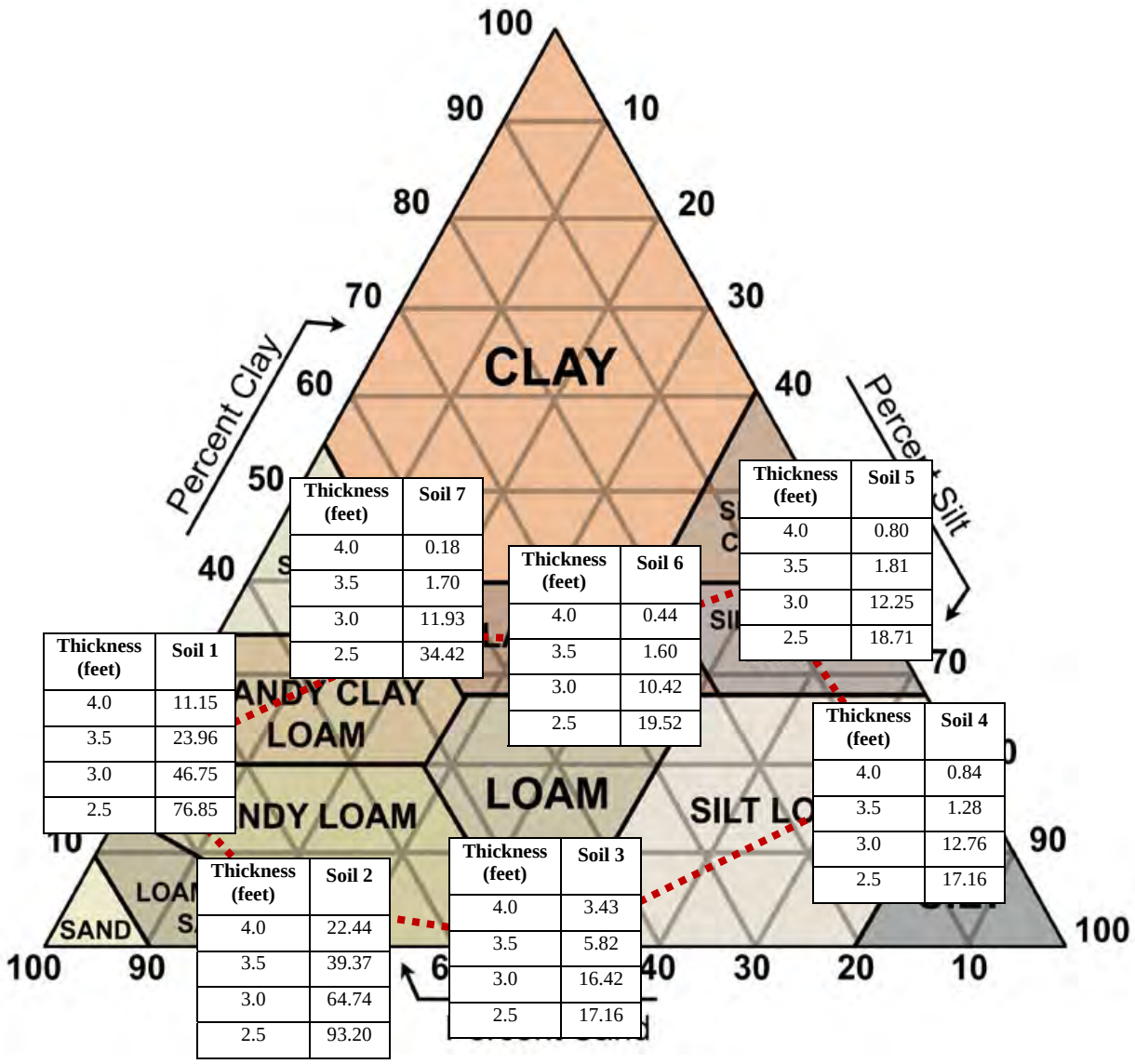



**Figure 19. Summary of Simulation Results for Ecozone 3**
*Downward percolation rates shown are in (mm/year).*

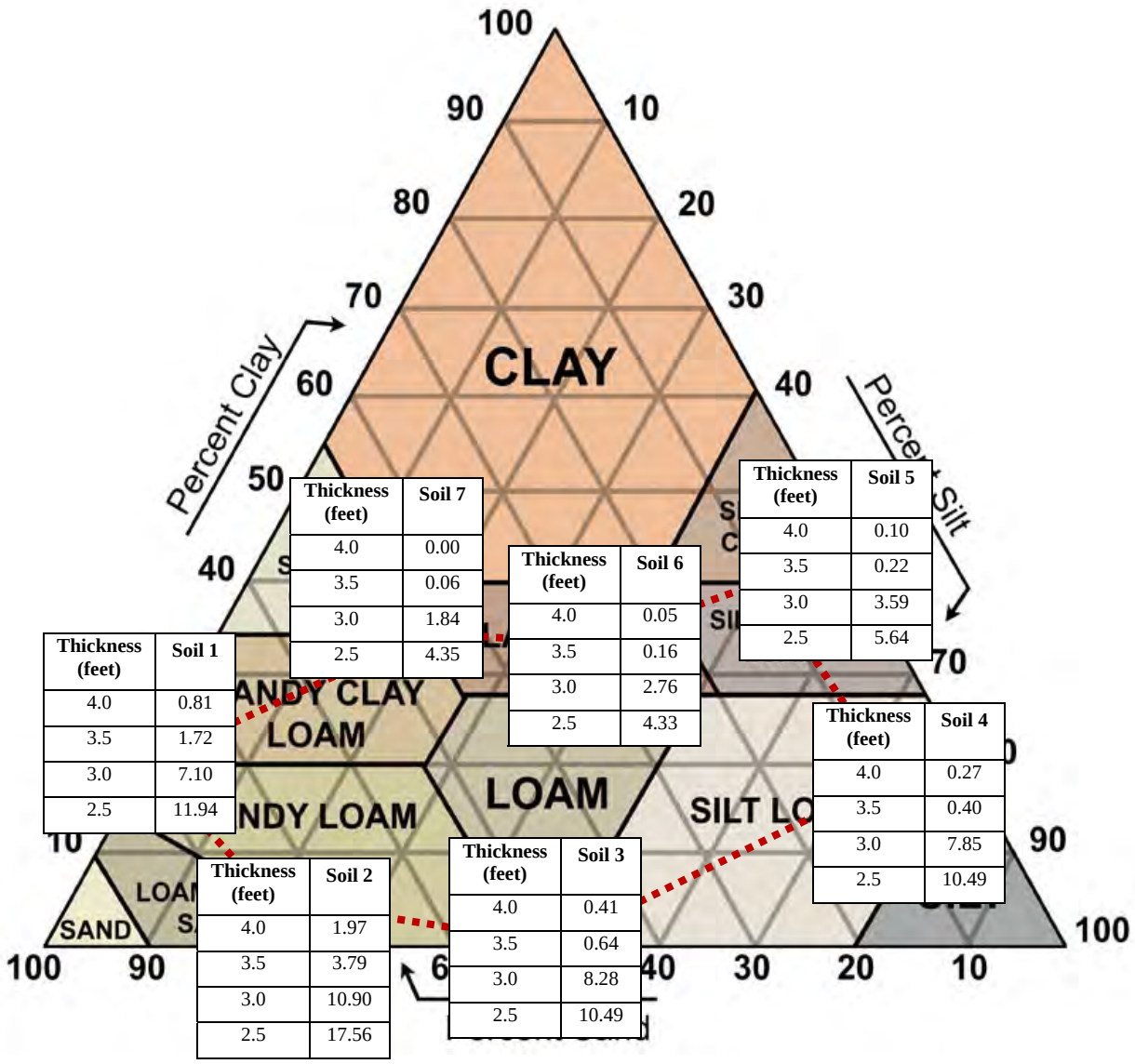
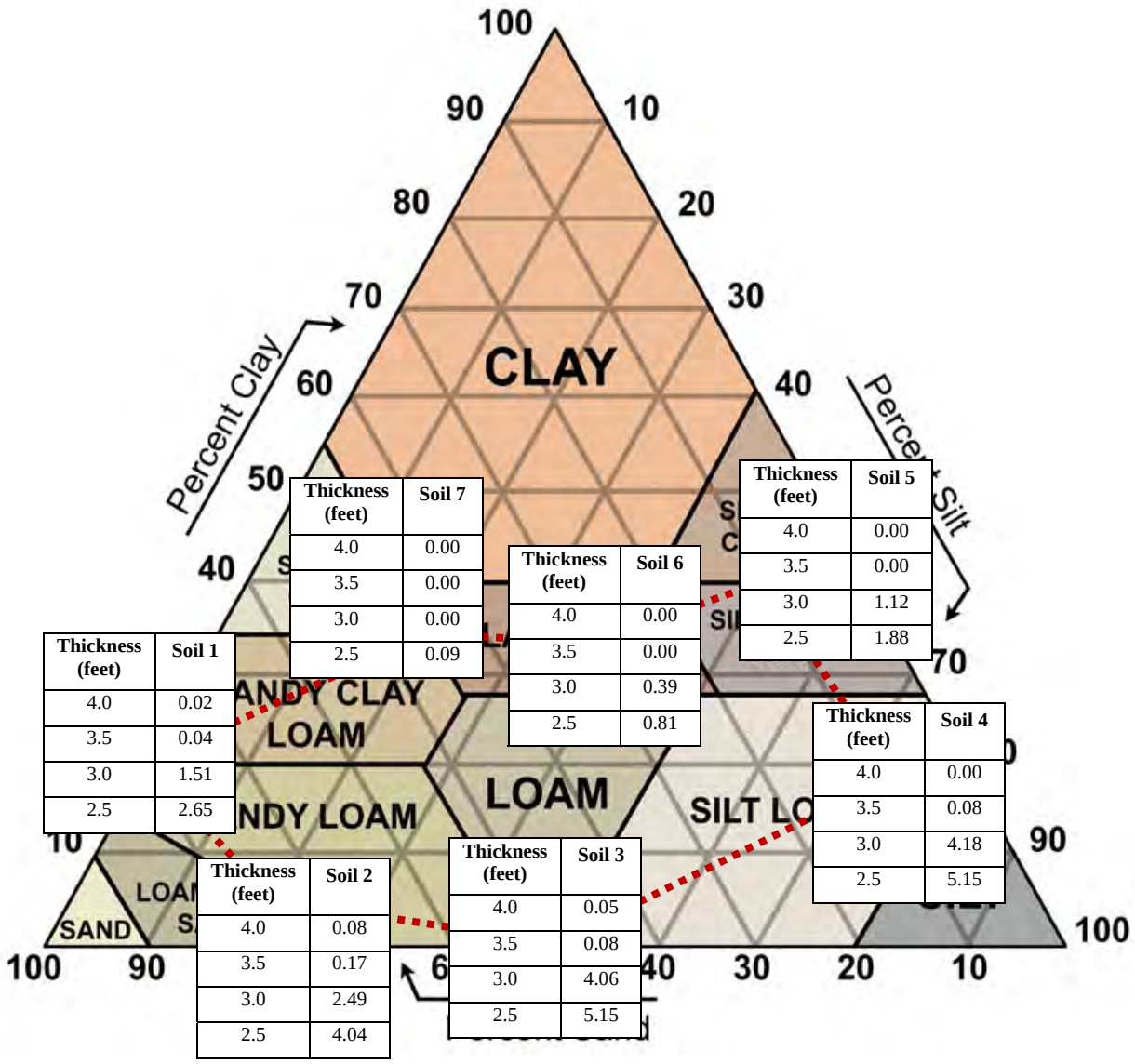



**Figure 20. Summary of Simulation Results for Ecozone 4**
*Downward percolation rates shown are in (mm/year).*




| Thickness (feet) | Soil 1 |
|---|---|
| 4.0 | 0.02 |
| 3.5 | 0.04 |
| 3.0 | 1.51 |
| 2.5 | 2.65 |

| Thickness (feet) | Soil 2 |
|---|---|
| 4.0 | 0.08 |
| 3.5 | 0.17 |
| 3.0 | 2.49 |
| 2.5 | 4.04 |

| Thickness (feet) | Soil 3 |
|---|---|
| 4.0 | 0.05 |
| 3.5 | 0.08 |
| 3.0 | 4.06 |
| 2.5 | 5.15 |

| Thickness (feet) | Soil 4 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.08 |
| 3.0 | 4.18 |
| 2.5 | 5.15 |

| Thickness (feet) | Soil 5 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 1.12 |
| 2.5 | 1.88 |

| Thickness (feet) | Soil 6 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 0.39 |
| 2.5 | 0.81 |

| Thickness (feet) | Soil 7 |
|---|---|
| 4.0 | 0.00 |
| 3.5 | 0.00 |
| 3.0 | 0.00 |
| 2.5 | 0.09 |

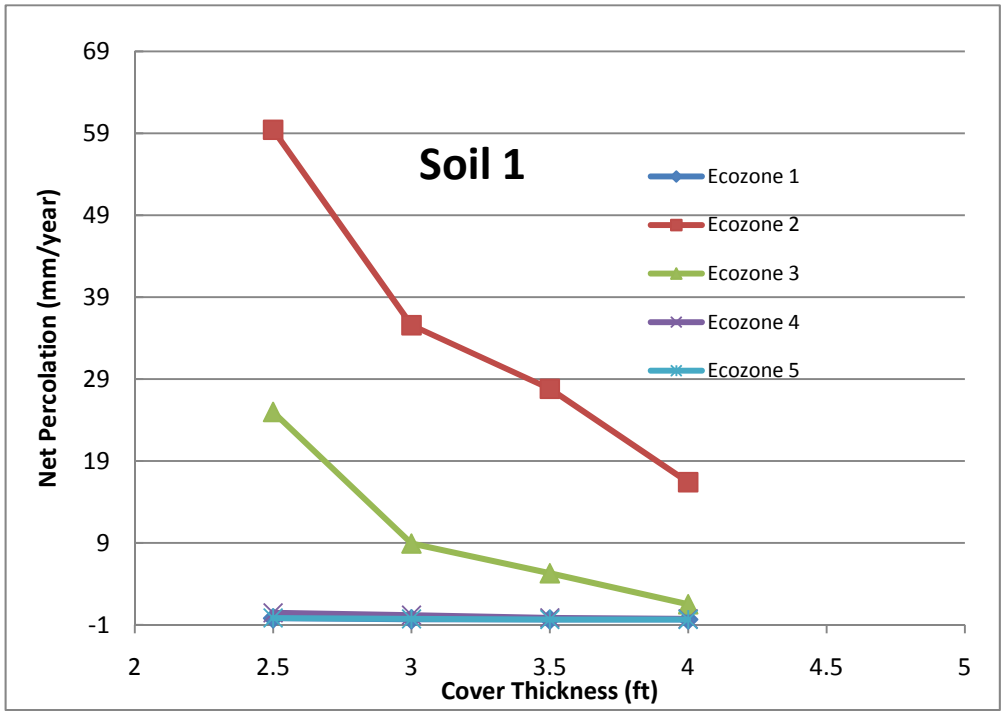
**Figure 21. Summary of Simulation Results for Ecozone 5**
*Downward percolation rates shown are in (mm/year).*

## 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)**

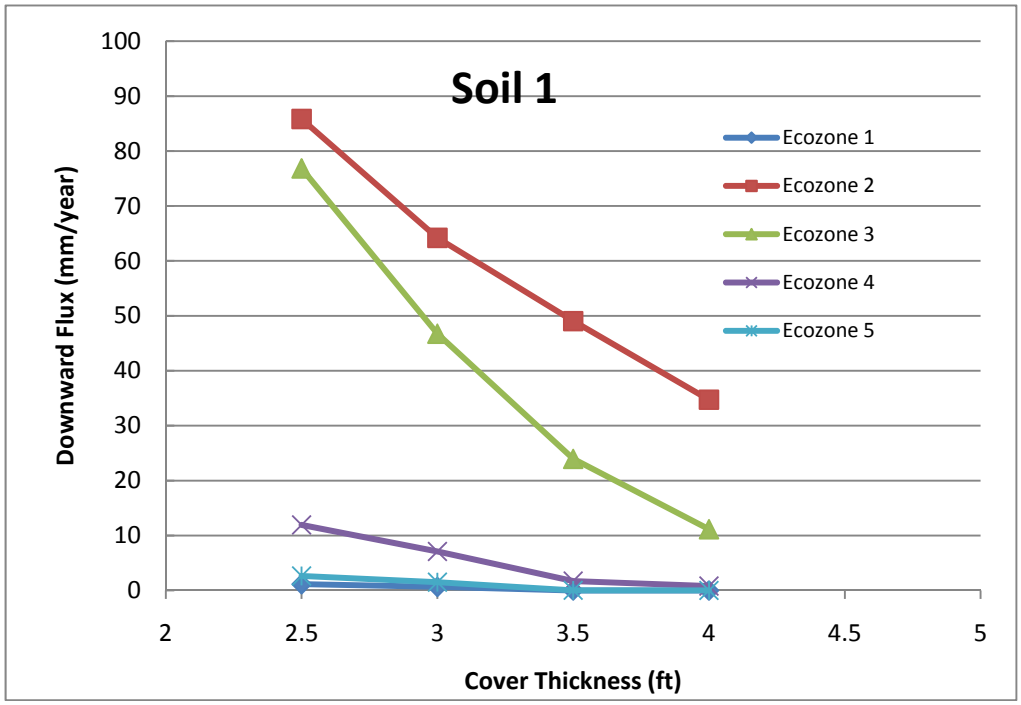
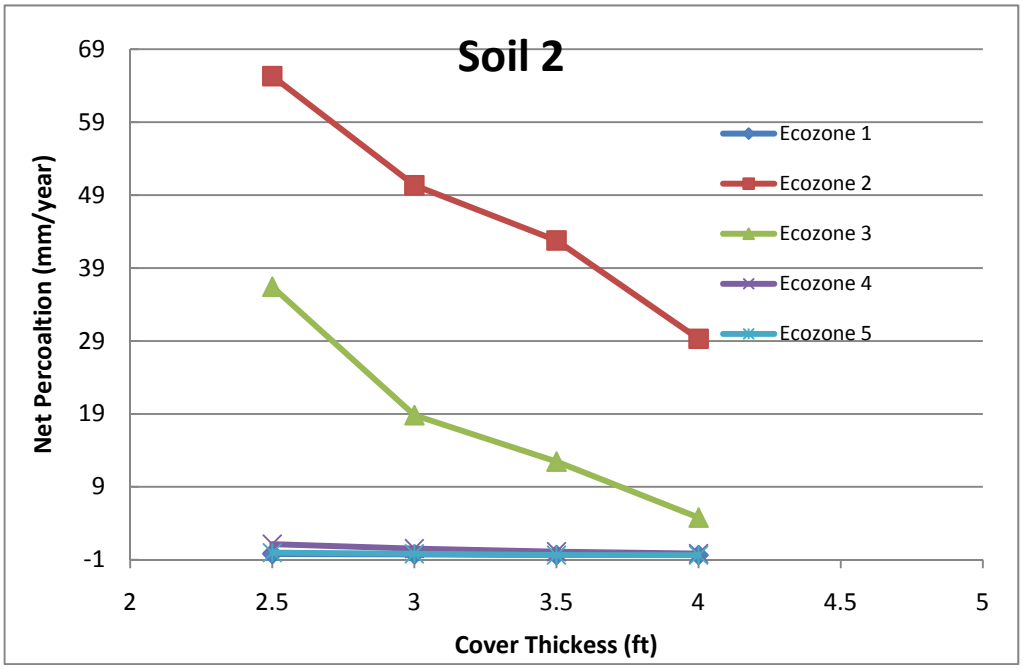



**Figure 22. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 1**

**(a)**




**(b)**

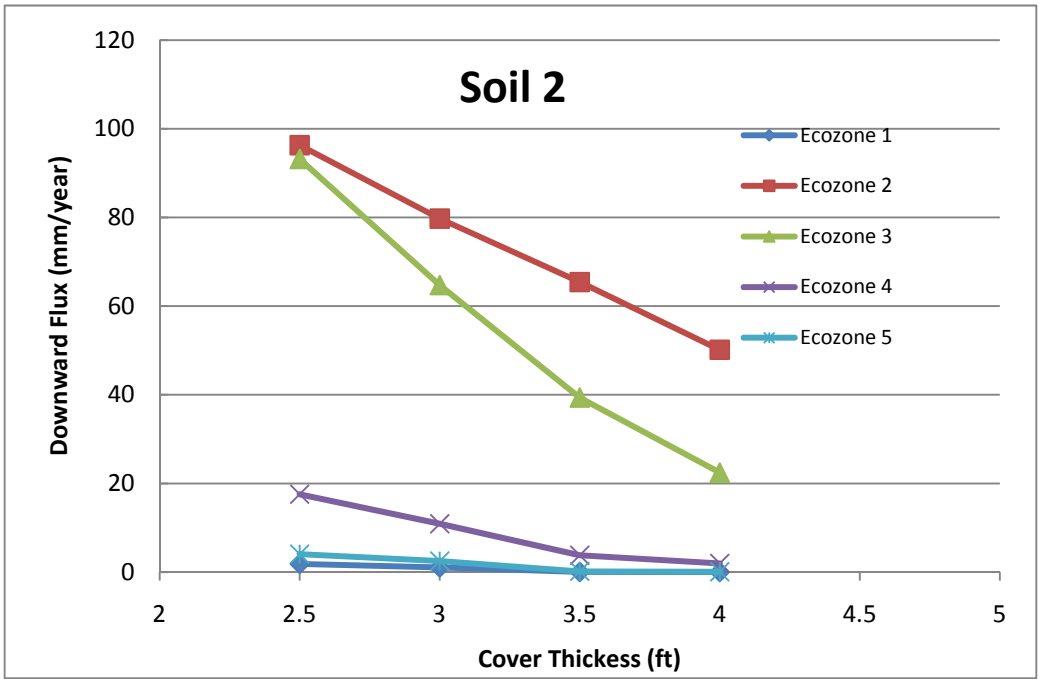
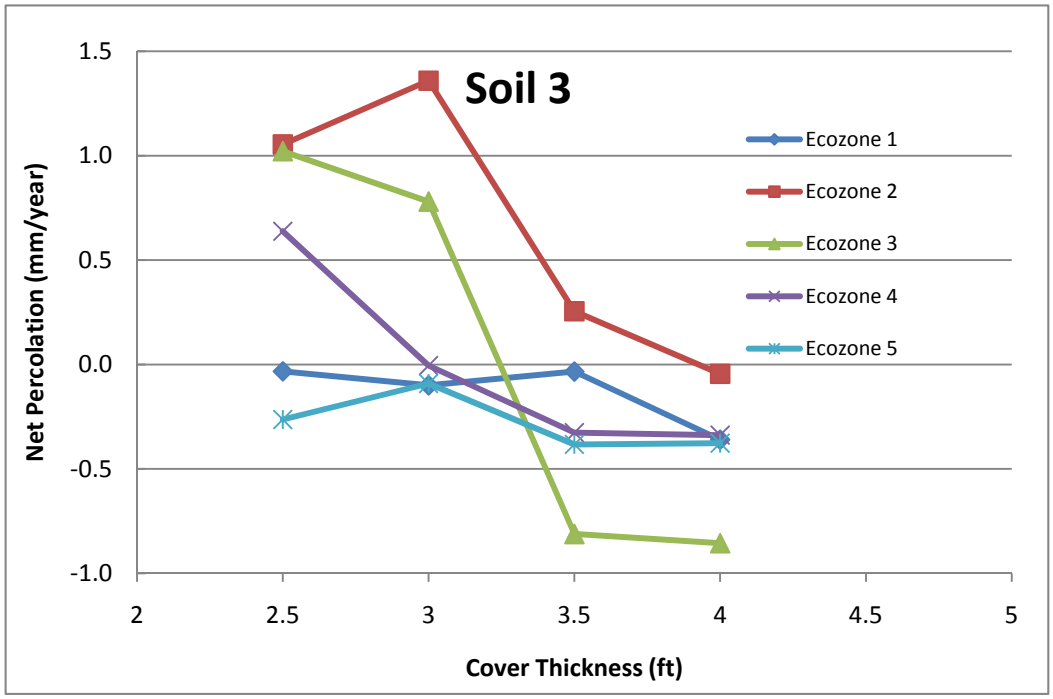



**Figure 23. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 2**

**(a)**




**(b)**

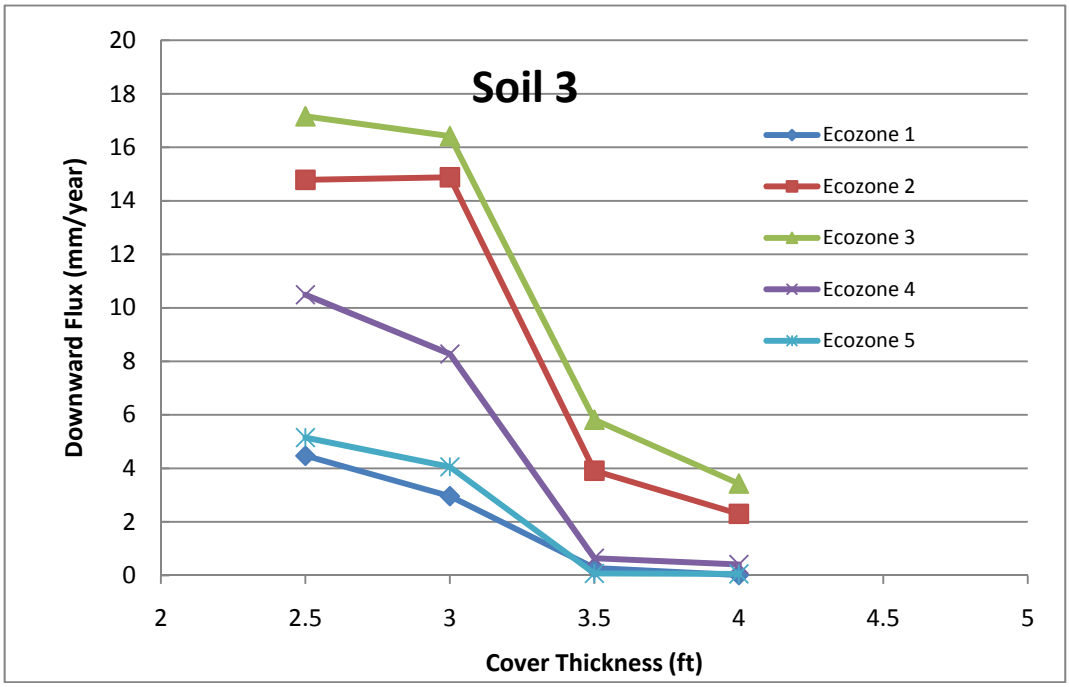
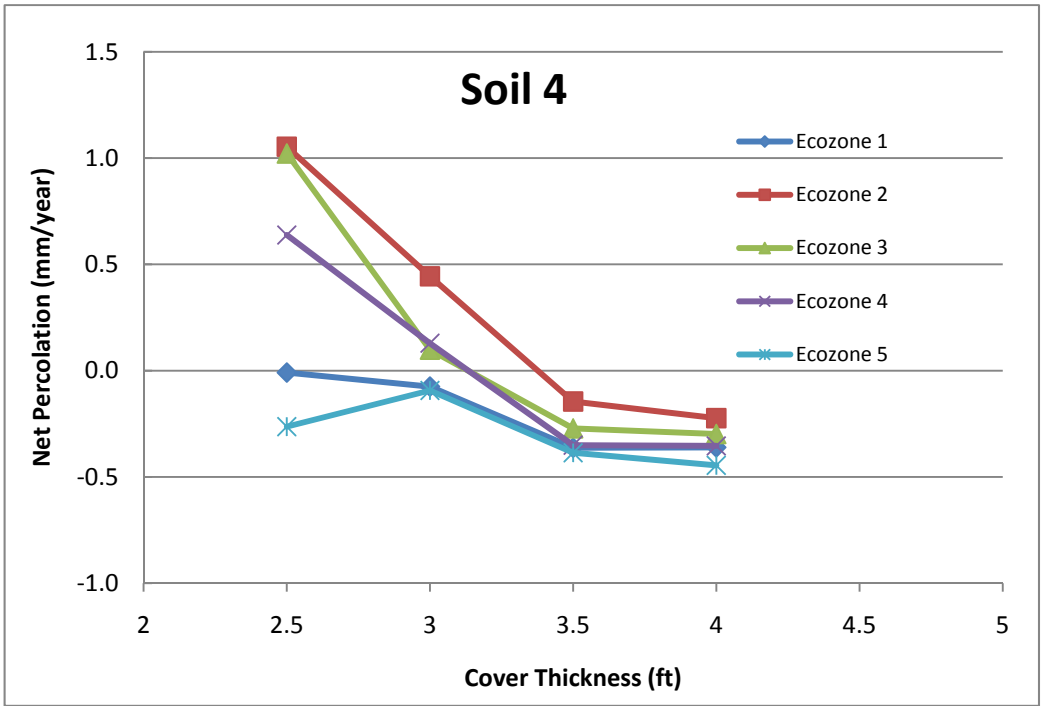



**Figure 24. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 3**

**(a)**




**(b)**

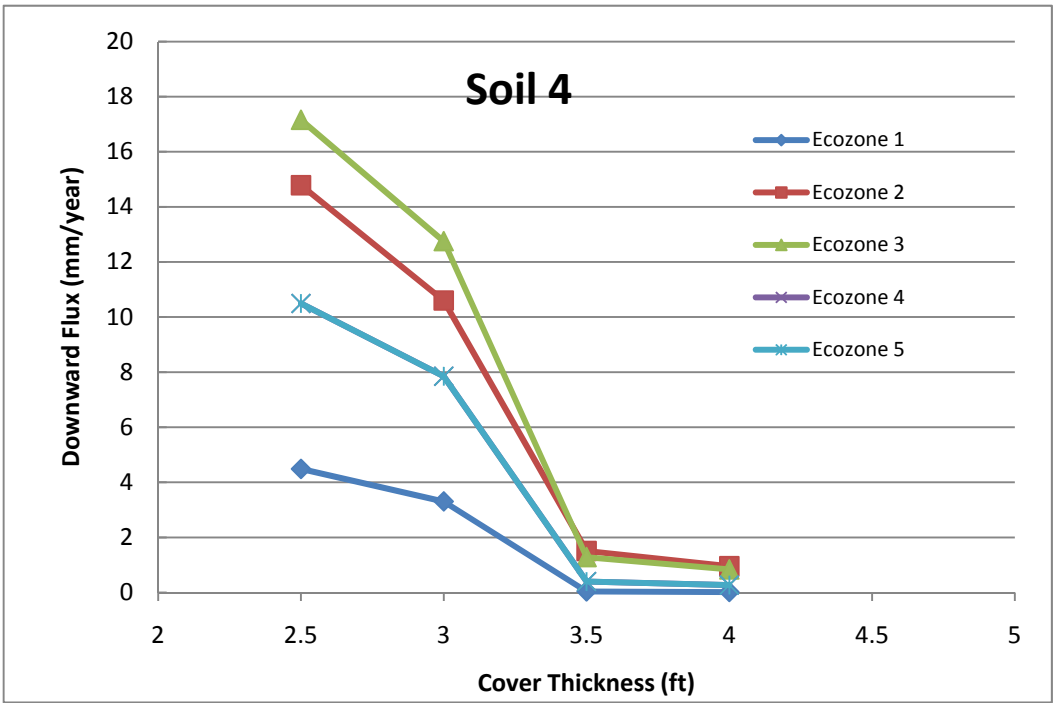
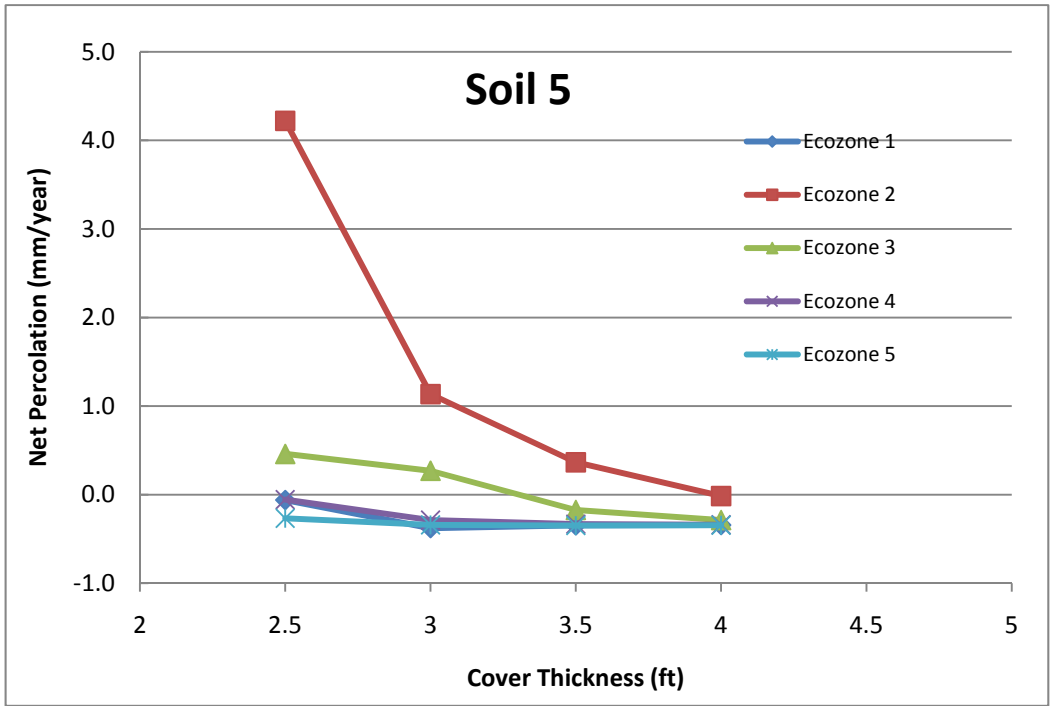



**Figure 25. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 4**

**(a)**




**(b)**

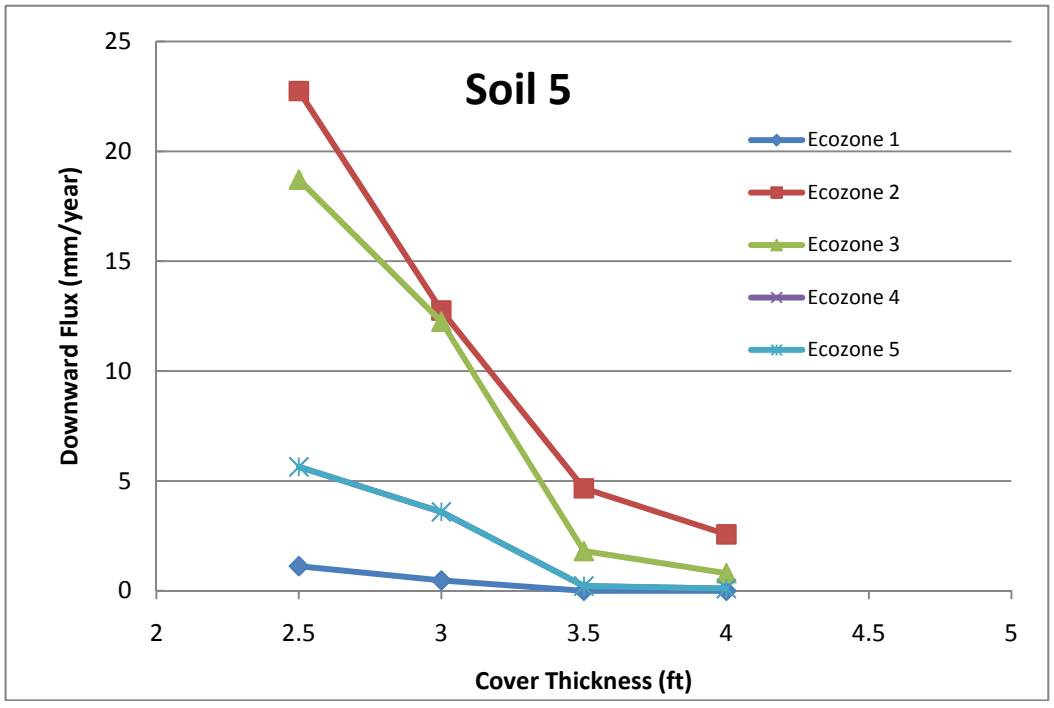
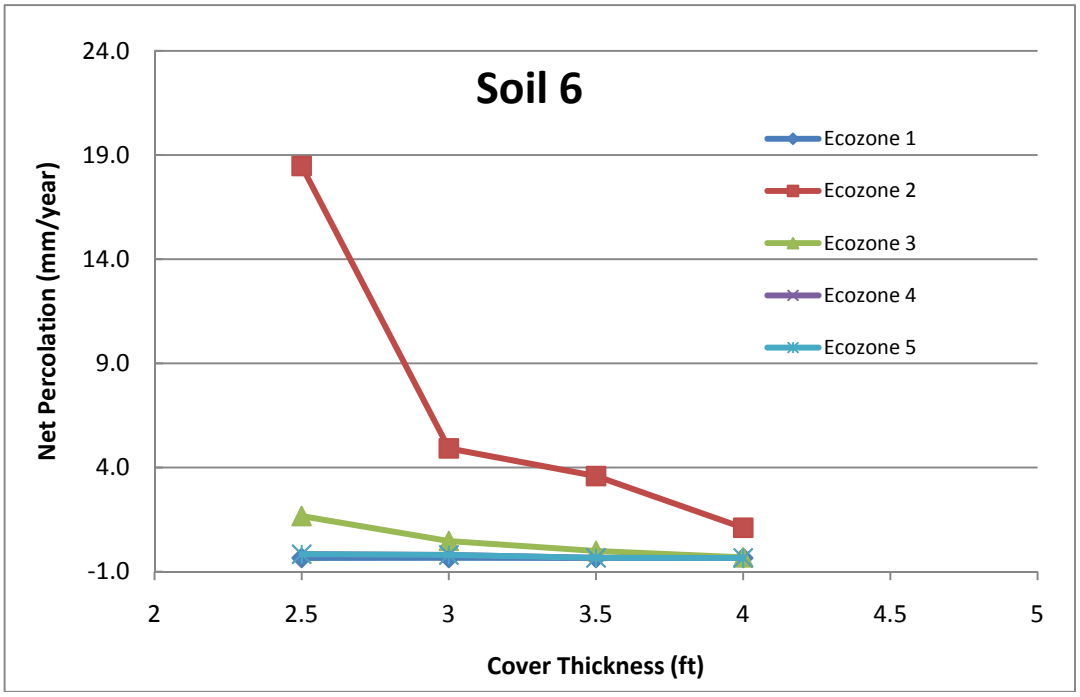



**Figure 26. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 5**

**(a)**




**(b)**

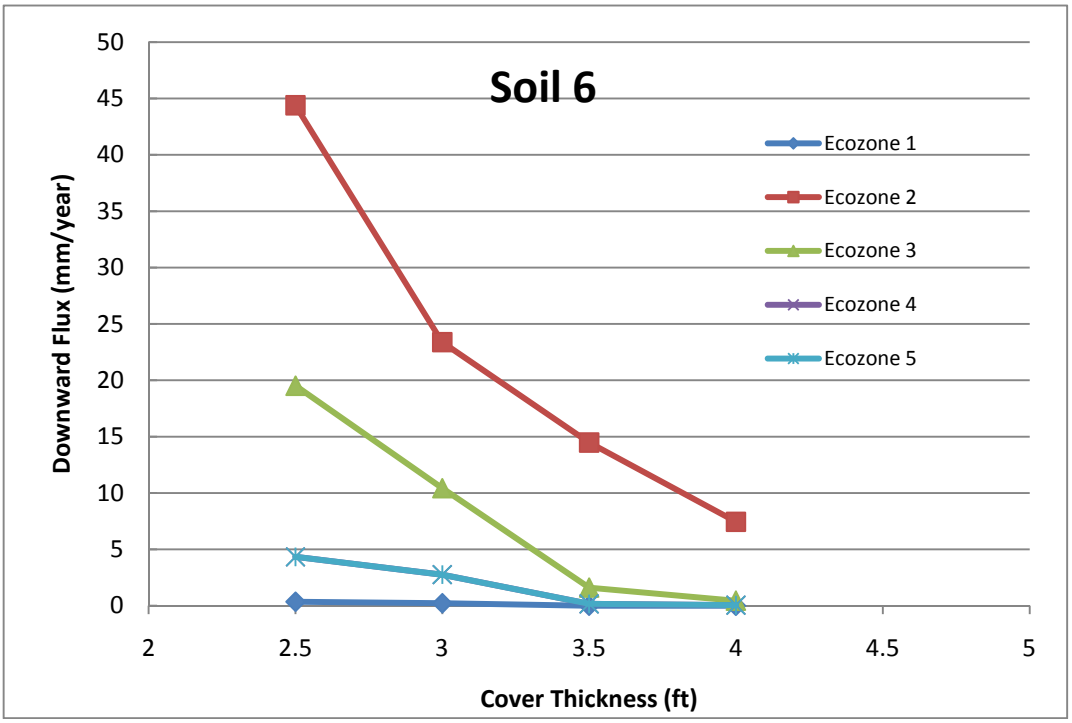
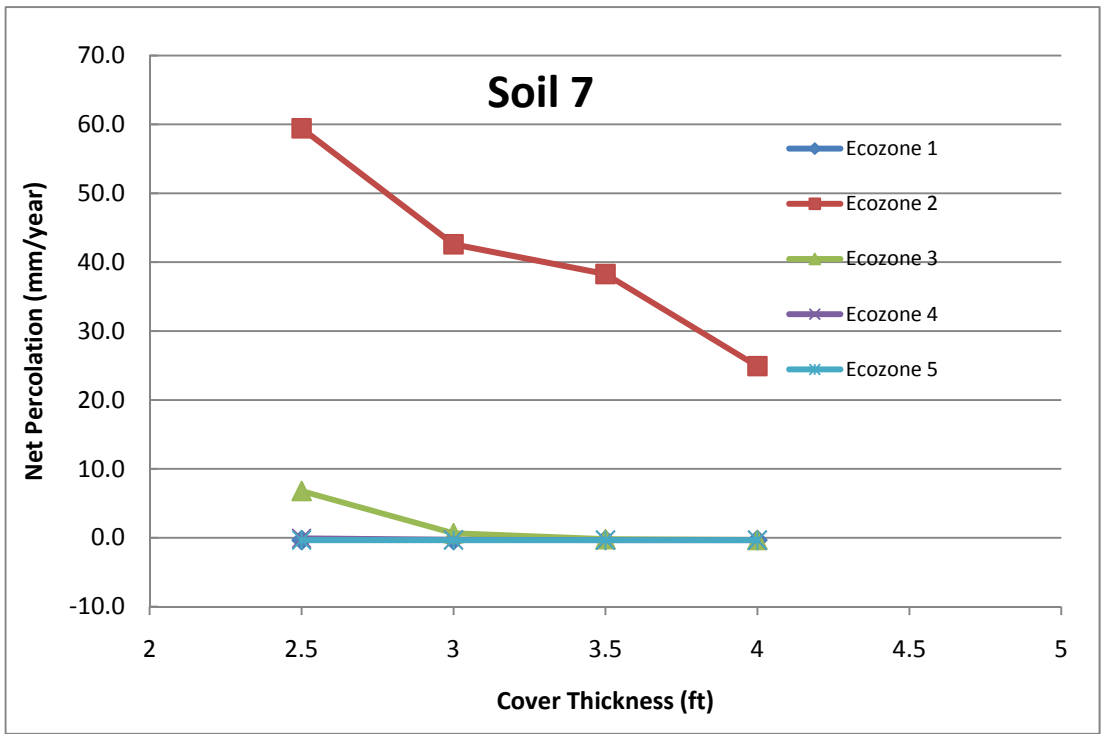



**Figure 27. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 6**

**(a)**




**(b)**

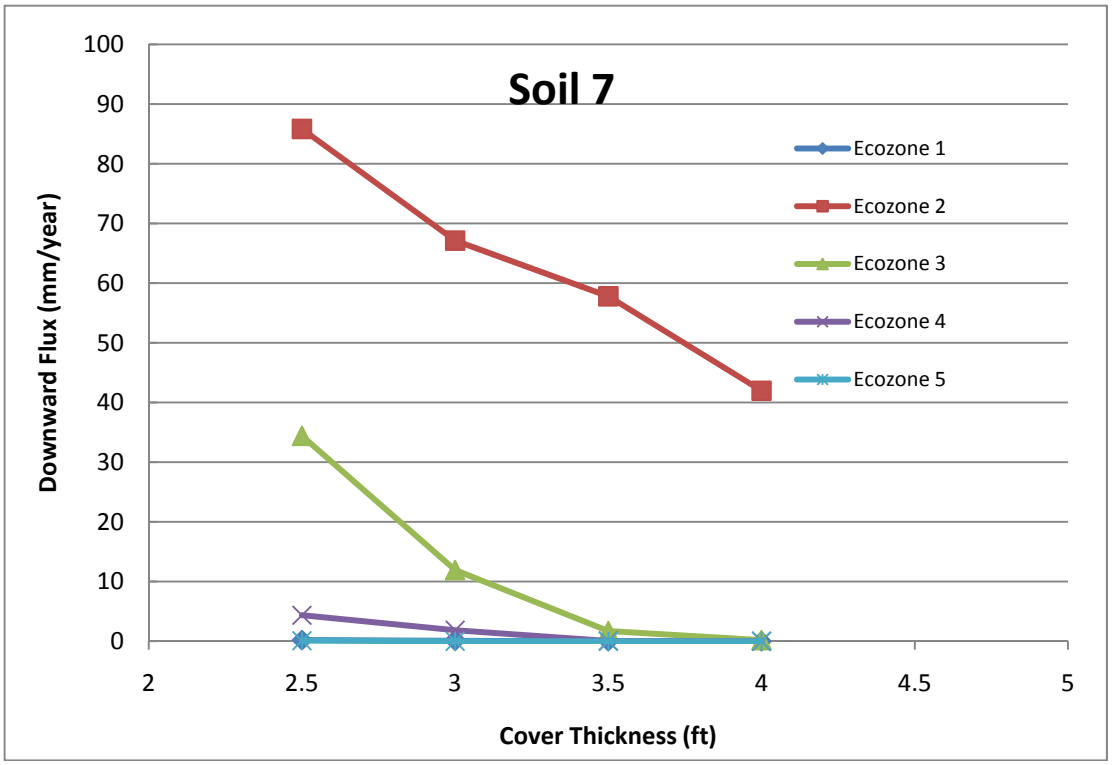



**Figure 28. Variation of (a) Net Percolation and (b) Downward Flux with Cover Thickness for all Ecozones for Soil 7**

## 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**

| | Downward Flux | | | Net Percolation | | |
|---|---|---|---|---|---|---|
| **Ecozone** | ***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.

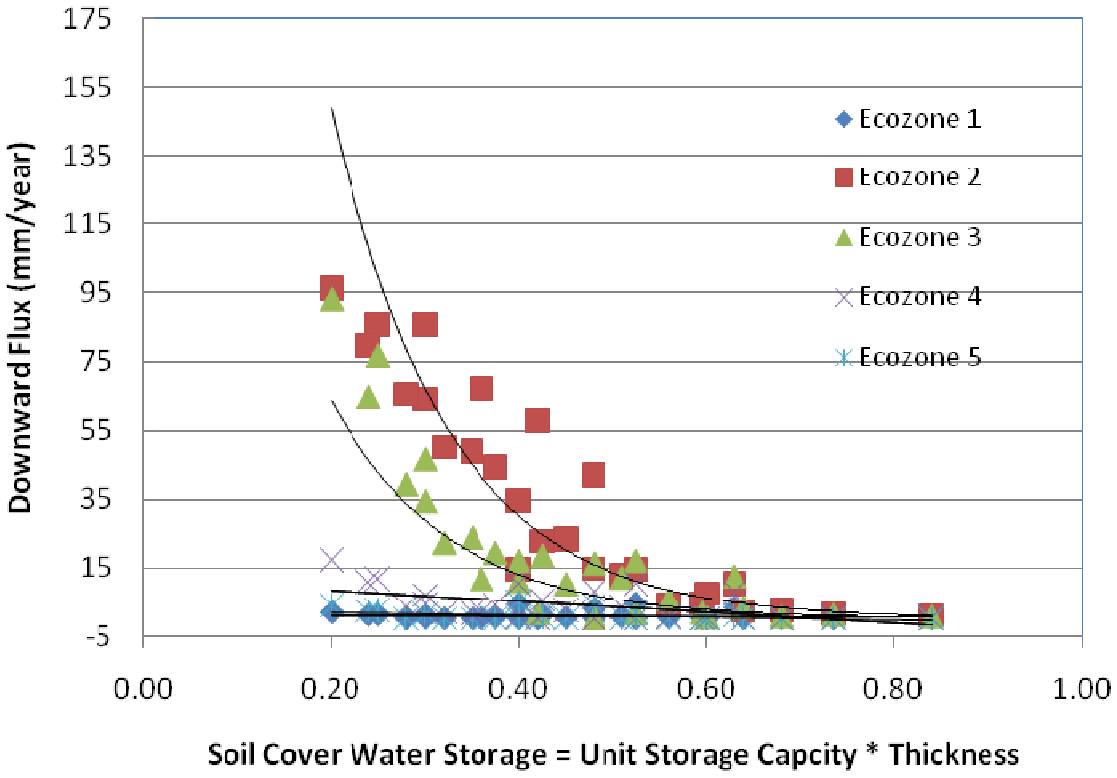



**Figure 29. Downward flux versus total water storage capacity**

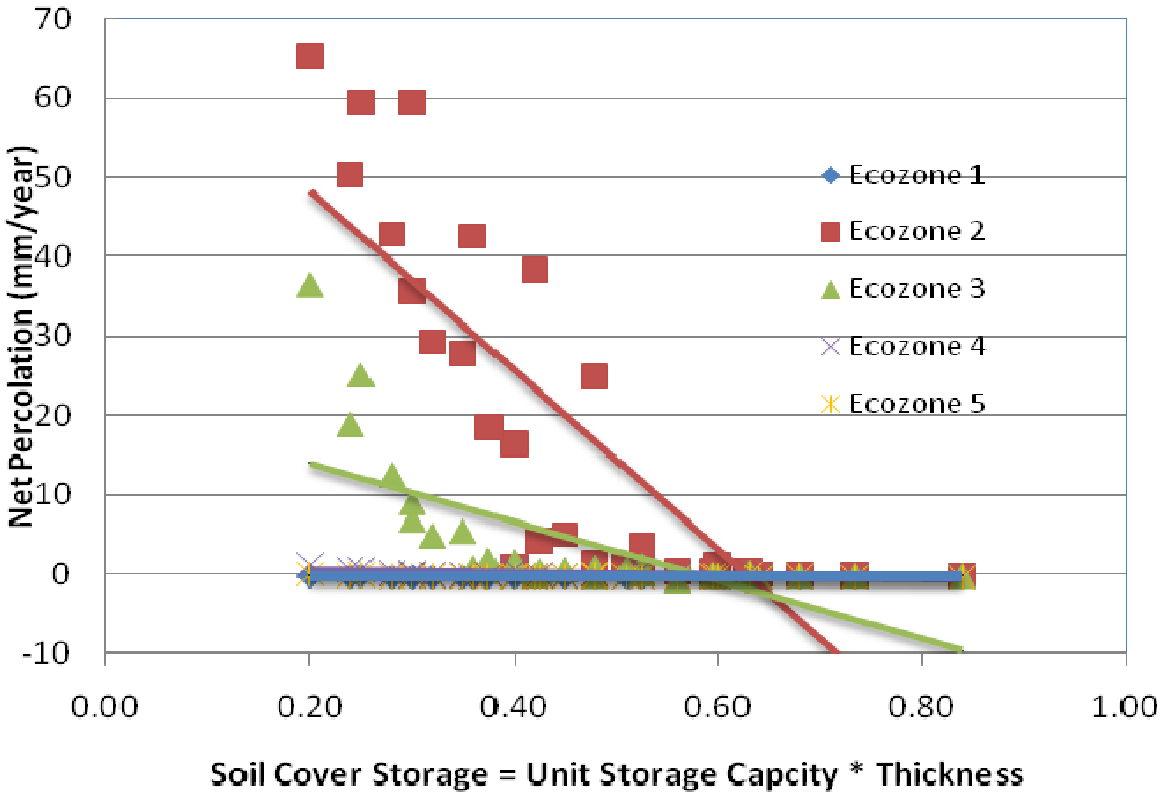



**Figure 30. Net Percolation versus total water storage capacity**

### *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 course-grained material, along with a low $K_s$. The saturated hydraulic conductivity of waste from previous laboratory studies ranged from $1 \times 10^{-8}$ m/s (0.086 cm/d) (Bleiker et. al., 1993) to $1.3 \times 10^{-3}$ m/s ($1.1 \times 10^{4}$ 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: S**imulated 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.

# 6. References

Albright, W.H., Benson, C.H., and W.J. Waugh. 2010. *Water Balance Covers for Waste Containment Principles and Practice.* Reston, Virginia: ASCE Press.

Allen, R.G., Pereira, L.S., Raes, D., and M. Smith. 1998. *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements.* FAO Irrigation and drainage paper 56. Food and Agriculture Organization of the United Nations. Available online (http://www.fao.org/docrep/X0490E/X0490E00.htm). Accessed 9/9/2011.

Allen, R.G. Pruit W.O. Businger J.A. Fristschen, L.J. Jensen M.E., and F.H. Quinn. 1996. Evaporation and Transpiration. Chapter 4, p. 125-252 in: Wooton et al (Ed), ASCE Handbook of Hydrology. New York, N.Y.

McGuire, P.E., Andraski, B.J., and R.E. Archibald. 2009. Case Study of a Full-Scale Evapotranspiration Cover. *Journal of Geotechnical and Geoenvironmental Engineering.* 135(3): 316-332.

Benson, C. H., and X. Wang. 1998. Soil Water Characteristic Curves for Solid Waste. *Environmental Geotechnics Report* 98-13, University of Wisconsin-Madison, WI.

Blaney, H.F., and W.D. Criddle. 1950. Determining Water Requirements in Irrigated Areas from Climatological and Irrigation data. *USDA Soil Conservation Service.* SCS-TP96. 44 pp.

Bleiker, E.D., McBean, E., and G. Farquhar. 1993. Refuse Sampling and Permeability Testing At The Brock Westand Keele Valley Landfills. *Proceedings, Sixteenth International Madison Waste Conference : municipal & industrial waste,* September 22-23, 1993. 548-567.

Brouwer, C., and M. Heibloem. 1986. *Irrigation Water Management Training Manual #3.* Food and Agriculture Organization of the United Nations. Available online (http://www.fao.org/docrep/S2022E/s2022e00.htm#Contents). Accessed 8/24/2011.

Chapman, S.S., Griffith, G.E., Omernik, J.M., Price, A.B., Freeouf, J., and D.L. Schrupp. 2006. *Ecoregions of Colorado* (color poster with map, descriptive text, summary tables, and photographs): Reston, Virginia, U.S. Geological Survey (map scale 1:1,200,000).

Chadwick, G. 2007. *UNSAT-H Simulation of Soil Moisture Fluxes During 1983 for Proposed 2-ft and 3-ft Covers at RMA. August, 2007.*

Chen, T., and Chynoweth, D.P. 1995. Hydraulic Conductivity of Compacted Municipal Solid Waste. *Bioresource Technology.* 51(2-3): 205-212.

Cleland, D.T., P.E. Avers, W.H. McNab, M.E. Jensen, R.G. Bailey, T. King, and W.E. Russell. 1997. National hierarchical framework of ecological units. In: *Ecosystem Management: Applications for sustainable forest and wildlife resources,* ed. M.S. Boyce and A. Haney, pp. 181-200. New Haven, CT: Yale University Press.

Doesken, N. J., Pielke Sr., R.A., and O.A.P. Bliss. 2003. *Climate of Colorado.* Colorado Climate Center, http://ccc.atmos.colostate.edu/climateofcolorado.php. Accessed 9/2/2011.

Han, B., Scicchitano V., and P.T. Imhoff. 2011. Measuring Fluid Flow Properties of Waste and Assessing Alternative Conceptual Models of Pore Structure. *Waste Management.* 31(3): 445-456.

Homer, C. C. Huang, L. Yang, B. Wylie, and M. Coan. 2004. Development of a 2001 National Landcover Database for the United States. *Photogrammetric Engineering and Remote Sensing.* 70(7): 829-840. Accessed at http://www.mrlc.gov/pdf/July_PERS.pdf.

Jang, Y. S., Kim, Y. W., and S. I. Lee. 2002. Hydraulic Properties and Leachate Level Analysis of Kimpo Metropolitan Landfill, Korea. *Waste Management.* 22(3): 261-267.

Kazimoglu Y. K., McDougall, J. R., and I. C. Pyrah. 2006. *Unsaturated Hydraulic Conductivity of Landfilled Waste.* Proceedings of the 4th International Conference on Unsaturated Soils, April 2-5, 2006, Arizona, USA, ASCE, Virginia, USA, 1525-1534.

Korfiatis, G. P., Demetracopoulos, A. C., Bourodimos, E. L., and E.G. Nawy. 1984. Moisture Transport in a Solid Waste Column. *Journal of Environmental Engineering.* 110(4): 780-796.

Omernik, J.M. 1995. Ecoregions – A Framework for Environmental Management, in Davis, W.S., and Simon, T.P., eds., *Biological Assessment and Criteria - Tools for Water Resource Planning and Decision Making.* Boca Raton, Florida, Lewis Publishers, p. 49-62.

Sammis, T.W., J. Wang, and D.R. Miller. 2011. The Transition of the Blaney-Criddle Formula to the Penman-Monteith Equation in the Western United States. *Journal of Service Climatology* 5(1) 1:11.

Sievering, H., Burton, D., and N. Caine. 1992. Atmospheric Loading of Nitrogen to Alpine Tundra in the Colorado Front Range. *Global Biogeochemical Sciences.* 6 (4): 339-346.

Stoltz, G., and J.P. Gourc. 2007. *Influence of Compressibility of Domestic Waste on Fluid Permeability.* Proceedings of the 11th International Waste Management Landfill Symposium (Sardinia, 2007), S. Margherita di Pula, Cagliari, Italy, October 1-5, 2007, CISA Environmental Sanitary Engineering Centre, Italy.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. *Soil Survey Geographic (SSURGO) Database for Colorado.* Available online at http://soildatamart.nrcs.usda.gov. Accessed June 2011.

United States Environmental Protection Agency. 2011. Ecoregions. Available online at: http://www.epa.gov/wed/pages/ecoregions/co_eco.htm. Accessed 9/5/2011.

# 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.