INVESTIGATING THE USE OF ECOZONES IN THE DESIGN OF WATER BALANCE COVERS FOR WASTE CONTAINMENT BY ANALYZING THE SENSITIVITY OF COVER EFFECTIVENESS TO CLIMATE, VEGETATION AND SOIL PARAMETERS

by

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ABSTRACT

Water-balance landfill covers are a relatively new and innovative design for waste containment that does not require the previously mandated clay layers or geomembranes that are expensive to manufacture or import. The designs of these covers are often based on one-dimensional unsaturated flow modeling to simulate water flux into and out of the cover. Water balance covers are engineered to minimize percolation through the bottom of the cover by managing the storage and removal of water in the cover. The covers store water from precipitation events during the wet seasons and that water is subsequently released due to evapotranspiration in the warmer growing seasons. It has been widely accepted that detailed site specific investigations are required to fully characterize the climate, vegetation and soil parameters that determine the effectiveness of water balance covers. Recent research (Cadmus, 2011) has suggested that the design of water balance covers can be done in a more generic manner, using "ecozones," or regions of similar climate and geographic properties, to define the parameters used in modeling. It is important to understand to what extent it is viable to use ecozones in lieu of site-specific characterization. For this project a sensitivity analysis is conducted on select climate, vegetation, soil parameters and the timing of precipitation patterns using a combination of HYDRUS 1-D and UCODE. It was found that cover effectiveness is highly sensitive to soil parameters, particularly saturated hydraulic conductivity and the fitting parameters in the van Genuchten equation, α and n. Water balance covers were also found to be sensitive to the timing of precipitation events in relation to the growing season and periods of maximum PET. Cover effectiveness has shown to be highly sensitive to a variety of parameters that vary significantly within large ecozones. A monte carlo analysis was conducted for two ecozones in Colorado, USA (the front range and western slope). At each ecozone it was determined that variability in climate, vegetation and soil parameters is significant enough to effectively rule out generic cover methodology for the two ecozones. Due to the large variability and uncertainty in climate, vegetation and soil parameters within an ecozone, the methodology of designing water balance covers in a generic manner based on ecozones is demonstrably questionable.

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1.0 INTRODUCTION

For modern waste disposal, landfill covers are needed to prevent the seepage of precipitation through the underlying waste. In the EPA's federal regulations for landfills, they identify the importance of the design and operation of landfills that will prevent the release of contaminants to groundwater as well as the importance of closure-post closure plans (EPA, 2012). A typical landfill is composed of three members; 1) bottom liner, 2) leachate collection system and 3) closure/post closure design. The bottom liner is constructed with compacted clay and overlying geotextile. This bottom layer is designed to limit, through low hydraulic conductivity (K), the percolation of contaminated liquids into the subsurface and in turn preventing the contamination of soils and groundwater. Percolation through waste is often referred to as "leachate." A leachate collection system is designed to collect this percolation, which is pumped out of the landfill and treated. A closure/post-closure design is implemented once the landfill ceases to accept waste. This includes two primary components. First, a gas system that is used to control the flow of gases out of the waste that is generated as material degrades. Second, a final cover is emplaced to prevent the percolation of precipitation into the underlying waste. Traditional designs implement a clay and geomembrane component that is equivalent to the bottom liner (EPA 2012). Geomembranes are generally made of a high density polyethylene of various thicknesses. These final covers must have a permeability equal to or less than the permeability of the bottom liner, generally a hydraulic conductivity with a maximum of $1.0*10^{-5}$ cm/sec, as well as an erosion layer (EPA 2012).

Due to the high costs of installing these traditional covers, alternative designs have been implemented that use natural processes to prevent the infiltration of precipitation into the underlying waste. These alternative covers, often referred to as water balance covers and used from here on out, use the storage capacity of native soils to hold water during precipitation events. Cartoons showing the cross sections of water balance cover compared to traditional covers can be seen in figure 1-1. Subsequently the soil is emptied through evaporation and the transpiration by plant life on the surface. By managing the available storage in a cover through soil type and cover thickness an effective waste cover can be designed (Albright 2010). Water balance covers have displayed effectiveness in certain climate regimes such as arid or semi-arid climates whereas in other more wet regions water balance covers have shown only a limited success (Albright, 2002; Albright, 2004).

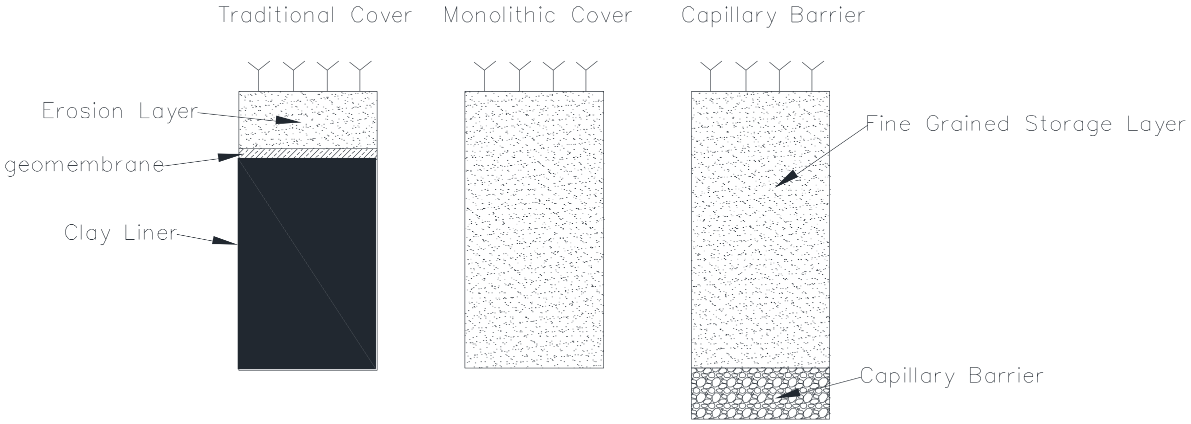

Figure 1-1: Cross section of a traditional cover and two common water balance covers. Water balance covers use a fine grained profile so store water which is removed through PET. Traditional cover used low permeable materials and geomembranes to prevent percolation.

Water balance covers are an attractive alternative design due to the possible reduced materials costs associated with them, depending on the availability of appropriate native soils. They do not require the import of clay materials as well as the use of geomembranes. There are also reduced costs in the construction of these covers because clay layers are required to be placed in many smaller lifts with strict compaction requirements as well as moisture conditioning whereas water balance covers can be layed in larger lifts and have less stringent compaction requirements. On the other hand, there are increased costs associated with the use of water balance covers, particularly due to the increased design costs associated with the need for site specific investigations and computer modeling (Albright, 2010). The high costs associated with the design process of water balance covers prompted the state of Colorado to explore generic cover designs. Similar to how the EPA has streamlined guidance for traditional covers, the state of Colorado hopes to streamline the design of water balance covers in the same manner. This will be done through the implementation of generic water balance cover designs based on ecozones, methods which are outlined in the Cadmus [2012] report, thus eliminating the need for site specific modeling. In this thesis a method will be outlined which is used to evaluate the feasibility of water balance covers based on generic designs using generic soil and plant types and ecozones.

1.1 Water Balance Cover Design

The performance of water balance covers is based on a variety of climate, vegetation and soil parameters. It is necessary to design a cover with sufficient storage capabilities to hold the specified precipitation for the site. During the growing season, stored water is removed through evapotranspiration (ET). Soil acts much like a sponge, holding a certain amount of water based on the characteristics of the porous media, before a certain saturation is reached when water begins to drain due to gravity. The specific field capacity of soil, θ_c, is the water content at which a soil will begin to drain freely due to gravity. Typically θ_c is defined as the volume fraction of water in a soil when a suction of 33kpa is applied. The cover will hold water up to the field capacity, at which point subsequent additions of water reduce the matric suction of the porous media resulting in the percolation of water through the bottom of the cover. In an ideal sense, this means that when the soil is at the field capacity, for each drop of water added to the top of the cover profile, an equal amount of water will drain out of the cover and into the underlying waste.

Stored water is primarily removed through the suction forces of the root network of plant life. Roots take up water by capillary forces. Based on the characteristics of the specific root, a specific suction is applied to the pore water. At low water contents the matric suction of the soil profile may be greater than that of the roots and thus the water is retained in the soil. The specific water content at which the suction in the soil is greater than that of the roots is defined as the wilting point, θ_m. The wilting point varies depending on the plant species. The total amount of water a cover can store, total storage capacity S_c, is defined as the thickness of the cover (L) multiplied by the difference between the field capacity of the soil and the wilting point (Eq 1.1)

$$S_c = L(\theta_c - \theta_m) \tag{1.1}$$

In this simplistic calculation the storage capabilities of a cover can be increased by increasing the thickness of the cover. The thickness of a cover is limited based on the root depth of the surface vegetation. The capabilities of PET to remove water below the root zone is significantly decreased and as such cover profiles should not be significantly thicker than the root depth. One of the key assumptions in the previous calculation for the storage capacity of a cover is that the degree of saturation throughout the cover profile is constant. In reality there is a gradient of moisture conditions in the cover, such as decreasing moisture content with depth or when water moves below the bottom of the root zone (Albright, 2010). Using an iterative process it is possible to estimate the storage capacity of a cover which takes into account gradient moisture conditions.

Capillary barriers can also be used to increase the effective storage capacity of the cover. Capillary barriers are formed by the placement of a relatively coarse-grained material under a relatively fine-grained material. The rapid change in hydraulic conductivity across the interface between fine and coarse-grained materials restricts water flow at lower moisture contents (Lu, 2004). Flow from the fine material to the coarse material will only begin when the matric suction in the coarse material is relatively high compared to that of the overlying fine material (Khire, 2000). Physically this means there must be greater potential in the fine-grained material than the coarse material. Water will build up in the fine material until the suction in the fine-grained media is lower than the suction in the dry underlying coarse-grained material, at which point water will begin to percolate into the coarse material. For the remainder of this study monolithic covers, that is a cover with essentially a single material throughout the profile, will be explored. Capillary barrier can be used to increase the available storage in a cover but do not impact the feasibility of generic cover design and are not included in further numerical modeling.

1.2 Numerical Modeling

Numerical modeling is typically used to estimate percolation through a cover (Khire, 2000; Albright, 2010). Long term percolation rates are compared to those of a traditional geomembrane cover to demonstrate that the water balance cover will be equivalently effective at preventing percolation into the waste. Equivalency is defined as a water balance cover resulting in the same or less percolation than a traditional design for the same site (Benson, 2002)(See environmental protection agency title 40, 40 CFR 258.60-Closure Criteria). For permitting a water balance cover, many regulatory committees require an equivalency demonstration through modeling, which includes showing that the proposed water balance cover is as effective as a traditional cover. A variety of 1-D unsaturated flow models have been used to simulate water flow through water balance covers including HYDRUS 1-D, UNSAT-H and LEACHM (Ogorzalek, 2008; Bohnhoff, 2009). These models calculate water flow using a discretized solution to Richards' (1931) equation for unsaturated flow

$$\frac{d\theta}{dt} = \frac{d}{dz}\left[K\left(\frac{d\varphi}{dz} + \cos(\alpha)\right)\right] - S, \tag{1.2}$$

where θ is the volumetric water content,*t* is time, *z* is the spatial coordinate, $K(\varphi)$ is the unsaturated hydraulic conductivity, φ is the pressure head, α is the angle of flow from vertical, and *S* is a sink term. One of the key assumptions in the Richards' equation is that the air pressure gradients in unsaturated media is insignificant with regard to fluid flow (Simunek, 2009). It has been shown that particularly in arid and semiarid climates with dry soils vapor fluxes play a dominant role in water fluxes (Saito, 2006). Due to the fact that water balance covers tend to be implemented in arid and semiarid regions it is important that models take into account vapor fluxes. This is done in HYDRUS 1-D using a liquid and vapor mass balance (Saito, 2006)

$$\frac{d\theta_T(\varphi)}{dt} = \frac{d}{dz}\left[(K + K_{vh})\left(\frac{d\varphi}{dx} + \cos(\alpha)\right) + (K_{LT} + K_{vT})\frac{dT}{dz}\right] - S(h), \tag{1.3}$$

where θ_T is the total volumetric water content, *z* is the spacial coordinate, *T* is temperature, *K* is the hydraulic conductivity for the liquid phase, K_{LT} is the thermal hydraulic conductivity for the liquid phase, K_{vT} is the thermal hydraulic conductivity for the vapor phase, and K_{vT} is the isothermal hydraulic conductivity for the vapor phase (Simunek, 2009). All further simulations conducted in this project use this method to account for vapor fluxes in the cover profile in place of Richards' equation.

The numerical model implemented in this project uses a series of nodes in one dimension where the flow is calculated from one node to the next. Time is also discretized with user-defined time steps. Finer discretization, both spatially and temporally, will increase model accuracy and provide a better approximation of percolation. Important input parameters when modeling water balance covers include meteorological data, vegetation and soil properties. These properties define the parameters, boundary conditions and sources and sinks in equation 1-3. In this section, the importance of each of these parameters will be discussed as they relate to simulating flow in alternative landfill covers. HYDRUS 1-D (Simunek, 1999) is a free-to-use 1-D modeling software that is widely used for modeling vertical flow in unsaturated media. For the remainder of this section all input parameters discussed and model outputs will be in reference to HYDRUS 1-D, but the principles can be applied to other unsaturated flow models.

To solve for equation 1-3 it is required to specify the initial and boundary conditions for the model. The initial suction head in all cells within the 1 dimensional soil column must be specified. Boundary conditions must be set for both the top and bottom of the soil column. An atmospheric boundary condition at the top including specified fluxes from precipitation and potential evapotranspiration with a free draining bottom is commonly used when modeling water balance covers, where fluxes are calculated using soil properties and pressure head (Khire 1999, Khire 2000, Bohnoff 2009). An atmospheric boundary condition allows for the flux of water between the soil and atmosphere. Monitored covers have shown that runoff plays a generally insignificant role in the total water balance (Benson, 2002). For monitored covers in the Alternative Cover Assessment Program (ACAP) for a variety of climates the average runoff is typically less than 4% of the water balance, and even smaller for arid and semi-arid climates (Albright, 2004). It has also been shown that it is difficult to accurately estimate runoff in arid and semi-arid regions using numerical models (Scanlon, 2002; Scanlon, 2005). Because of this it is acceptable to ignore runoff at the top boundary. A free draining bottom boundary condition assumes there is no material below the soil column and that water can freely drain out of the cover and into the waste (Simunek 2012). Some models have included a boundary condition that takes into account the underlying waste, though for the case of this project a free draining boundary condition is assumed to be sufficiently accurate for estimating sensitivities of input parameters.

Input climate parameters into HYDRUS 1-D are precipitation, wind speed, radiation, relative humidity and temperature. This data is used to calculate potential evapo-transpiration (PET) using either the Penman-Monteith equation or the Hargreaves formula. Another option is to directly input estimates for potential evaporation (PE) and potential transpiration (PT). The time steps at which this data is entered influence the results of the simulation. Parameters estimated at large time intervals can result in significant error in the model. Parameters estimated at very small time intervals are generally more accurate (Scanlon 2002). Data at smaller time intervals are often not readily available and it has been determined that daily data are often sufficient (Albright, 2010). For all simulations conducted in this study precipitation and PET data is input as daily rates (Length/day).

Estimating these climate parameters are a major challenge in the design of water balance covers. In ideal conditions a meteorological station (met station) is used to define the range of climate parameters used in modeling. The difficulty is in gathering enough data over a long period of time, ideally years, to fully define the climate at the site. Because of the cost of met stations and the limit of their availability other methods are often used to define the climate parameters. Precipitation data is readily available online through sites such as the NOAA

National Climatic Data Center. Radiation is often estimated using solar inclination, latitude and elevation (Benson, 2011). Estimating climate parameters is particularly difficult due to the limited availability of certain data at each particular site. Precipitation events tend to be concentrated in shorter periods of time and not distributed over an entire day, however daily data is often only available online and generally only on a daily scale, incorporating variations in precipitation rates can increase model accuracy. To represent this, HYDRUS has a built in function to simulate these variations in precipitation rates as a cosine function (equation 1.4) where $\overline{P}$ is the daily precipitation rate and Δt is the average precipitation rate duration

$$P(t) = \bar{P}(1 + \cos(\frac{2\pi}{\Delta t} - \pi). \qquad 1.4$$

All simulations conducted in this report use this mehtod built in HYDRUS to model variations in precipitation rates.

It is important to define the growing season for the vegetation on the cover, which is dependent on the climate of the project area (Roesler, 2002). When plant life is dormant, transpiration will be effectively zero. Leaf area index (LAI) is used to define the ratio of leaf coverage capable of transpiration compared to the area of ground below the vegetation. LAI is used in models to breakdown potential evapo-transpiration (PET) into separate potential transpiration (PT) and potential evaporation (PE) values. The growing season directly affects the LAI at various times throughout the year, with an increase in the LAI at the beginning of the growing season and a decrease at the end (Winkler, 1999). Transpiration out of the cover is calculated using a root water uptake model. In HYDRUS 1-D either Feddes [1978] or the van Genuchten, [1985], model can be used to simulate root water uptake (HYDRUS 1-D). To account for the stress on the plant due to the limited availability of water, the *α(h)* function is included in the Feddes model, which numerically is simply the ratio of actual transpiration to potential transpiration. The Feddes equation is defined as a sink term S (volume of water per unit time) as a function of stress response function $\alpha(h)$ ($0 < \alpha < 1$) , and the potential water uptake rate S_p.

$$S(h) = \alpha(h)S_p \qquad 1.5$$

The potential water uptake rate, S_p, is function of the plants root system, and can be defined using equation 1-6 assuming root uptake is not uniform with depth;

$$S_P = b(z)T_P, \qquad 1.6$$

where $b(z)$ is function which describes the distribution of water uptake as a function of root depth. An exponentially decaying root density with depth is recommended in Albright et al. (2010). In this model a linearly decreasing root density is used. T_P is the potential transpiration (PT) defined by the meteorlogical setting and the LAI of the plant as described earlier. The total transpiration rate (T_a) can be found by combining equations 1-5 and 1-6 and integrating;

$$T_a = T_P \int_0^L a(h(z))b(z)dz, \qquad 1.7$$

Hydrus is capable of generating daily variations in transpiration. This function is meant to simulate real world tranpiration mechanisms where 76% of transpiration takes place between 6 AM and 6 PM with the the remaing 24% taking place at night. A maximum transpiration rate take place at noon. This is represented through a function that gives transpiration a sinusoidal shape, with the peak at 12 noon and the trough at 12 midnight (Simunek, 2005) where $\bar{T}_p$ is the daily transpiration rate.

$$T_p(t) = 0.24\bar{T}_p \qquad t < 0.264\ d, t > 0.736\ d \qquad 1.8$$

$$T_p(t) = 2.75 * \bar{T}_p \sin\left(\frac{2\pi t}{1\,day} - \frac{\pi}{2}\right) \quad t\epsilon(0.264d, 0.736d) \tag{1.9}$$

Therefore the following vegetation input parameters need to be defined to calculate the flux of water out of the cover due to transpiration.

- Leaf Area Index (LAI) and potential evapo-transpiration (PET) during each time step over the course of the simulation.
- The depth plant roots extend beneath the surface.
- A stress response function *α(h)* of the plant.

LAI and PET are user defined discretized variables in HYDRUS. LAI needs to be directly entered into the model, while PET can either be directly input or HYDRUS can calculate it in the model using the Penman Monteith equation. For all simulations conducted in this project PET is directly input into the model. The reason for this is to allow for the ease of conducting a sensitivity analysis and is discussed further in section 3.

The model uses the soil water characteristic curve (SWCC), which defines matric suction as a function of water content, to estimate soil parameters over time. There are multiple models for defining the SWCC included in HYDRUS: the Brooks and Corey (1964) model, the modified van Genuchten model (1980) and the Durner model (1994). Hereon the modified van Genuchten equation will be used. The van Genuchten equation is based on four parameters for modeling the SWCC;

$$S = \left[\frac{1}{1+(a\varphi)^n}\right]^m, \tag{1.10}$$

where S is the degree of saturation, φ is the soil suction and α, m and n are fitting parameters (Lu, 2004). The van Genuchten [1980] model is combined with the Maulem equation to estimate unsaturated hydraulic conductivity (equation 1.11, 1.12).

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \qquad 1.11$$

$$m = 1 - \frac{1}{n}, \quad n > 1 \qquad 1.12$$

Where K_s is the saturated hydraulic conductivity, S is the soil saturation and m is a fitting parameter as a function of n. The fitting parameters α and n directly influence the shape of the SWCC. The field capacity and wilting point for a particular soil is determined based on the SWCC, such that the available storage in a cover is directly influenced by α and n.

When modeling water balance covers it may be important to incorporate hysteresis to model variations in the wetting a drying SWCC because of the cycles of wetting and drying a cover will experience over the course of a year. Hysteresis is incorporated through the Kool and Parker [1987] modified version of the Scot et al. [1983] model in HYDRUS and used in all simulations conducted hereon. These methods assume that the residual water content and the fitting parameter n are constant between the wetting and the drying curves with only α varying. It is published that the following relationship (equation 1.13) is an acceptable approximation for α (Kool and Parker [1987]; Nielson and Lucknar [1992];

$$\alpha^w = 2\alpha^d \qquad 1.13$$

where α^w represents the wetting curve and α^d the drying curve. These parameters can be directly determined by conducting a soil water characteristic curve on a site sample (ASTM D6836). The challenge with this method is due to both the time required to conduct each test and the expense associated with laboratory testing. A common alternative is estimating the van Genuchten parameters based on the grain size distribution of the on-site soil. A full grain size distribution, ASTM D422, is a quick and relatively inexpensive test, and the van Genuchten parameters can be estimated based on this grain size distribution using published literature (Schaap, 1999). The hydraulic conductivity can be directly measured by conducting ASTM D5084. Soil characterization and testing are one of the significant costs associated with the design of water balance covers and is reduced through the implementation of generic cover designs based on ecozones.

1.3 Sensitivity Analysis and UCODE_2005

Sensitivity analyses are used to evaluate the relative impact certain parameters in a numerical model will have on particular outputs. If small changes in an input parameter, such as the climate, vegetation and soil parameters outlined in the previous section, greatly change a particular output, for example, percolation rates, then, it can be said that percolation rates are highly sensitive to the input. On the other hand, if changes in an input parameter has little to no effect on percolation rates than it is said that the sensitivity is low. This process is useful in guiding field work, such that it is important to accurately define parameters which have a high impact on percolation rates, while best estimates may be sufficient for parameters that have a low impact.

A sensitivity analysis is a useful tool in assessing the feasibility of generic water balance cover design based on ecozones. The methodology for designing generic covers based on ecozones will be discussed further in the next section. Variability in climate, vegetation and soil parameters is expected within an ecozone, with more variability for larger regions. Sensitivity of percolation need to be low to parameters that are highly variable to ensure consistent and effective cover performance within a region when implementing generic cover designs based on ecozones.

UCODE_2005, [Poeter et al. 2005], is a code written for conducting sensitivity analysis, calibration and uncertainty analysis and is designed to be integrated with a vast array of models in a variety of fields. At its most basic level, UCODE_2005 adjusts specified parameters within input files for a code and then reads the desired model results from the output files.

Sensitivities are a method used in this project to analyze the relative impact that variations in a parameter will have on percolation rates. Sensitivites are calculated in the same manner as a slope, such that there is a change in y, percolation rate, over a change in b, the parameter. A high sensitivity shows that smaller changes in the input parameter will have a larger impact on percolation rates. In order to compare sensitivities of one parameter to another, all sensitivities are converted to a composite scaled number (composite scaled sensitivities). A common method for comparing these sensitivities is to look at the ratio of each parameters sensitivity and compare it to the maximum sensitivity such that the parameter with the highest composite scaled sensitivity will have a ratio to the maximum equal to 1. The parameter with the composite scaled sensitivity needs to be defined with the lowest precision and the parameter with the highest composite scaled sensitivity needs to be defined with the most precision. If parameter A has a ratio to the maximum of 0.1 and parameter B has a ratio to the maximum of 1, than it can be said that precision of parameters B needs to be 10 times that of parameter A. Using sensitivities it is possible to address the precision with which parameters need to be defined to implement generic cover methodologies.

For the purpose of this project UCODE_2005 will integrate well with HYDRUS 1-D. The code will only be used to conduct a sensitivity analysis, the predictive and calibration capabilities of UCODE_2005 will not be used. When in sensitivity mode, UCODE_2005 runs through an iterative loop to test the sensitivity of a particular model output to changes in specified input parameters. For this research we will be testing the sensitivity of total yearly percolation through the cover profile to changes in climate, vegetation and soil parameters. These specific parameters will be discussed in the following sections. The model process can be seen in figure 1-2. Central-difference sensitivities are the most accurate sensitivity method available in the UCODE_2005 code. The disadvantage of this method is that is requires twice the computing time to run the simulation, but because of the short run times for HYDRUS-1D the central-difference method can be implemented despite the extra iterations. In this method each parameter is perturbed in two directions, forwards and backwards, by a specified fraction of the starting values. The model is run after each perturbation and the total yearly percolation is read from the HYDRUS 1-D output files. This process is repeated for each parameter, at which point the simulation will stop. The sensitivity to each parameter is calculated using equation 1.14.

$$\frac{\Delta y'}{\Delta b} = \frac{y'(b+\Delta b)-y'(b-\Delta b)}{(b+\Delta b)-(b-\Delta b)}, \qquad 1.14$$

where $\Delta y'$ is the change in the specified model output, Δb is the perturbation of the perameter, $y'(b+\Delta b)$ is the specified output due to the forward perturbation, $y'(b-\Delta b)$ is the specified output due to the backward perturbation, $(b+\Delta b)$ is the perturbation parameter in the forward direction, and $(b-\Delta b)$ is the perturbed parameter in the backward direction. Sensitivities are then converted to a dimensionless number, composite scaled sensitivities. Composite scaled sensitivities are simply the slope of a line that demonstrates how a percentile change in a parameter, b, will change an output, $\Delta y'$. Physically this means that changes in a parameter with a large composite scaled will result in a greater $\Delta y'$.

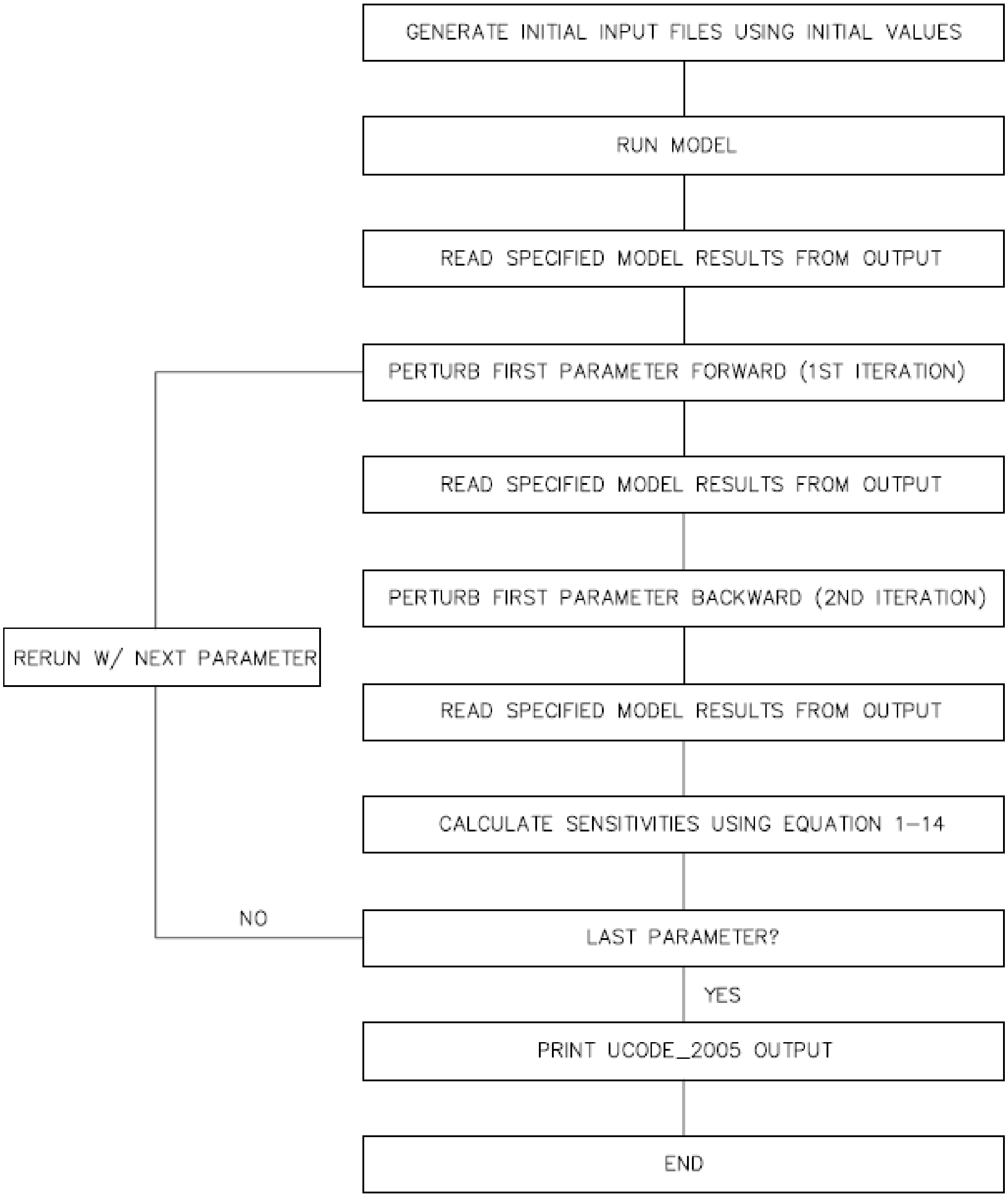

Figure 1-2: Flow chart for the operation of UCODE_2005 with perterbations in two directions.

1.4 Designing Generic Covers Based on Ecozones

The effectiveness of water balance covers is directly related to climate and geographic properties that control the flux of water into and out of the cover. Climate parameters such as precipitation and potential evapotranspiration (PET) directly affect the flux of water into and out of the cover. Precipitation is generally the source of all the water that enters the cover. PET directly defines how much water may be removed from the cover at any time as a function of temperature, wind, humidity and solar radiation. Vegetation parameters define the capacity of plant life to remove water from the soil profile. Different plants transpire at different rates based and the size of their leaves, root depth and growing season. The soil properties define the storage capacity of cover as well as the flow of water through the cover. Due to the spatial and temporal variations of climate, vegetation and soil parameters that control cover performance, it has been generally required by state regulatory guidelines that site specific characterization of these properties, particularly soil characteristics, is necessary for the proper design of water balance covers (Winkler, 1999; Albright 2010). The site investigations required to estimate the precipitation, evapotranspiration, soil characteristics and vegetation characteristics at a site are one of the most difficult and expensive aspects of the design and modeling process. An EPA report was released in September 2011 addressing the idea of designing a generic water balance cover based on ecozones (Cadmus, 2010). Ecozones, as defined in Omernik (1995), are used to quantify areas of similar climate and geography. Generic designs could then be used within specific ecozones, reducing the need for site specific characterization and modeling.

Current regulatory committees are attempting to implement regulations on the design of water balance covers based on ecozones. The objective of this is to reduce the costs associated with field testing, site investigations, computer modeling, design and regulatory costs. In the current permitting process it is required that the proposed water balance cover must demonstrate equivalency to traditional designs. Through the implementation of generic design requirements based on ecozones, the amount of field testing and modeling required to demonstrate equivalency could be significantly reduced, and in some cases eliminated entirely.

Ecozones have been recognized as areas of similar vegetation and climate. The scale at which these ecozones are defined varies greatly, from the global scale to local variations. Omernik (1995) combined what he labeled single-purpose frameworks for vegetations, hydrology, climate and soils, into one comprehensive framework that defines ecozones based on all of these parameters. Ecozones are the attempt to distinctly quantify areas as being effectively the same based on a mosaic of the frameworks discussed above. The error within this process is directly related to the scale at which the ecozones are defined. It is impossible to determine the dominance of one factor over another on a site specific basis by looking at an ecozone. At smaller scales ecozones will more accurately define the site, while at larger scales there is more uncertainty in each factor; climate, hydrology, soil and vegetation. The scale of these ecozones is defined at various levels, with level 1 being the most general with each increasing level becoming more precise (Omernik 1995).

A common method for defining the climate in which a cover may be favorable or un-favorable is a precipitation to PET ratio (P/PET) (Albright, 2010). It has been shown that when the P/PET ratio for a site exceeds a specific threshold, accumulation of water in a cover profile may occur (Apiwantragoon, 2007). On the other hand, if the ratio is below the threshold then the opposite may occur with water being removed from the cover. The P/PET ratio is a good metric for defining ecozones as they pertain to cover performance. Regions with a higher P/PET ratio will generally accumulate more water and as a result it can be expected that there may be relatively more leachate generated compared to a cover in a region with a lower ratio. Hereon the P/PET ratio will be used to define similarity in climate between sites as they pertain to cover performance.

Because it has been widely accepted that detailed site specific characterization of parameters is important to the effective design of water balance covers, it is then important to ask whether or not ecozones are capable of defining these properties with enough precision to design an effective cover. Ecozones are not inherently precise to single parameters, such as P/PET, they are simply a mosaic of parameters working together to define regions of similar climate, vegetation and soil. Within each ecozone there is both variability and uncertainty in each parameter within the mosaic. Variability comes from the natural changes in parameters across the ecozone, and thus smaller ecozones will tend to have less variability. Uncertainty comes from a lack of available data to fully define the region. Further research must be conducted into the sensitivity of the effectiveness of water balance covers to various parameters before ecozones can be successfully implemented in the design of water balance covers.

2.0 OBJECTIVES

The objective of this research is to evaluate the feasibility of the implementation of ecozones on the design and modeling of water balance covers. The precision of ecozones required to effectively define the climate, vegetation and soil parameters that control the effectiveness of water balance covers is in question. There has been limited research into the amount of precision that is needed to fully define the array of parameters that control the operation of water balance covers to effectively implement generic design methods. This idea is the logical follow up to the EPA report release in 2011. The research question that will be answered in this thesis is

"To which climate, vegetation and soil parameters is the effectiveness of water balance covers for waste containment most sensitive?"

By answering this question it may be possible to evaluate the feasibility of using ecozones and generic soils in the design of water balance covers. If the sensitivity is high to a parameter, it will be assumed that more precise site investigation will be needed to fully characterize that parameter. If both the sensitivity of a parameter is high and variability of that parameters within an ecozone is also high than the validity of generic cover methodologies is put into question. If the sensitivity to a parameter is low, then ecozones at large scales may be sufficiently precise to fully characterize the parameter, and as such the validity of generic cover methodologies are supported. Cover effectiveness will be evaluated solely on percolation. As more percolation is allowed cover effectiveness is considered to have decreased. Therefore in this project the sensitivity of estimated percolation rates to climate, vegetation and soil parameters will be directly estimated, which can be interpreted to demonstrate the sensitivity of cover effectiveness to these parameters.

These results will be useful to consultants that are working on the design of water balance covers, regulators and can help guide further research into the implementation of generic cover design methodologies. In the case of an equivalency demonstration a consultant can use these sensitivity analysis results to more effectively design a numerical model. Parameters that cover effectiveness is highly sensitivity need to be precisely defined in the field. Other parameters that demonstrate a low may be estimated using online databases and precise field estimates may be unnecessary. Regulators can use these results to better implement generic cover methodologies. The results of this project outline a set of conclusion and recommendation for regulators to follow. Finally, this research will build a foundation for further research into generic cover methodologies.

3.0 METHODS

The sensitivity of water balance covers to a variety of climate, vegetation and soil parameters was tested using a combination of HYDRUS 1D and UCODE_2005. The relative sensitivity of cover performance to variations in these parameters provided insight into the feasibility of the generic cover design methodology discussed in section 1.3. These sensitivities were compared to observed variations in real-world data sets for ecozones in Colorado and conclusions were made on the feasibility of generic cover designs. Colorado is an ideal location to focus this research because it is currently a state where local regulatory committees are beginning the implementation of generic cover design methodologies as well as that the arid to semi-arid climate of the region is favorable for effective water balance cover performance (Benson 2002; Albright, 2004; Albright, 2010).

3.1 Sensitivity Analysis Model Setup

Many of the input parameters for HYDRUS are input as time series, that is a list of data for each variable as a function of time. UCODE is only capable of adjusting a single variable at a time and is not capable of adjusting time dependent variables input as arrays. To account for this, an intermediate code needs to be written to generate time-dependent variables as a function of a single user defined input parameter which UCODE is capable of adjusting. Figure 3-1 demonstrates how all three codes will work together. UCODE adjusts a series of input parameters, discussed in the following sections, in the “parameter file” code, written using Python. The “parameter file” code directly writes the HYDRUS input files creating the necessary time dependent arrays as a function of a single or group of user defined variables. HYDRUS is then run using these input files and generates the HYDRUS output files. These files are condensed into the results that are of importance when assessing the effectiveness of water balance covers (these will also be discussed later in this section). UCODE then reads these results and changes parameters in the “parameter file” python code. This program loop is then rerun multiple times until all inputs in the “parameter file” have been adjusted and the sensitivities calculated (see figure 3-1). The final model results will show the sensitivity of the cover to the user defined input parameters in the “Parameter File” code.

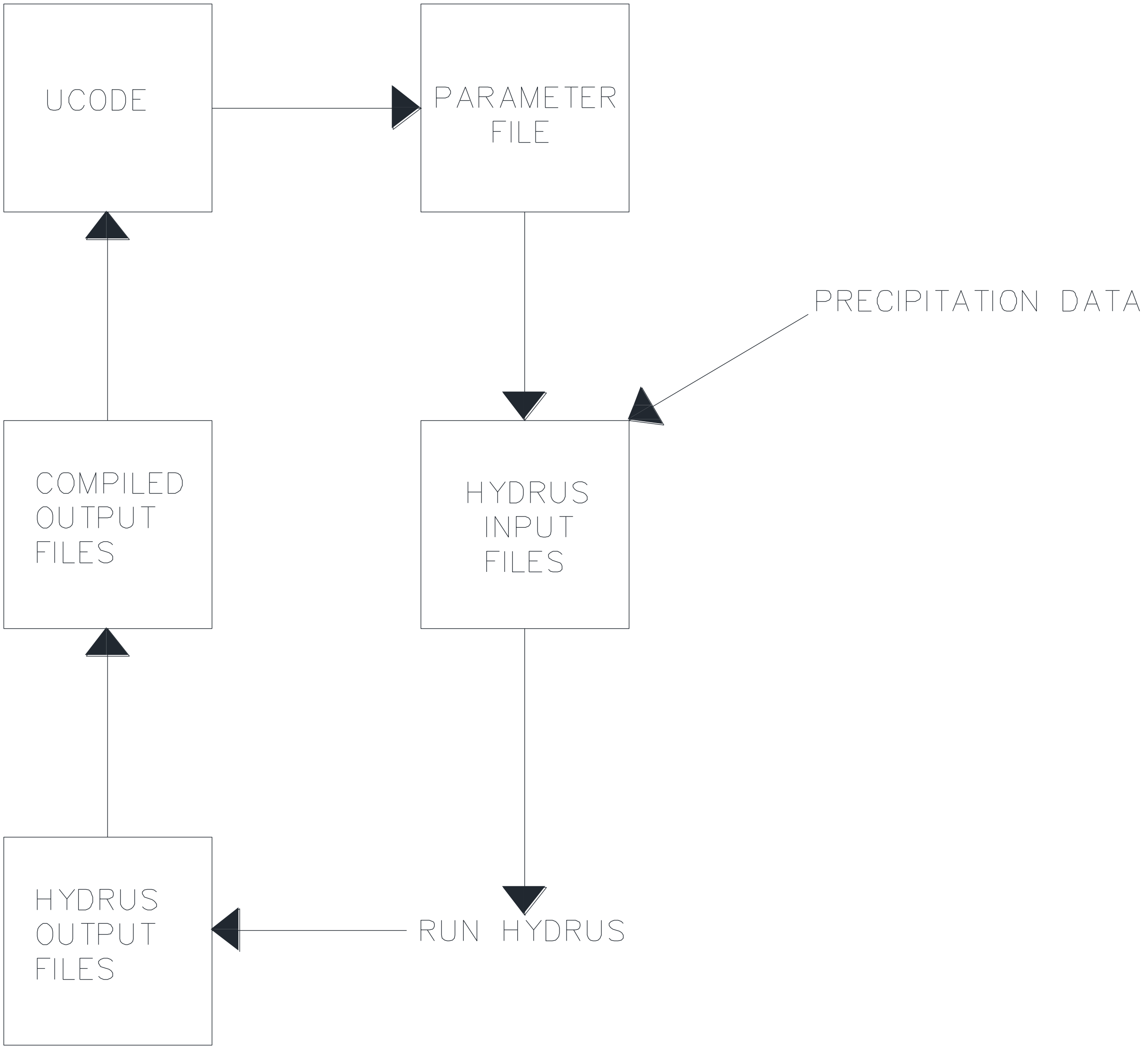

Figure 3-1: Hypothetical model loop for calculating the sensativity of cover effectiveness to climate, vegetation and soil input parameters. These input parameters are written into the "parameter file" which in turn creates the HYDRUS input files.

3.2 Model Set-Up

GENERAL MODEL SET-UP

For all simulations, a 91.44 cm (3 ft.) monolithic cover is used. The cover is assumed to be homogeneous with no variation in material throughout the soil profile. The profile is discretized into 101 nodes of equal size, with all flow assuming to occur in the vertical axis. Water flow with hysterisis, vapor flow and root water uptake is modeled within the soil profile. All time information is input in days including precipitation, PET and leaf area index. HYDRUS was set to calculate daily variation in transpiration and precipitation using the functions outlined in section 1. The initial time step is set to 0.001 d with a minimum time step of $1*10^{-5}$ d and a maximum of 5 d. All simulations are run for 365 days starting with January 1st as day 1. Outputs are printed at the end of each day for the entire simulation. The model is set to 1000 maximum iterations with a pressure head tolerance of 1 cm. Modeling was conducted on a Sony VAIO running Windows 7 Professional with a 1.73 GHz Intel Pentium M processor and 1.00 GB of ram.

INITIAL CONDITIONS

A spin-up was conducted to generate the initial conditions for all model runs. For each simulation an average year for the ecozone in which the model is being conducted, that is average climate and vegetation parameters, are set as inputs and ran 5 consecutive times, thus generating a 5-year simulation. Average climate parameters are determined based on a total yearly precipitation to total yearly PET ratio (P/PET). The modeled year for the spin-up has a P/PET ratio that is similar to the average for the region. A new spin-up is conducted for each simulation that uses differing initial soil parameters. For the spin-up the initial soil condition is considered to be dry with a suction set to -10000 cm. The resulting matric suction as a function of depth in the soil profile is then input into future simulations for the initial soil conditions.

BOUNDARY CONDITIONS

The top of the soil profile is designated as an atmospheric boundary condition with surface layer as outlined in Section 1. The bottom of the profile is set to be free-draining; although literature does report that there is interaction between the underlying waste and the soil profile (Albright et al. [2010]) with some published models assigning a seepage face boundary condition with a constant head (Ogorzalek et al. [2008]). This boundary condition is appropriate if the properties of the waste can be identified, but waste tends to be highly variable and therefore accurately defining this waste material is difficult. Using a free-draining boundary condition is a conservative approach that is used for this project which is recommended in literature and used in multiple published models (Khire, 2000; Benson, 2007, Albirght, 2010).

SOIL AND VEGETATION MODELS

The soil hydraulic characteristics are described by the van Genuchten – Mualem model, discussed in Section 1. Hysteresis is turned on in the model to account for the frequent changes in wetting and drying the cover will experience during the course of the simulation. An initial wetting curve is used. Root water uptake is calculated using the Feddes et al. [1978] model, see section 1 for details. Root density as a function of depth was calculated using an exponentially decaying root density with depth as recommended by Albright et al. [2010] and discussed in section 1. The exponential decay rate is set to 0.13 d^{-1} (Winkler, 1999).

3.3 Data Selection

For this project two ecozones were selected to conduct the sensitivity analysis. These regions were selected from the draft guidance documents entitled “Draft Guidance for Water Balance Covers in Colorado” released in August 2012. In these draft guidance documents Colorado was broken down into 5 ecozones outlined in figure 3-2. Two of the five ecozones were selected for this analysis based on the availability of data as well as variability in climate within the regions. Ecozone 2 does not fall under the guidance for generic water balance cover design outlined in the draft guidance and therefore will not be used. Regions 1 and 3 demonstrated the greatest variability in precipitation and PET data as well as had the largest amount of available meteorological data and therefore are selected for this analysis. Soils are spatially highly variable, and as such it was assumed that all soil types may be encountered within these ecozones.

Five theoretical sites are simulated for each of the ecozones. Sites were selected based on availability of meteorological data as well as their positioning within the ecozone. The five sites were selected to gather a best representation of the range of parameters for the region. Based on these criteria the 5 sites in the Front Range that had continuous precipitation and PET data from 2006 to 2011 and also were spread out across the region are, 1) Colorado Springs, 2) Broomfield, 3) Denver International Airport (DIA), 4) Longmont and 5) Trinidad. For the Western Slope the sites used in this study are, 1) Dinosaur National Monument, 2) Cortez, 3) Montrose, 4) Grand Junction and 5) Meeker. Although 6 years of data, as well as only 5 sites in each region, may not represent the full range of possible parameters for each region, they provide significant variation within the data sets to address the feasibility of generic cover design based on ecozones as well as perform the sensitivity analysis.

Meterologic data was found using the National Oceanic and Atmospheric Administration, NOAA, online climate data found in the National Climate Data Center. Daily data was published for precipitation, wind speed, relative humidity and temperature for each of the sites in the study from 2006 to 2011. This data source was used to obtain precipitation data used in the model as well as other data in the Penmen-Monteith equation, discussed in the next section, to calculate potential evapotranspiration, PET. To account for missing data points in the precipitation and PET data, often a result of error in measurement or equipment malfunctioning, the average value of the day before and day after for the missing measurement was used. Although this may account for some error in the model, it is assumed this error is minimal because missing data points are uncommon in the published data. Precipitation and PET data for the 10 sites can be found in appendix A.

Values for the vegetation and soil parameters were gathered directly from the databases included in the HYDRUS program. The types of vegetation and soil parameters can be specified in HYDRUS and the appropriate parameters are generated by the program. It is common for cheat grass to be used to vegetate water balance covers and is therefore the plant life chosen, for this model (Albright 2011). Input parameters for cheat grass used in this project can be found in appendix A. One of the advantages of water balance covers is that on site soils can be used in the construction of the cover. Soils are typically spatially variable and it is expected that all soil types may be encountered in ecozones of the size of the Front Range or the Western Slope. It is assumed that the onsite soil at for each location is a fine grained material suitable for water balance covers. Therefore only fine-grained soils will be used in this analysis with sandy materials that generally provide low storage being ignored.

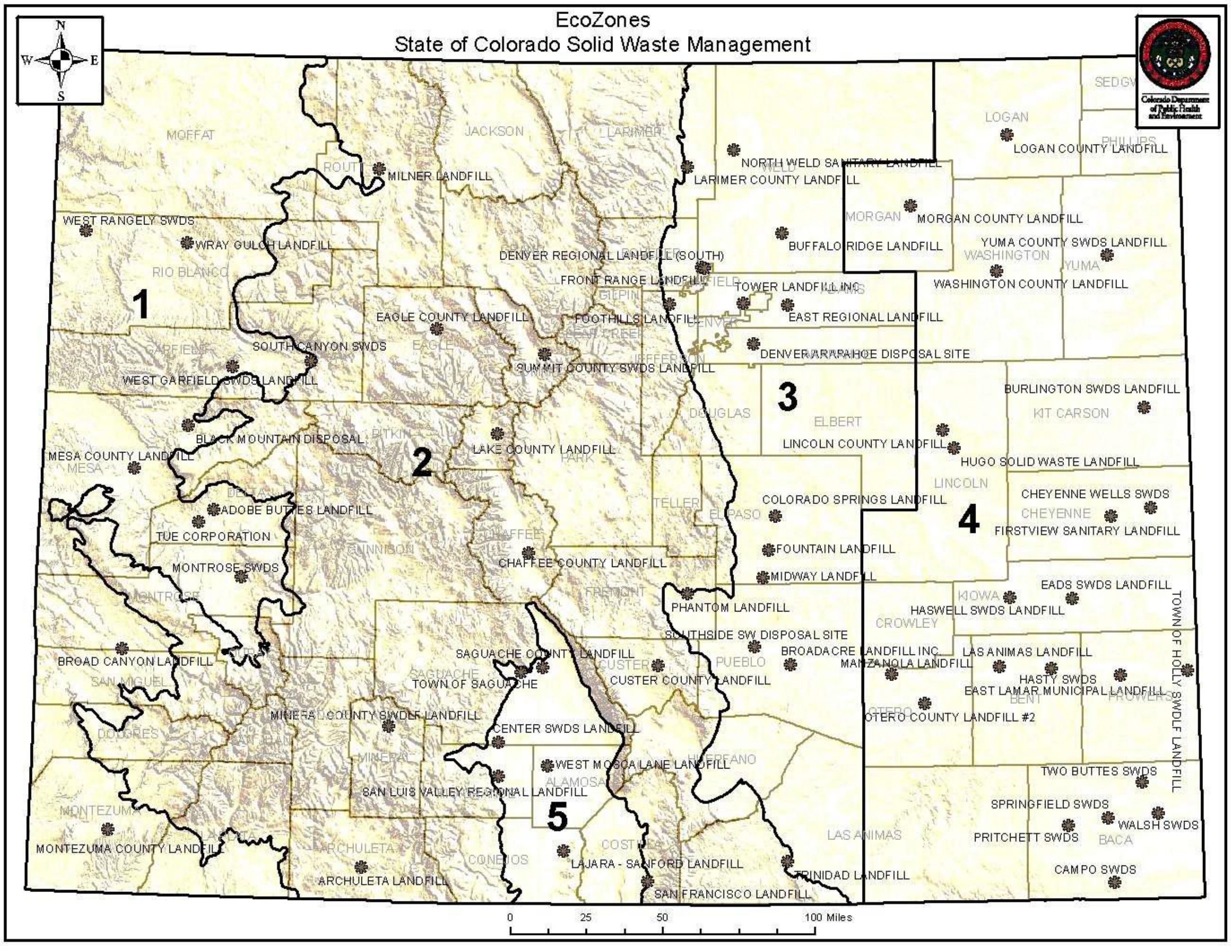

Figure 3-2: Ecozones of Colorado Outlined in the August 2005 draft report for the guidance of water balance covers in colorado (Colorado Department of Public Health and Environment).

3.4 Input Parameter Selection

HYDRUS 1-d requires numerous input parameters to define climate, vegetation and soil properties. It is important to limit the number of variables that will be used in the sensitivity analysis in order to limit the processing requirements and run times of the model. The following parameters will be included in the sensitivity analysis;

- Potential Evapo-Transpiration (PET)
- Leaf Area Index (LAI)
- Definition of growing season

- Precipitation
- Soil type
- Timing of precipitation events

As discussed earlier, defining PET is a major challenge in the design process of water balance landfill covers. This difficulty is primarily due to meteorological stations not providing solar radiation data along with precipitation, wind speed, temperature and humidity data. This radiation data is required in the calculation of PET using the penmen-monteith equation (eq. 3.8). Therefore, a method for estimating extraterrestrial solar radiation (R_a),using solar inclination (δ), latitude (φ), sunset hour angle (ω_s)(equation 3.2) and the Julian day of the year (J) (equation 3.1) will be used (Benson, 2011);

$$R_a = \frac{118}{\pi}\left(1 + 0.033\cos\left(\frac{2\pi}{365}J\right)\right)[\omega_s sin\varphi sin\delta + cos\varphi cos\delta sin\omega_s] \tag{3.1}$$

$$\omega_s = cos^{-1}[-(tan\varphi)(tan\delta)] \tag{3.2}$$

$$\delta = 0.409\sin(J\frac{2\pi}{365} - 1.39) \tag{3.3}$$

To determine the net solar radiation R_{ns} that will reach the surface elevation must be taken into account (equation 3.4) and so must albedo, α (equation 3.5);

$$R_s = (0.75 + 2 * 10^{-5}z)R_a \tag{3.4}$$

$$R_{ns} = R_s(1 - \alpha) \tag{3.5}$$

The net long wave radiation can be estimated using equation 3.6

$$R_{nl} = n\left[\frac{T_{max}^4 + T_{min}^4}{2}\right]\left(0.34 - 0.14\sqrt{e}\right)[1.35\frac{R_{ns}}{R_s} - 0.35) \tag{3.6}$$

Where n is the Stefan-Boltzman constant and e is calculated using equation 3.7 where RH is the relative humidity;

$$e = 0.6108 \exp\left[\frac{17.27T}{T+237.3}\right]\left(\frac{RH}{100}\right) \tag{3.7}$$

Once the net radiation and net long wave radiation have been estimated the PET can be calculated using the penmen-monteith equation (equation 3.8)

$$PET = \frac{0.408\Delta(R_n - G) + \varepsilon\left(\frac{900}{T+273}\right)U(e_s - e)}{\Delta + \varepsilon(1 + 0.34U)} \tag{3.8}$$

Where U is the wind velocity, Δ is the slope of the curve relating to e_s and T is mean temperature for the time step.

There are some inherent uncertainties associated with this method because estimations of PET are based on the day of the year instead of actual site specific data. This method does not take into account variations in cloud cover. This may result in an over-estimation of PET particularly during precipitation events when cloud cover is high. Despite these errors, it is believed this method will be sufficient in evaluating the relative sensitivity of cover effectiveness.

Correctly identifying the leaf area index (LAI) for the vegetation cover can significantly affect the model results. LAI is input into HYDRUS as an array, with each data point corresponding with the LAI for that time step. For example, if the model is run for 1 year with a 1 day time step, LAI would be defined for 365 points, one for each Julian day in the year. Again, UCODE needs to vary individual parameters and therefore a function needs to be written that describes LAI as an array based on a few individual parameters.

In the Parameter File python code, four parameters were developed to define LAI over an individual year (365 days). In this code the LAI index is defined as recommended in Cadmus 2011 (figure 3-3) with a linear increase in LAI from the beginning of the growing season until it reaches a maximum. In the fall when plant life begins to go dormant, LAI begins to decrease linearly until it reaches 0, defined as the end of the growing season. The Parameter File code requires four inputs to define the LAI as a function of time; start of the growing season, end of the growing season, maximum LAI, and a LAI slope factor. The start of the growing seasons is defined as the Julian day when plants begin to transpire, generally the last frost date, and end of the growing season is the day of the first frost. The maximum LAI is the highest value of LAI the vegetation will reach over the course of the year. And finally the slope describes the rate of increase/decline in LAI at the beginning and ends of the growing season.

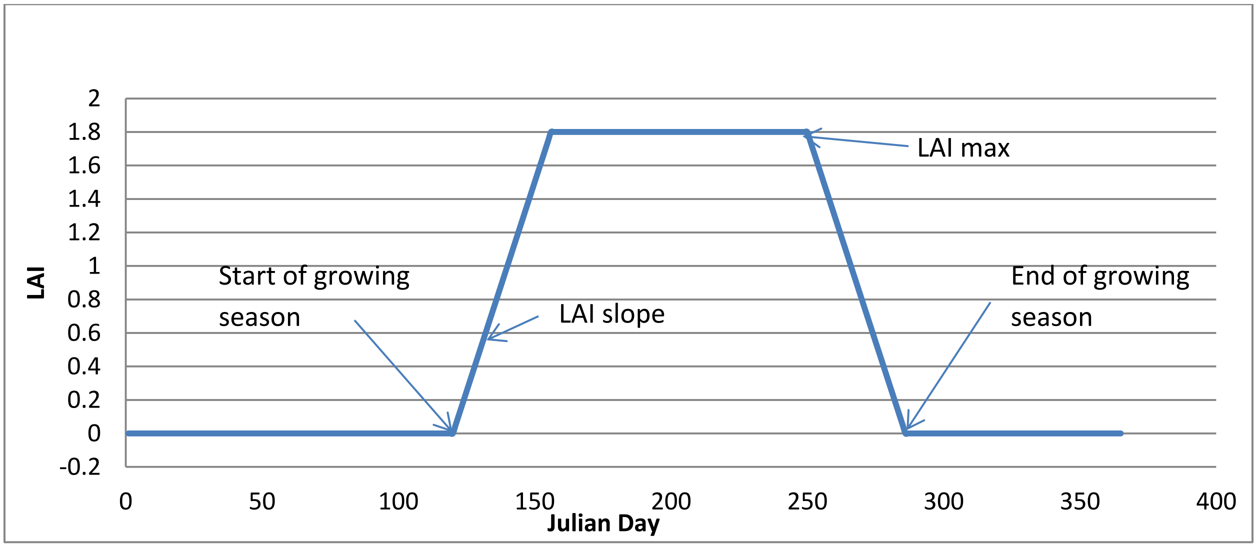

Figure 3-3: LAI as defined by the growing season (Cadmus, 2011)

There are multiple possible approaches to testing the sensitivity of cover performance to precipitation. First is the sensitivity of the cover to total yearly precipitation. In the most basic design process, as outlined in section 1.2, the cover needs to have a storage capacity equal to the total yearly precipitation for the site. That means the cover must be able to hold all of the yearly precipitation, which in an ideal situation is completely emptied by ET. In a real world scenario ET and precipitation are both temporally variable and therefore ET covers do not perform in this conceptual ideal. This approach assumes the cause of cover failure is the relative inability of ET to effectively remove the stored water, and that over time this accumulation of water in the cover will lead to percolation. This approach has been observed in the reports from the Alternative Cover Assessment Program, ACAP (Roesler et al 2002, Abichou et al 2005, Ogorzalek et al 2008). The challenge associated with testing the covers sensitivity to total yearly precipitation is that UCODE, again, needs to vary only one number between set ranges. In order to solve this problem a precipitation factor will be used. For each model run, a factor will be varied that is multiplied by each of the precipitation data points for a selected modeling year. This precipitation factor is written into the Parameter File python code and can be included in the Ucode sensitivity runs. In this manner it is possible to simulate variations in total yearly precipitation by adjusting each days' precipitation by a factor, with a factor of less than 1 representing a relatively dry year compared to the average for the ecozone and a factor greater than 1 for wet years. The models sensitivity to the precipitation factor can be interpreted as the covers sensitivity to total yearly precipitation.

A second approach is to assume that the cover is relatively more sensitive to individual large precipitation events. This means that there will be spikes in percolation through the bottom of the cover that correlate with large rain events. This pattern has also been seen in monitored water balance covers in the Water balance cover Assessment Program (Roesler 2002). To test the sensitivity of the cover to individual large precipitation events, various rain events throughout the year will be changed to a specific storm event between a 2-year event and a 25-year event. It is expected that the timing of this event may effect the simulation results. These large events will be added to the simulation at various points in the year to address the impact of both the magnitude of the events as well as their timing. These additions in storm events will not be included directly in the sensitivity analysis, instead the sensitivity analysis will be conducted an additional time with the inclusion of the large storm events. Changes in the models sensitivities from the simulation without large storm events as well as variation in total yearly percolations will then be analyzed to make conclusions on the sensitivity of water balance covers to large storm events.

Finally, the covers sensitivity to soil parameters will be tested. As discussed in section 1.2 and 1.3.4 the total available storage in the cover and the unsaturated fluid flow phenomena within the profile is defined by soil properties. Three soil parameters will be included in the sensitivity analysis. Fitting parameters α and n in the van Genuchten equation (equation 1-10) are used to define the soil water characteristic curve and define the storage capabilities of the soil profile. The third parameter is the saturated hydraulic conductivity, k_s. All three of these parameters are dependent on the soil type, particularly the grain size and pore size distributions of the soil (Lu, 2004). The USDA soil classification system will be used to define soil types. In this system soils are classified based on their model abundance of clay, silt and sand. A free government program called Rosetta, as well as a variety of other published works, estimate the van Genuchten parameters based on the soils classification in the USDA soil classification system (Schaap, 1999). The database built into HYDRUS 1D uses the Carsel and Parish [1988] estimates of van Genuchten parameters based on the soil's USDA classification.

3.5 Forward Model Runs

Forward model runs are used to estimate the range of possible percolation rates for the front range and the western slope. Generally covers that allow high percolation rates are considered failing with regulations generally requiring between 0 mm/year and 5 mm/year of percolation for the cover to be considered effective. A 100 simulation Monte Carlo analysis will be conducted to estimate a range of percolation rates for both ecozones. Soil parameters are set set as a point estimate, with the K_s, α, and n of the profile remaining constant for a silty loam material. The start of the growing season, end of the growing season, LAI, precipitation factor and PET factor are randomized for each simulation. The start of the growing season varies between the earliest lat frost date for the region and latest last frost, see appendix A, and the end of the growing season varying between the earliest first frost and latest first frost. LAI is set to vary between 1.0 and 2.6. The precipitation factor varied between the average low end precipitation factor and average high end factor, see appendix A. The PET factor varied between the average low end PET factor and average high end factor, see appendix A. The model was run for the model year at each site to take into account variations in precipitation and PET patterns.

The results of these analyses will test the feasibility of implementing generic cover designs at the scale of the front range and western slope. If the 90th percentile percolation rates demonstrate high percolation rates than it can be assumed that generic cover methodologies are infeasible at this scale. If the 90th percentile percolation rates tend to be low, generic design methodologies may be feasible.

4.0 RESULTS AND DISCUSSION

In this section, the results of the sensitivity analysis is presented. The importance of these findings and the implications they have on the feasibility of generic water balance cover designs is discussed. All input data for the simulations including precipitation, PET, P/PET ratios, soil parameters and root density can be found in the Appendix.

4.1 Sensitivity Analysis Results

FRONT RANGE

A sensitivity analysis is conducted in two ecozones; the Front Range of Colorado and the Western Slope. From 2006 to 2011, the average precipitation rate for the Front Range among the five sites is 34.69 cm/year. The average PET rate is 114.6 cm/year. Soil types within the ecozone are highly variable, ranging from clays to silts to sands. The mean last frost date is on Julian day 124 (May 4th) and the average first frost is on Julian day 275 (October 2nd) for an average growing season of 151 days. Rooting depth was set to 1 m with an exponentially decreasing root density with depth (Albright [2010], Pellant [1996]). The model is run 5 times, once for each of the five sites. The design year for the site should be representative of an average year at that location. A year is determined to be representative based on the P/PET ratio. The year with a P/PET ratio that is most similar to the average from 2006 to 2011 for that particular site is selected for the design year. The following design years are used in this analysis;

- Colorado Springs (2007). A P/PET of 0.318, representative of the site average from 2006-2011 of 0.331.

- Broomfield (2010). A P/PET of 0.246, representative of the site average from 2006-2011 of 0.252.
- DIA (2010). A P/PET of 0.309, representative of the site average from 2006-2011 of 0.332.
- Longmont (2006). A P/PET of 0.350, representative of the site average from 2006-2011 of 0.353.
- Trinidad (2007). A P/PET of 0.289, representative of the site average from 2006-2011 of 0.312.

A spin-up was conducted by running the Colorado Springs (2007) data set for 5 consecutive years with identical P, PET, LAI and growing season for each year. The Colorado Springs data is used for the spin up based on that the P/PET ratio for the site in 2007, 0.318, is the most similar to that of the average for the region, all 5 sites, from 2006-2011, 0.316. The hydraulic conductivity was set at 16 cm/d, an α of 0.032 and an n of 1.325. This material is representative of a soil that is classified between a silt loam and a loam. The spin-up is conducted with initially dry soils, a matric suction of 10000 cm. After a five year simulation the soil suction as a function of depth can be seen in figure 4-1. This soil profile is used for the initial conditions in the sensitivity analysis. The perturbation amount for each variable had to be adjusted to ensure model convergence and that sensitivities are greater than 0. K_s, α, n, precipitation factor (PF) and PET factor (PETF) is set to perturb by 10% each iteration. The start of the growing season (SG), end of the growing season (EG), LAI slope (LS) and LAI are set to perturb by 20% each iteration. The simulation takes less than 1 minute to complete.

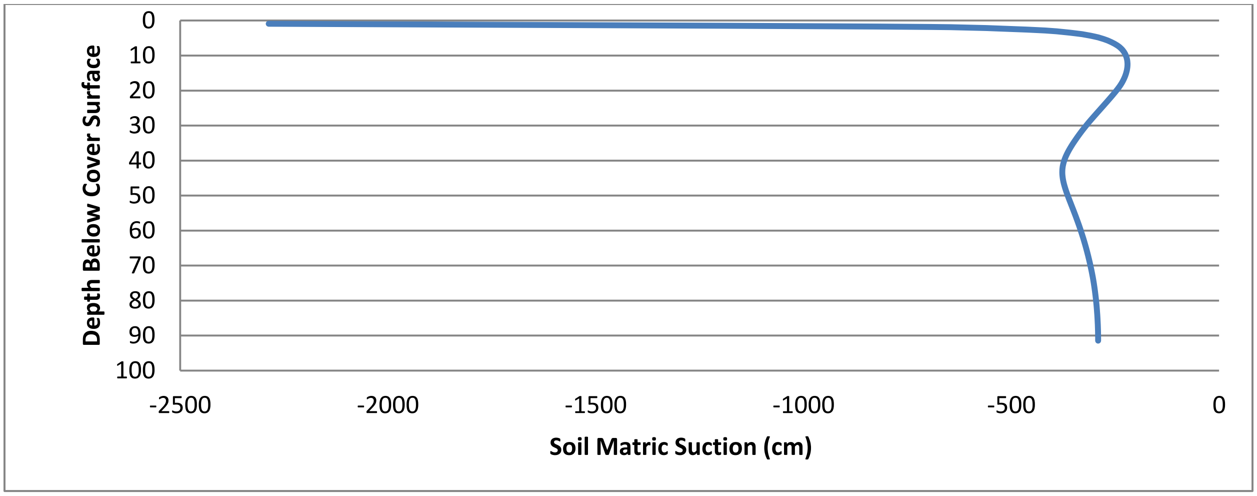

Figure 4-1: Results of the model spin-up displaying the soil matric suction with depth. This profile information is used as the initial conditions in the sensitivity analysis.

The cover at Colorado Springs is highly sensitive to the soil parameters α, n, and K_s and relatively insensitive to the LAI, the slope of the increase in LAI (LS) and total yearly precipitation. The cover is only moderately sensitive to the definition of the growing season and the total yearly PET as represented by the moderate sensitivity to the PET factor, start of the growing season and end of the growing season. Table 4-1 displays the sensitivities in order of the parameter that has the greatest impact on cover performance to least.

Table 4-1: Colorado Springs (2007) sensitivity analysis model results.

Parameter	Composite Scaled Sensitivities	Ratio to Maximum
α	0.402795	1
n	0.375979	0.933425191
Ks	0.134286	0.333385469
Start of growing season	0.065918	0.16365074
End of growing season	0.054079	0.134259114
PET factor	0.043434	0.107831279
LAI	0.028872	0.071678149
LAI slope	0.009242	0.022944078
Precipitation factor	0.00147	0.003650641

Additional sensitivity analyses are conducted on the 4 remaining sites in the Front Range. The results of this sensitivity analysis can be seen in table 4-2 and figure 4-2. Covers in Broomfield and Trinidad demonstrated similar sensitivities as the cover in Colorado Springs, but at Longmont and DIA the covers have noted increased sensitivities to total yearly precipitation, PET, the growing season and LAI. The modeled cover in Longmont shows particularly high sensitivities to the precipitation and PET factors with composite scaled sensitivities of 30.677 and 41.513, an increase of multiple magnitudes compared to the Colorado Springs, Broomfield and Trinidad sites. It is also noted that the sensitivity to the precipitation factor is highly variable from site to site with little to no consistency in the sensitivities. The causes for these discrepancies in sensitivities from one site to the next within an ecozone can be seen in the distribution of precipitation and PET at each site.

Table 4-2: The relative sensitivities of cover effectiveness to a variety of parameters at 5 sites located in the Front Range of Colorado.

Parameter	Colorado Springs (2007)	Broomfield (2010)	DIA (2010)	Longmont (2006)	Trinidad (2007)
Start of growing season	0.06592	0.05390	1.08370	3.40814	0.06480
End of growing season	0.05408	0.05027	1.62265	1.86021	0.05522
LAI slope	0.00924	0.00405	0.02965	0.56051	0.00667
LAI	0.02887	0.03676	0.72558	1.91239	0.03861
α	0.40280	0.40898	1.10210	5.66048	0.43622
N	0.37598	0.37754	27.4609	16.72370	0.40958
K	0.13429	0.13653	0.39687	41.35310	0.14577
Precipitation factor	0.00147	0.00016	6.53742	30.67730	0.00231
PET factor	0.04343	0.04155	1.40343	41.51280	0.04800

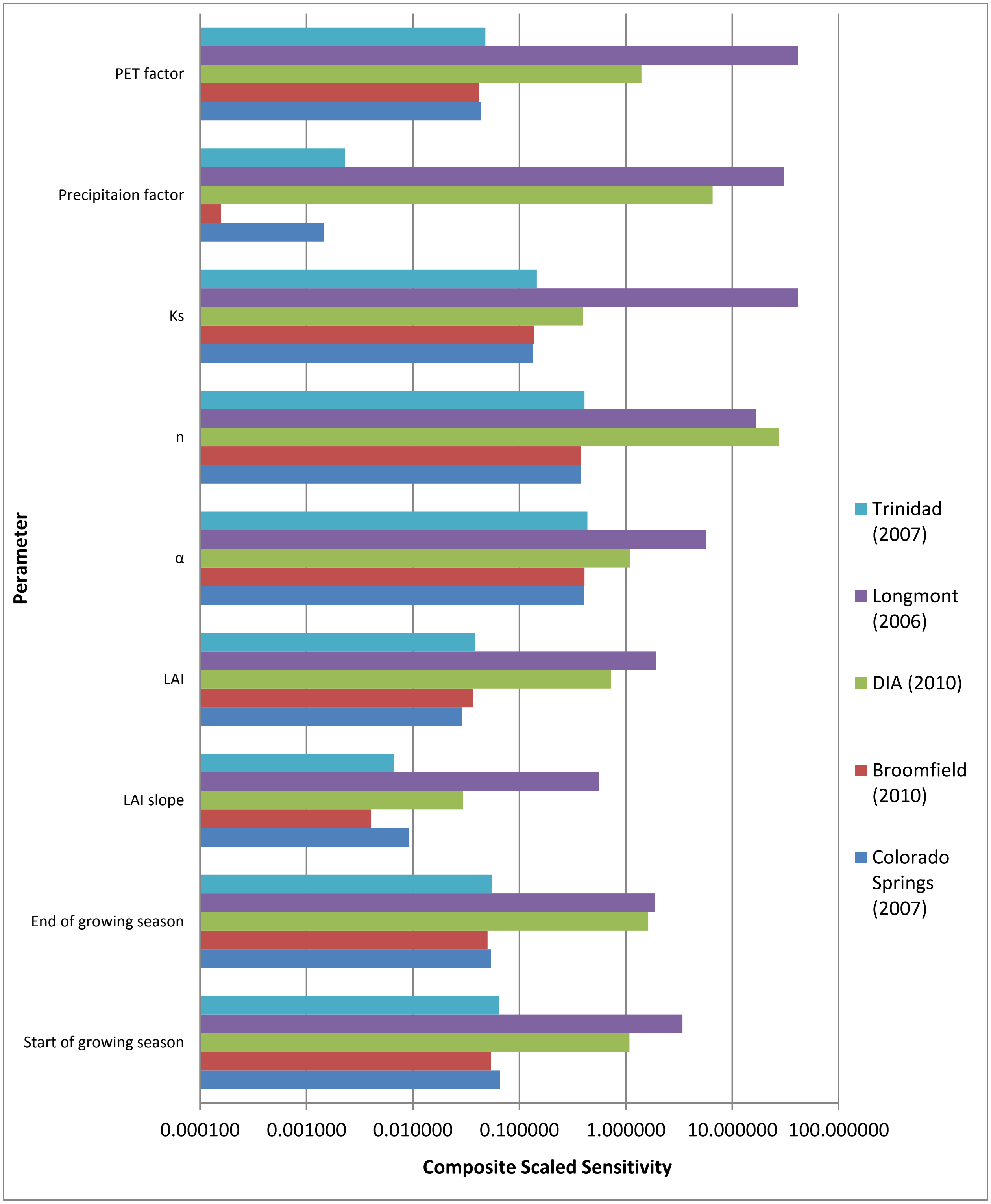

Figure 4-2: The relative sensitivity of cover effectiveness to select parameters at 5 sites located in the Front Range of Colorado. Colorado Springs, Broomfield and Trinidad displayed similar results, but DIA and Longmont showed increased sensitivities to multiple parameters.

Variations in the sensitivities at the five sites modeled in the Front Range bring up questions about the sensitivities of cover performance to the relative timing of precipitation events, PET and the growing season. This impact can be seen by looking at the distribution of precipitation and PET over the year at Colorado Springs (2007), DIA (2010), and Longmont (2006). The P\PET ratio at the three sites during their modeled year is similar, ranging from 0.309 at DIA to 0.350 in Longmont. All three of the ratios are within 11% of the ecozone mean of 0.316. Although these sites are hydrologically similar according to the P/PET ratio, they exhibit significantly different sensitivities due to the timing of precipitation events as well as the magnitude of individual storm events.

Colorado Springs, Longmont and DIA all experienced significantly varying precipitation patterns during the modeled years. In Colorado Springs (2007), precipitation events are all below 2.5 cm/day and take place generally between March and August as seen in figure 4-3. These are all small magnitude events without a single one breaching the 5.3 cm magnitude of a 2-year return interval event (Miller et al. [1973]). These small magnitude events tend to occur during the late spring and summer months which correspond to the period in which PET and LAI is at a maximum between May and August (figure 4-3). The precipitation patterns at Broomfield (2010), figure 4-4 and Trinidad (2007), figure 4-5, show the same patterns as the Colorado Springs site. These sites also showed lower sensitivities.

Longmont, on other hand, displays a pattern of precipitation events that differs from the Colorado Springs site. Precipitation events tend to be of a larger magnitude with five events exceeding 2.5 cm/day, as well as a single large event dropping over 15 cm of precipitation in a 24 hour period, shown in figure 4-6. This event exceeds the benchmark set for a 100-year return period storm (Miller, 1973). This event takes place in February, outside of the period of maximum PET between June and August. The other events of around 3 cm/day take place in March, September, October, November and December, before and after the period of peak PET and LAI. The patterns of precipitation and PET at DIA vary from the previous two sites, figure 4-7. PET peaks later, between July and September while only gradually increasing in the earlier months. Before this period of high PET, there are 4 storms that exceed 1 cm in magnitude. There is also a single large storm event of nearly 5 cm, which is nearing a 2-year return rate storm and takes place in the middle of July, when PET is peaking. The decrease in sensitivities compared to the cover at Longmont may be due to a combination of a lower magnitude large storm as well as the timing of the storm taking place in the middle of the summer months. The timing of the early storms as well as the individual large magnitude storm may be influencing the observed increases in sensitivities compared to the Colorado Springs, Broomfield and Trinidad covers.

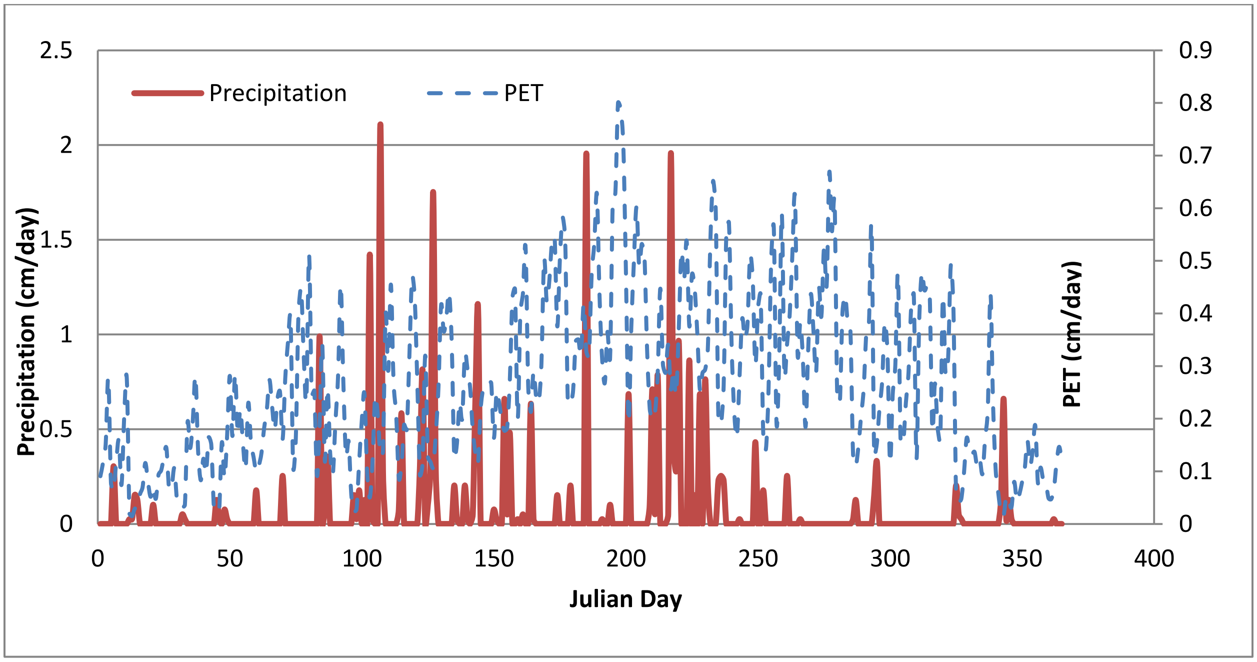

Figure 4-3: Distribution of precipitation and PET at Colorado Springs (2007). Precipiation events tend to be of a low magnitude and take place during the summer months when PET is high. This is a likely explanation for the low senstivities calculated for this sitee.

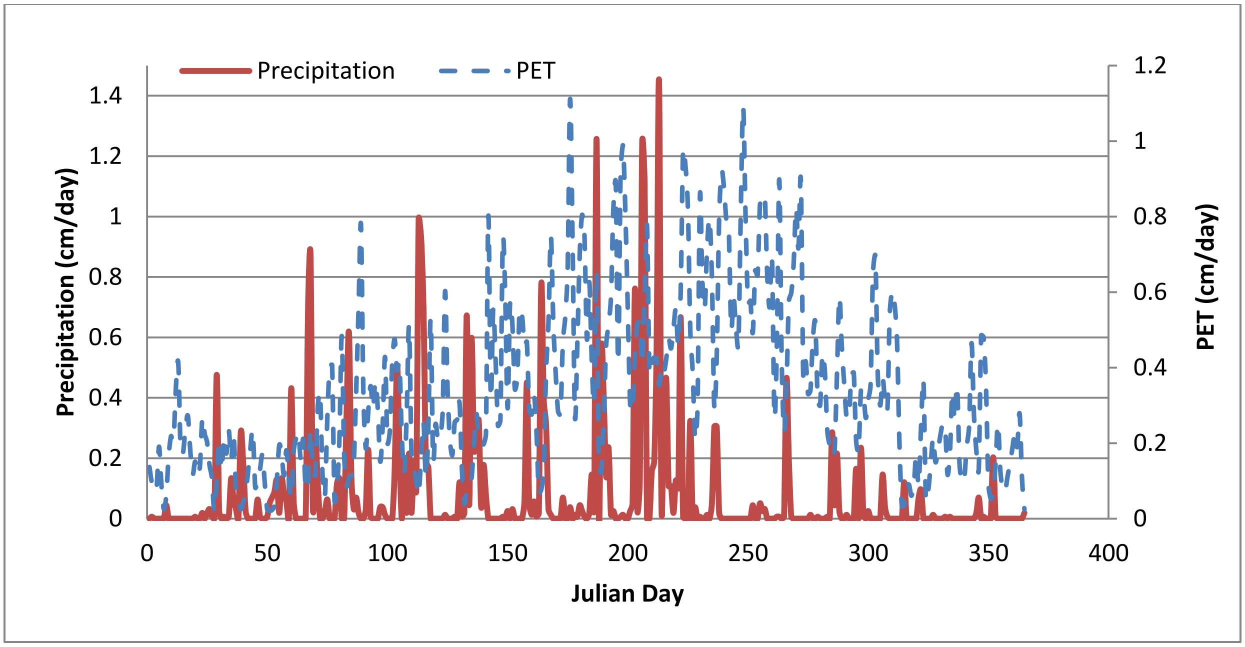

Figure 4-4: Distribution of precipitation and PET at Broomfield (2010). Precipiation events tend to be of a low magnitude and take place during the summer months when PET is high. This is a likely explanation for the low senstivities calculated for this site.

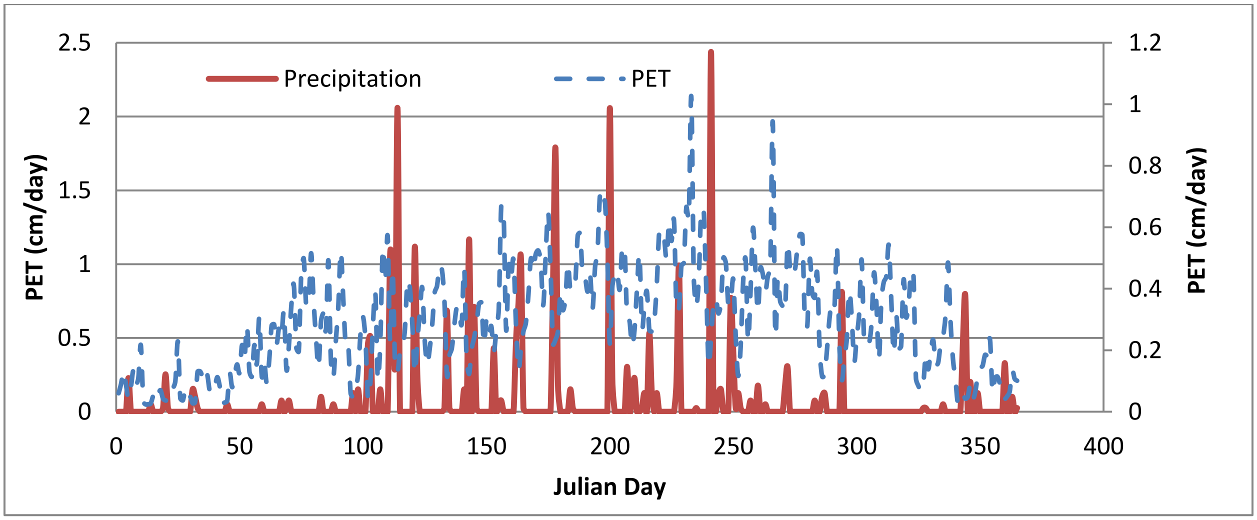

Figure 4-5: Distribution of precipitation and PET at Trinidad (2007). Precipiation events tend to be of a low magnitude and take place during the summer months when PET is high. This is a likely explanation for the low senstivities calculated for this site.

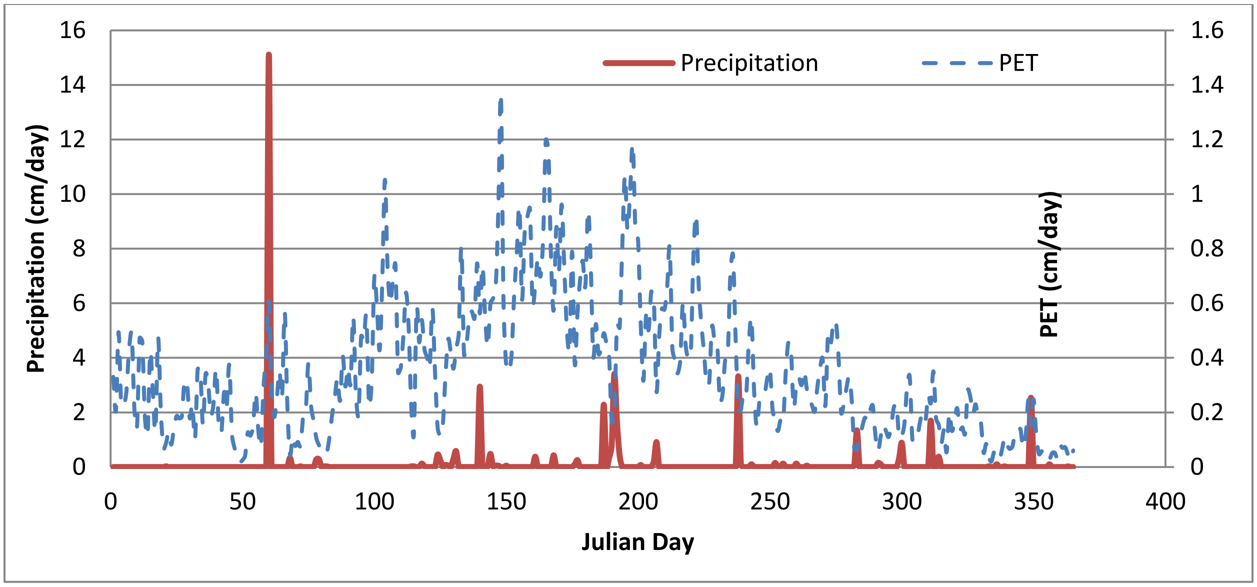

Figure 4-6: Distribution of precipitation and PET at Longmont(2006). A major percipiation event (100-yr return period) takes place before PET peaks. This is a likely cause of the calculated increased sensitivities at this site.

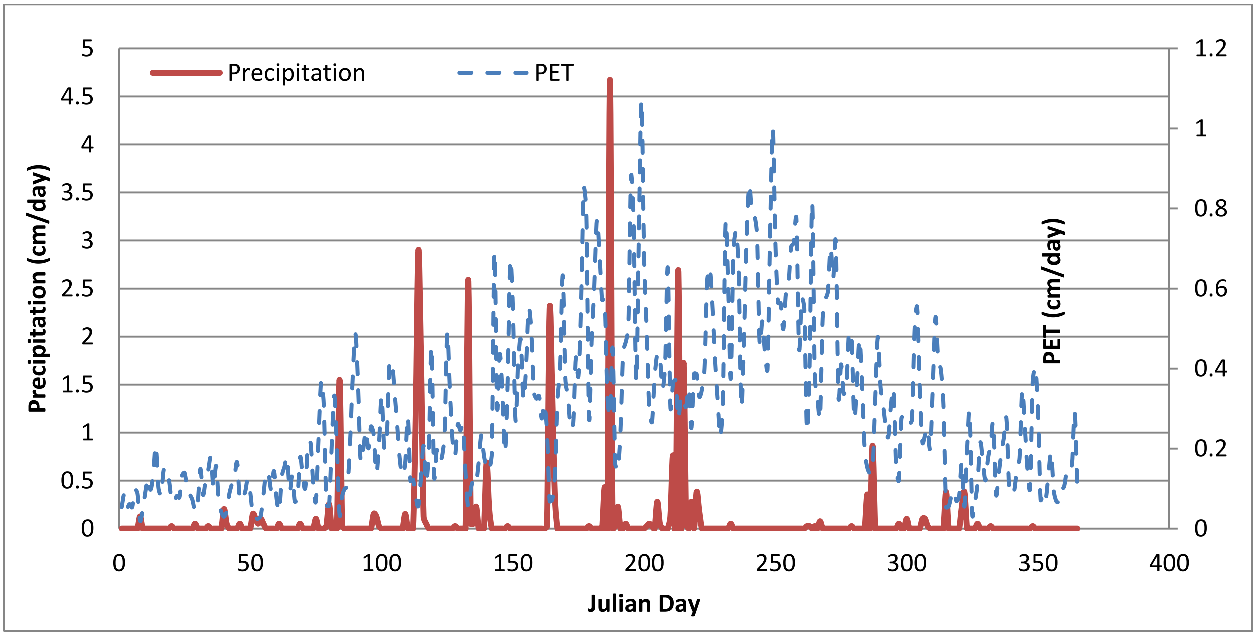

Figure 4-7: Distribution of precipitation and PET at DIA (2006). Precipitation events of significant magnitude take place before and after the summer months when PET is high. This is a possible explanation for the relatively high sensitivities modeled for this site.

These precipitation and PET patterns can explain the variations in sensitivities seen in the simulations. Increased sensitivity to soil parameters can be explained by the need for increased storage during the winter seasons when PET and LAI are low. Soil with greater storage capabilities can hold more of the water from these early events until PET and LAI pick up and in turn empty stored water from the cover profile. Variations in n and α affect the available storage in the cover and as they increase and decrease so does the storage capabilities of the soil. With less available storage for these early storms there will be noticeably more or less percolation as there parameters change.

The increased sensitivity to the precipitation factor and PET factor are also explained by these patterns for the similar reasons, that by increasing the magnitude of the precipitation events during the winter months the storage capabilities of the cover profile are exceeded and percolation occurs. It is expected that the sensitivity to precipitation factors increases for the Longmont and DIA sites. The same factor applied to small storms at the Colorado Springs site is a physically smaller increase in magnitude over a 24 hour period than the same factor applied to the large storms at the other sites, such that the observed increases in sensitivities may be partially artificial and may be correlated to the presence of a large magnitude storm event. Increases in sensitivity to the PET factor are also expected. The increased PET is more capable of removing the precipitation from the cover profile earlier and as a result less percolation can be expected. Again this may be indicative of the PET factor being correlated to precipitation patterns.

Finally, the increased sensitivities by multiple magnitudes to the definition of the growing season (start of the growing season and end of the growing season) from the Colorado Springs (2007) site to Longmont (2006) and DIA (2010) display the importance of precipitation timing. A longer growing season will encompass more precipitation events, during which periods the cover is more capable of handling the stress of storm events. Shorter growing seasons will result in more storms taking place before or after plant life is active. And as such more percolation is expected. The increased sensitivity to the start and end of the growing season again demonstrates the effect of precipitation timing, magnitude and storm events have on cover performance.

In UCODE the model is run once before parameters are perturbed to get initial model outputs. Figure 4-8 shows the total percolation through the cover as a function of time that is estimated during this initial runs for all five sites in the Front Range. The sites where sensitivities are generally low show small percolation rates. While at Longmont and DIA, which demonstrated higher sensitivities, percolation rates were also high. These results also hint at the importance of storm magnitude on cover performance as there are significant jumps in percolation that appears to respond to the major storm events at both Longmont and DIA, figure 4-6 and 4-7. There is more percolation in Longmont because of the greater magnitude of the early storm that takes place before PET peaks. The relatively lower percolation rates at DIA are likely due to the fact that there are more storms of a lower magnitude at DIA, compared to Longmont, which tend to occur during max PET. The importance of storm magnitude and timing will be explored further in section 5.

Although the effect of precipitation magnitude and timing relative to the growing season and periods of maximum PET are visually evident, these methods did not allow for a numerical characterization of the sensitivity of cover effectiveness to this observed pattern. Methods and results to a sensitivity run which incorporates precipitation timing and magnitude is outlined in section 6.

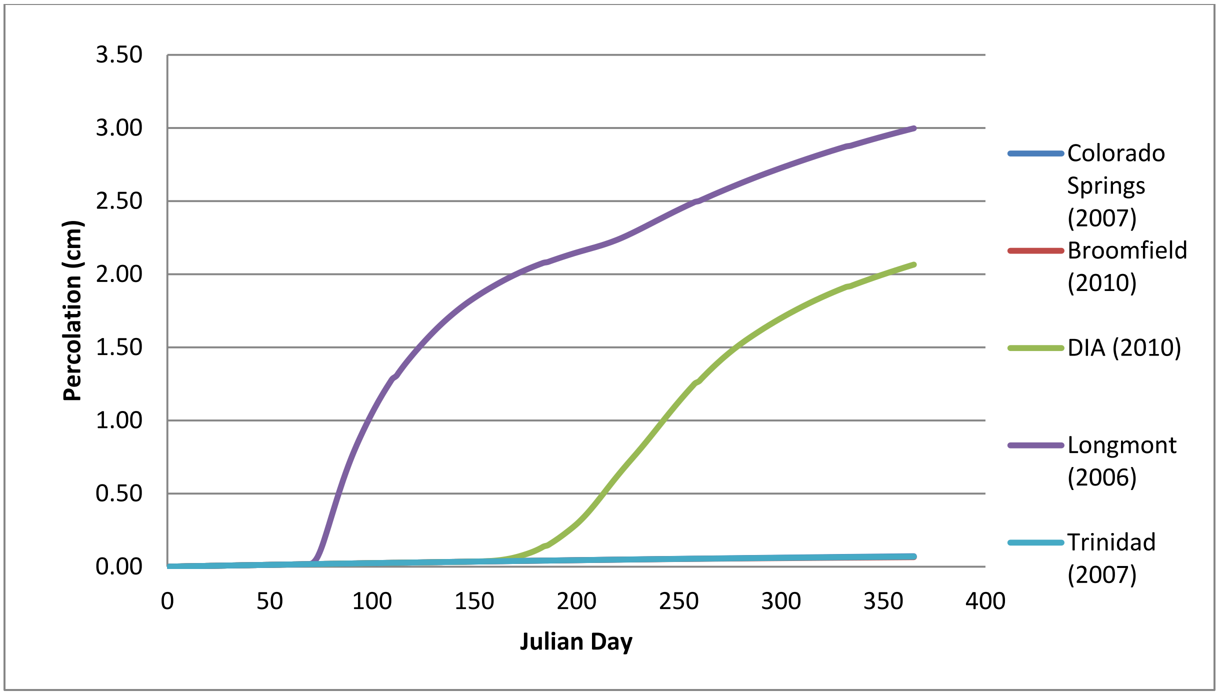

Figure 4-8: Percolation (cm) as a function of time, before perturbations, for the 5 sites in the Front Range.

WESTERN SLOPE

The sensitivity analysis conducted for the 5 sites in the Front Range where conducted again for five new sites located on the Western Slope. For each site the model is set up in the same manner as the model in the Front Range, with the same parameters being adjusted in UCODE and with identical perturbation amounts. Initial conditions were changed for these sites, using the location with an average P/PET ratio that most closely matched the average for each site between 2006 and 2011;

- Dinosaur National Monument (2008). A P/PET of 0.233, representative of the site average from 2006-2011 of 0.245.
- Cortez (2007). A P/PET of 0.279, representative of the site average from 2006-2011 of 0.278.

- Montrose (2007). A P/PET, of 0.314 representative of the site average from 2006-2011 of 0.307.
- Grand Junction (2006). A P/PET, of 0.350 representative of the site average from 2006-2011 of 0.353.
- Meeker (2007). A P/PET, of 0.287 representative of the site average from 2006-2011 of 0.312.

A spin-up is again run for 5 consecutive years conducted using the Meeker (2009) PET and precipitation data as it is most representative of the average year for the region based on the P/PET factor. The resulting soil profile, seen in figure 4-9, is used for the initial conditions in the sensitivity analysis. The years at each site used for modeling are selected in the same manner as the site for the Front Range. The average P/PET ratio for the region is 0.299.

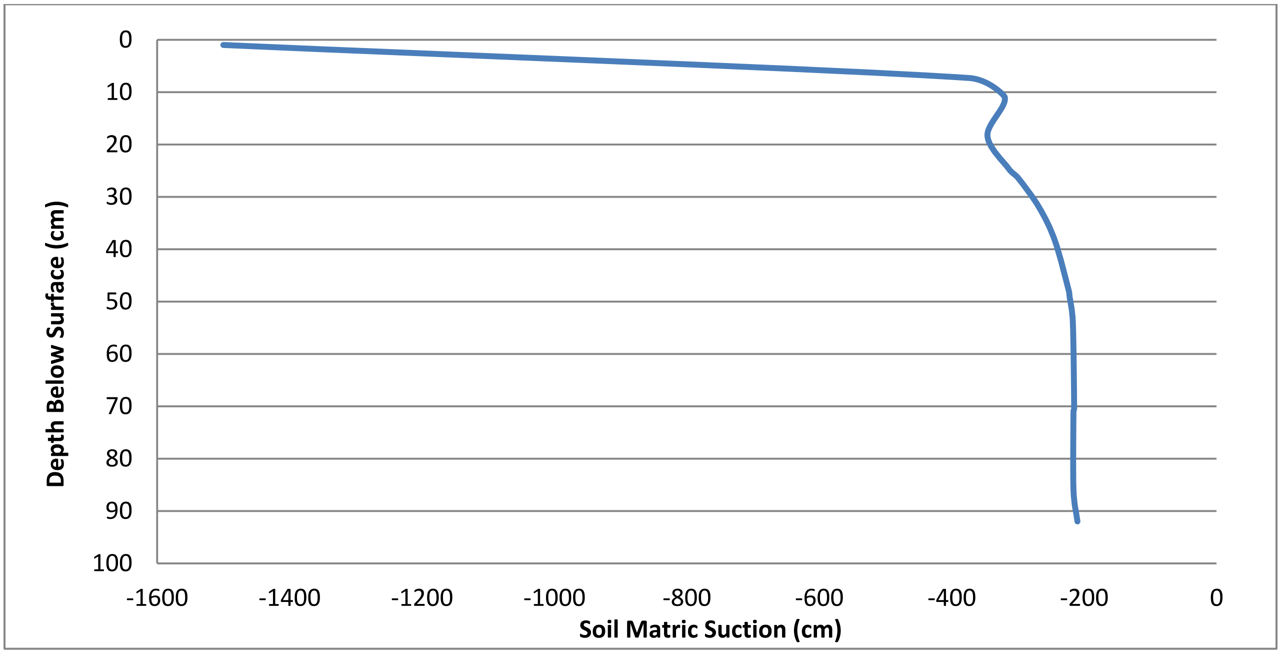

Figure 4-9: Result of the spin-up conducted for the Western Slope.

The results of these simulations demonstrate similar patterns in sensitivity to those conducted in the Front Range. Cover effectiveness generally demonstrates a high sensitivity to soil properties k_s, α and n. The precipitation and PET factors have a wide range of impact on cover effectiveness with sensitivities from low to moderate at Dinosaur Monument, Cortez and Montrose with higher sensitivities at Grand Junction and Meeker. LAI and LS display relatively low sensitivities at all sites. Sensitivity to the definition of the growing season tends to be low to moderate. Meeker looks to be an outlier in the data set with higher composite sensitivities to all parameters, while the other 4 sites tend to demonstrate similar sensitivities, except for precipitation factor which shows a large range of sensitivities within the five sites. All of these results follow the same patterns in sensitivities found in the Front Range sensitivity analysis and can be seen in table 4-3 and figure 4-10. These variations in calculated sensitivities can be explained by looking at the timing or precipitation and PET.

The patterns in precipitation for Meeker follow the same ones noted in the simulation for Colorado Springs (2007) which also demonstrated similar sensitivities. Precipitation for Meeker is dominated by storms of a low magnitude without single storm exceeding the 3.3 cm threshold that represents a 2-year return frequency (Miller, 1973). Second, the storms tend to take place during the growing season between April and September when PET also peaks. These patterns can be seen clearly in figure 4-11. The precipitation and PET patterns at Dinosaur National Monument (2008), figure 4-12, and Cortez (2007), figure 4-13, are similar to that of Meeker. All three of these sites demonstrate both similar precipitation patterns as well as similar calculated sensitivities.

Table 4-3: Results of the sensitivity analysis conducted at five hypothetical sites located on the Western Slope. All values are the composite scaled sensitivity.

Parameter	Dinosaur National Monument (2008)	Cortez (2007)	Montrose (2007)	Grand Junction (2006)	Meeker (2007)
Start of Growing Season	0.0554189	0.0663683	0.0831758	3.40814	0.064803
End of Growing Season	0.0462404	0.0421136	0.116894	1.86021	0.0552213
LAI slope	0.00484619	0.00586603	0.00691748	0.560514	0.0066645
LAI	0.0366192	0.0355835	0.0452206	1.90923	0.0386114
α	0.406384	0.398257	0.426955	5.66048	0.43622
n	0.376643	0.368374	12.1508	18.3064	0.409199
K_s	0.135788	0.133132	0.152612	41.3531	0.145765
Precipitation Factor	0.000252982	0.000743135	0.122254	30.6773	0.00230846
PET Factor	0.043592	0.0443035	0.0683843	41.5128	0.0480034

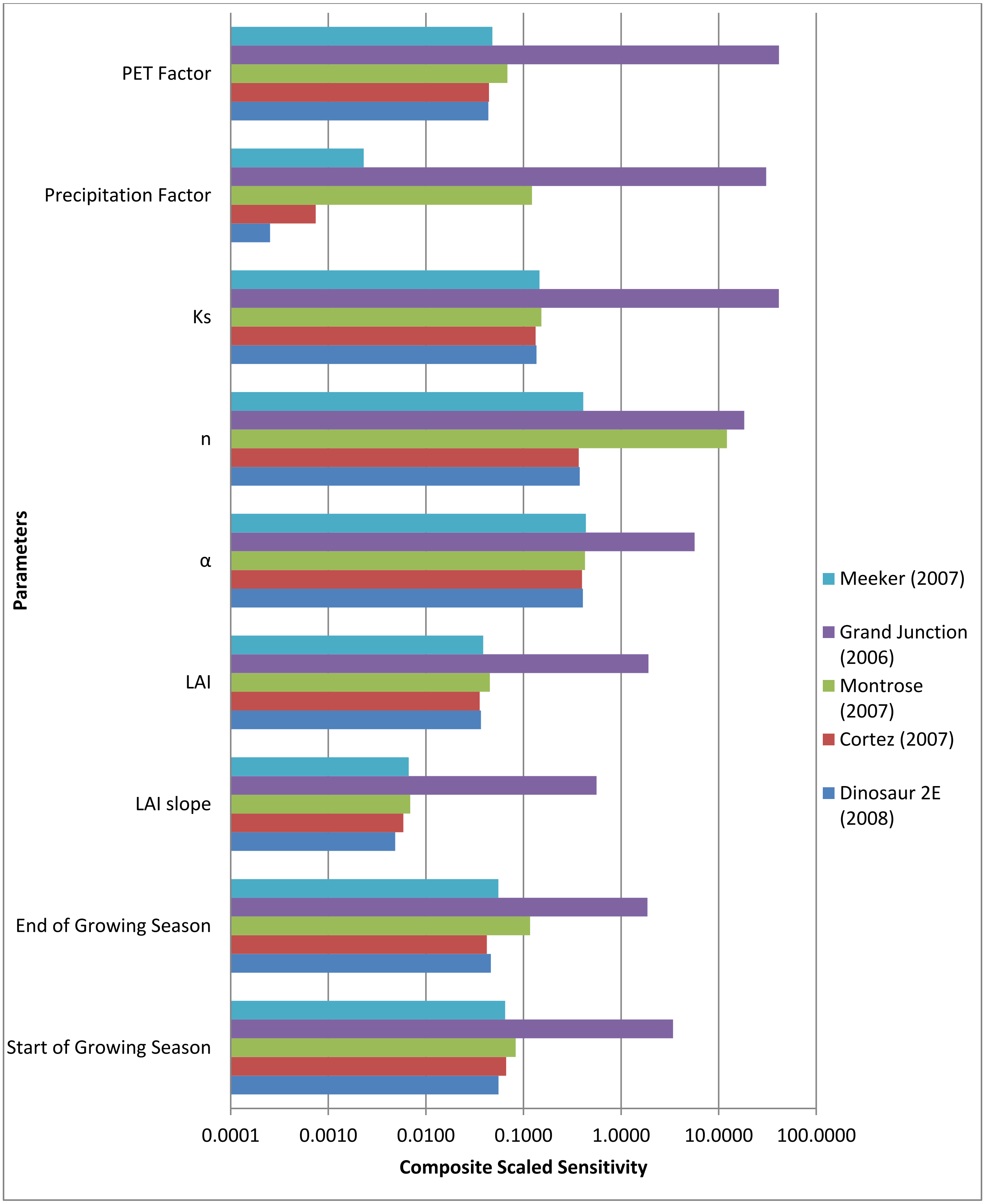

Figure 4-10: Chart showing the relative composite scaled sensitivities for five locations in the Western Slope. Sensitivities tend to be higher for the soil parameters at all sites. In general sensitivities at Grand Junction and Montrose tend to be higher than the other sites.

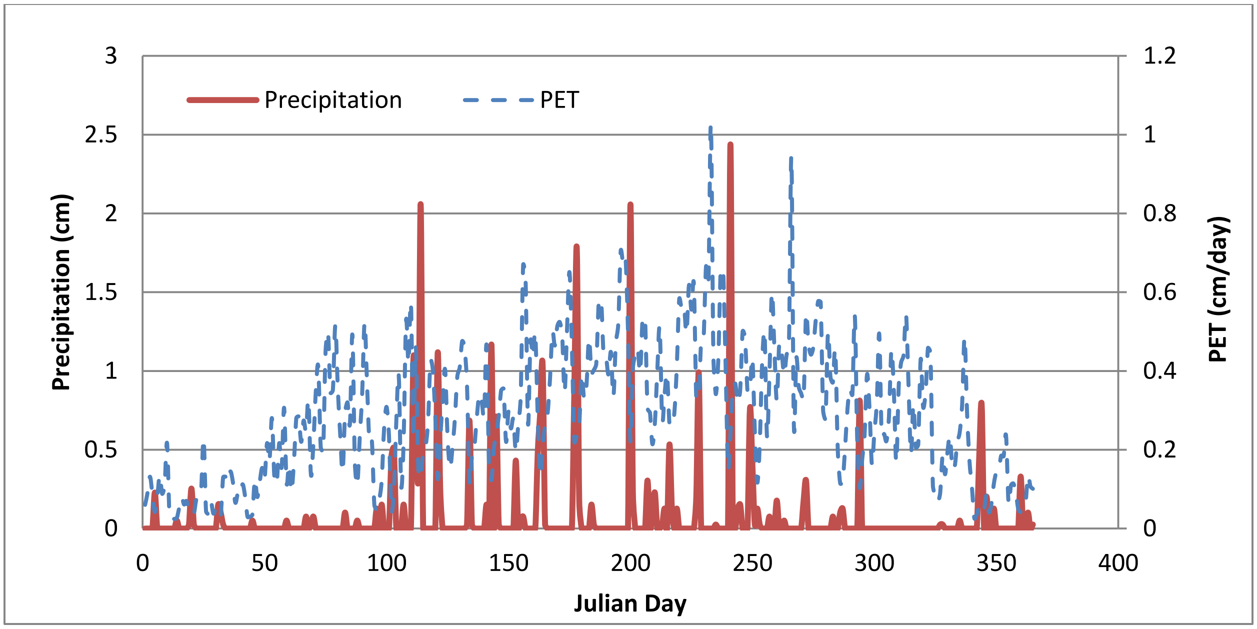

Figure 4-11: Distribution of precipitation and PET for Meeker (2007). Precipitation events tend to take place during the summer months when PET is high. This may explain the low sensitivities at this site.

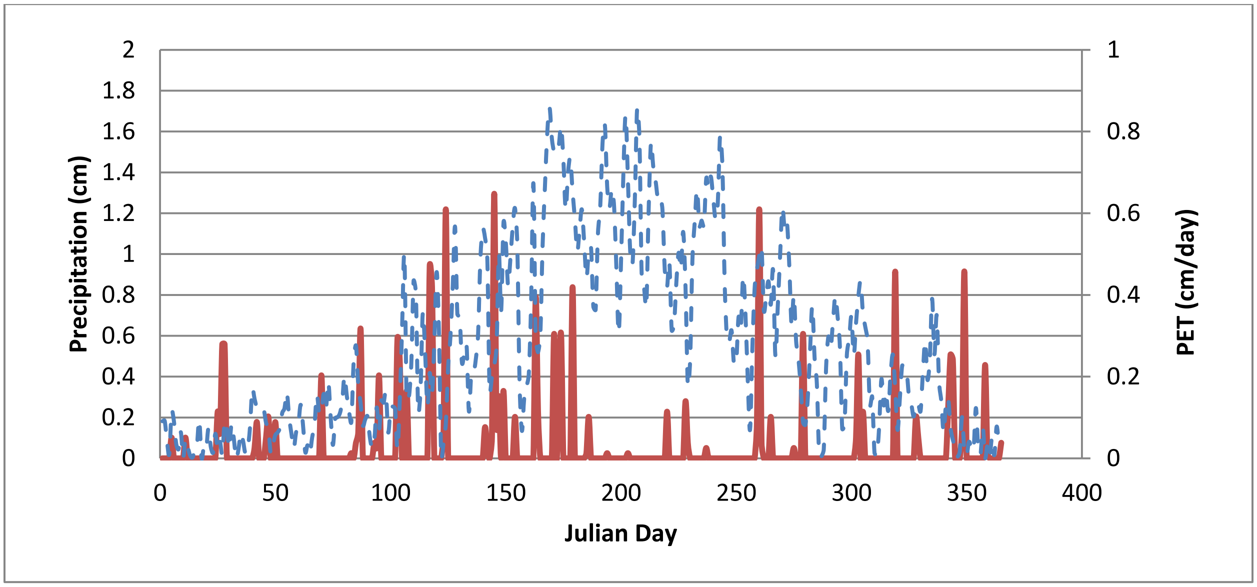

Figure 4-12: Distribution of precipitation and PET for Dinosaur National Monument (2008). Precipitation events tend to take place during the summer months when PET is high. This may

explain the low sensitivities at this site.

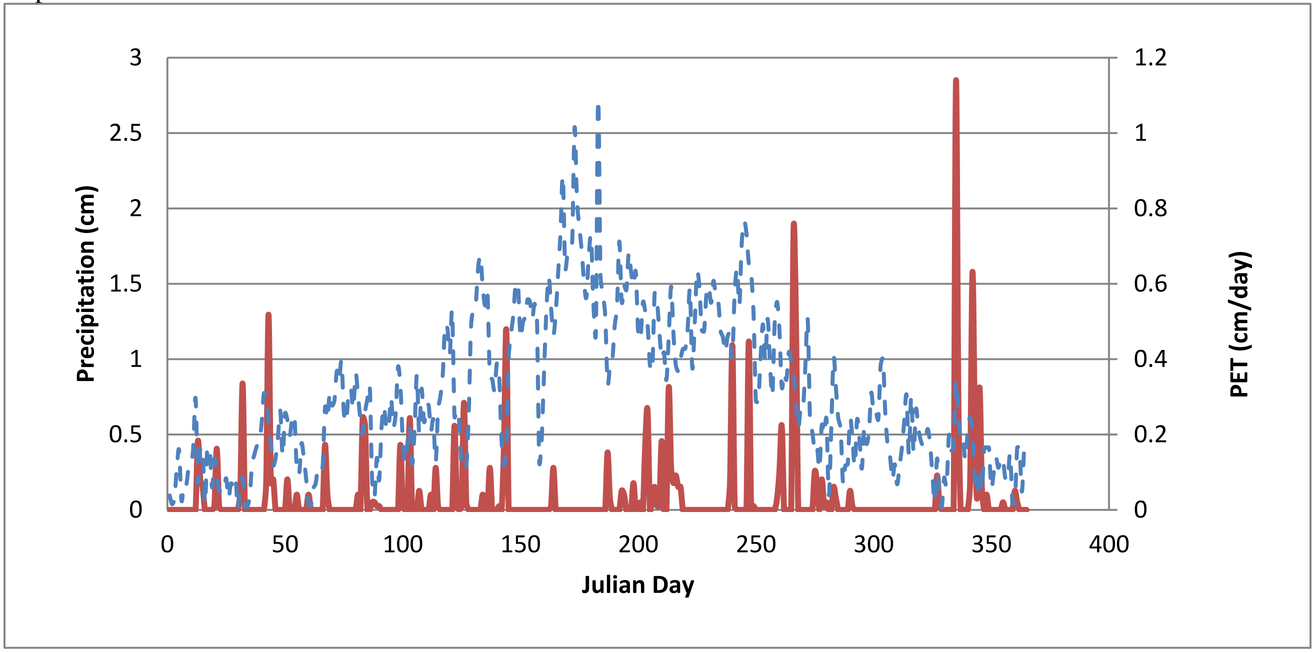

Figure 4-13: Distribution of precipitation and PET for Cortez (2007). Precipitation events tend to be of low magnitude which may explain the low sensitivities despite precipitation generally occurring outside of the period of peak PET.

The cover at Montrose displays a precipitation pattern that varies notably from Meeker which may result in the varied sensitivities in the n and precipitation factor. Precipitation again tends to take place during the growing season with the exception of two events, figure 4-14. There are two large magnitude events each that take place right around the beginning or end of the growing season. PET and LAI is low during and after the second major event, a magnitude greater than 6 cm/day, and therefore it is expected that an increase in the precipitation factor. The increase in sensitivity to *n* is expected because of the need for increased storage to hold the water from these large events until PET can remove this water.

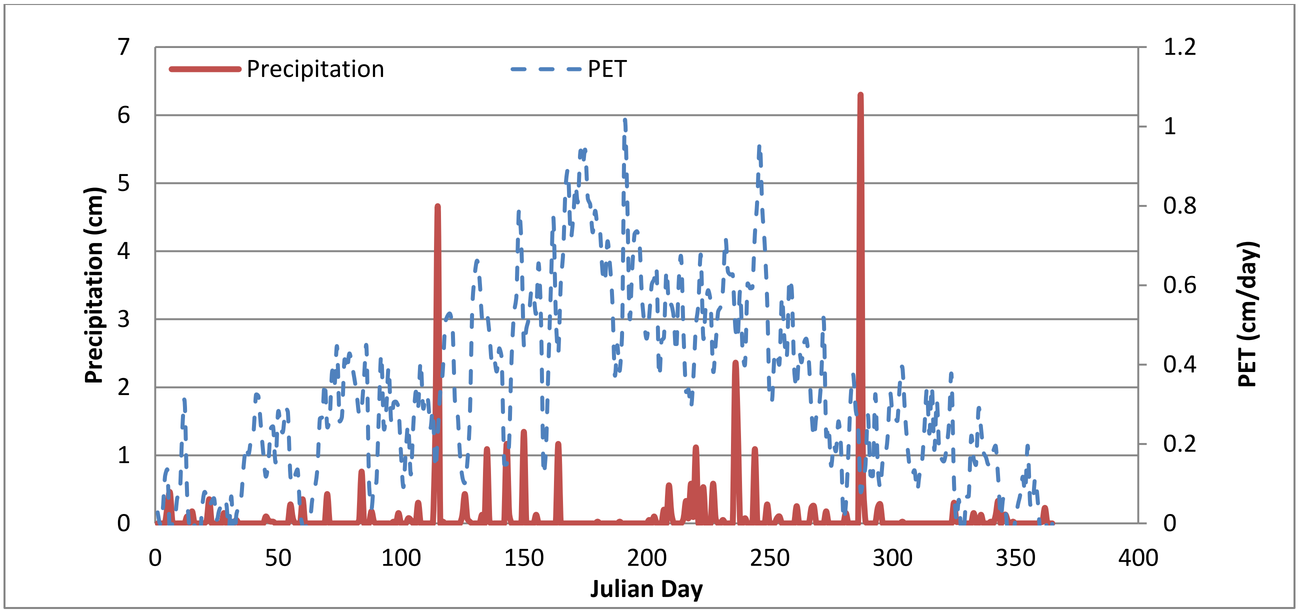

Figure 4-14: Distribution of precipitation and PET for Montrose (2007). Storm events of significant magnitude take place before and after the summer months when PET is high. This may explain the increased sensitivities modeled at this site.

The increased sensitivities calculated for the site at Grand Junction can be explained primarily through the timing of precipitation during the year. There is only one storm of significant magnitude, about 3 cm during January which exceeds the 2-year return rate magnitude for the location of 2.54 cm (Miller, 1973). Despite this, the majority of the precipitation takes place between January and March with a significant amount also from August to December, figure 4-15. The PET peaks during July, when the year was relatively dry. Therefore, although the magnitudes of the observed events are not particularly large, many smaller events take place primarily during periods of low PET. As a result changes in the magnitude of PET, precipitation or storage capabilities of the soil have a greater impact on the effectiveness of the cover.

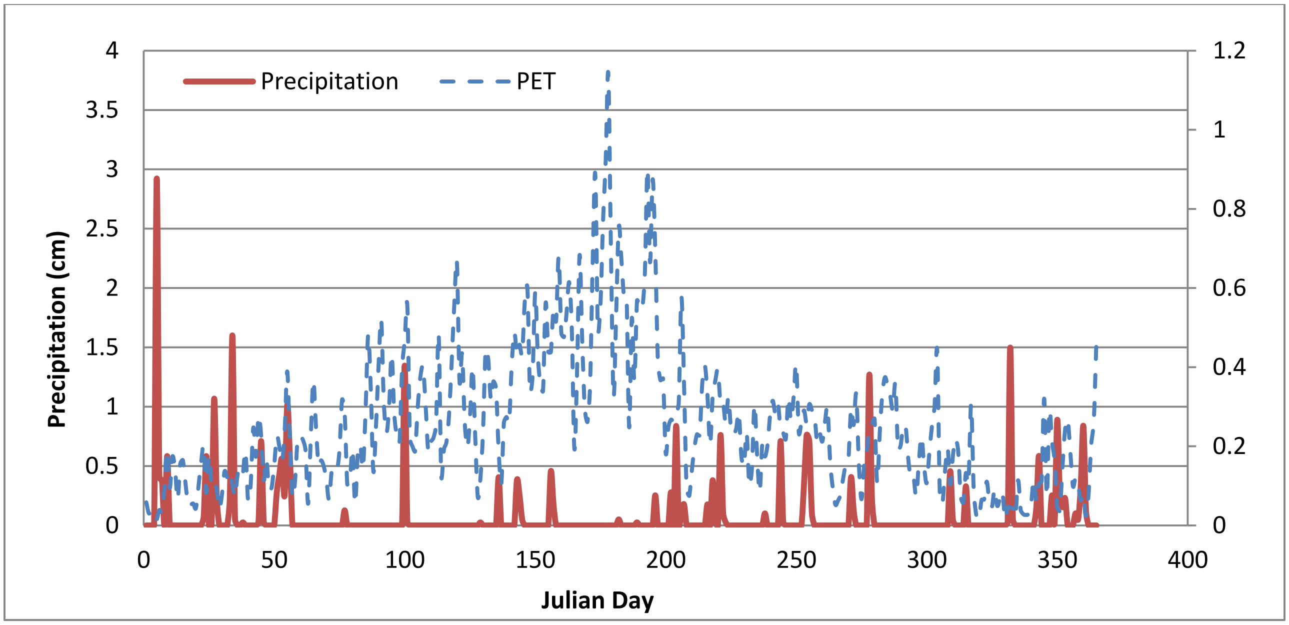

Figure 4-15: Distribution of precipitation and PET for Grand Junction (2008). It can be seen that precipitation events tend to be concentrated before and after PET peaks. This is a likely cause of the relatively high modeled sensitivities.

Based on these results it can be seen that cover effectiveness is generally the most sensitive to the soil properties that control the storage capabilities of the cover compared to the vegetation and climate parameters. Based on visual analysis of the timing or precipitation events in relation to the periods of high PET for a site it is evident that cover effectiveness is sensitive the timing of precipitation. It is also observed that the magnitude of individual events may have a significant impact on cover performance. The sensitivity of cover performance to both the timing of precipitation as well as to individual large events will be explored in greater detail in section 6.

Similar relationships between sites with high sensitivities and high percolation rates seen in the Front Range are also seen at the sites in the Western Slope. Figure 4-16 shows that Grand Junction has significantly more percolation in the model run before parameters are perturbed than the other 4 sites. Montrose has the second highest percolation which correlates with the slightly higher sensitivities. These high percolation rates can be explained by a combination of storm magnitude and timing. Grand Junction (2006) had many storms of low magnitude before and after peak PET, and even though these storms are all below 3 cm in magnitude, the modeled percolation is high.

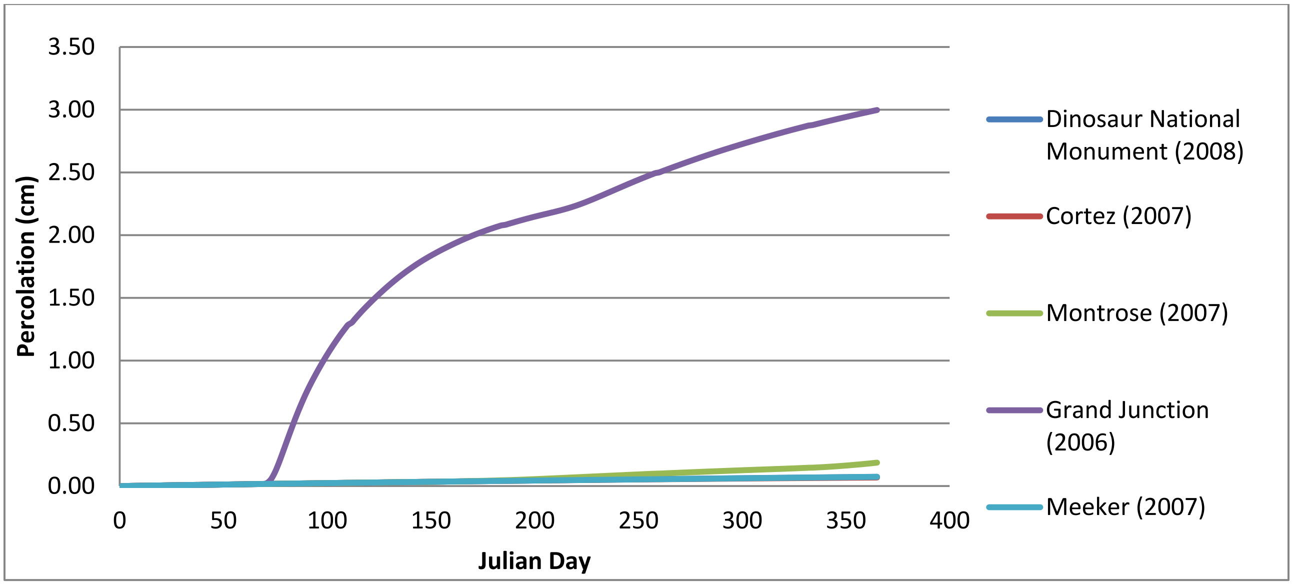

Figure 4-16: Percolation as a function of time before perturbations for the five sites in the Western Slope.

4.2 Forward Model Run Results

FRONT RANGE

The Monte Carlo analysis for the front range demonstrates a high range of possible percolation rates for the observed variability in the definition of the growing season, LAI and precipitation and PET factors in the front range. The minimum 50th percentile percolation rate is estimated using the Trinidad (2007) precipitation and PET record. At this site sensitivities were estimated to be low and therefore the impact of changes in variable parameters tends to be low. At DIA, which demonstrated higher sensitivities to the variable parameters, estimated percolation at low percentiles is high, 5.61 cm/year at the 50th percentile, see table 4-4. This is expected as small variations in parameters are expected to have a high impact on cover performance. Based on these results, at the 90th percentile estimated percolation rates at 4/5 sites exceeds 0.5 cm/year which can be interpreted as a failing cover in many situations.

Table 4-4: Results of the Monte Carlo analysis for the front range. Percentiles represent what percentage of the 100 simulations fell below the estimated percolation rates (cm/year). Even at low percentiles (50th) at 3 of 5 sites estimated percolation rates where over 0.5 cm/year which can be considered a failing cover.

Percentile	Colorado Springs (2007)	Broomfield (2010)	DIA (2010)	Longmont (2006)	Trinidad (2007)
50th	0.11	0.70	5.61	2.28	0.10
90th	1.21	0.17	10.33	3.49	0.95
95th	2.01	0.28	11.07	7.37	1.29
99th	2.52	0.41	11.92	9.96	2.14

WESTERN SLOPE

The monte carlo analysis for the western slope sites also demonstrates a significant range in possible percolation rates, though this range is smaller than the simulated percolation for the front range. The 50th percentile percolation rates varied from 0.08 cm/year to 0.48 cm/year, all which could be interpreted as a effective cover depending of regulatory requirements, see table 4-5. At higher percentiles estimated percolations begin to increase significantly. At the 90th percentile 3 of 5 sites covers appear to be ineffective. Similar to what was observed at the front range sites, locations that demonstrated high sensitivities to variable parameters, Montrose and Grand Junction, higher percolation rates were calculated at higher percentiles. At the other location where sensitivities are low, percolation rates tended to be less affected by variations in parameters. Based on this analysis generic cover designs appear to be ineffective for the western slope as variability in parameters is too great to effectively implement generic cover designs.

Table 4-5: Results of the Monte Carlo analysis for the western slope. Percentiles represent what percentage of the 100 simulations fell below the estimated percolation rates (cm/year). At higher percentiles (90th) at 3 of 5 sites estimated percolation rates where over 0.5 cm/year which can be considered a failing cover.

percentile	Dinosaur National Monument (2008)	Cortez (2007)	Montrose (2007)	Grand Junction (2006)	Meeker (2007)
50th	0.08	0.073	0.41	0.48	0.19
90th	0.12	0.147	3.96	1.70	2.21
95th	0.13	0.847	5.28	2.80	2.80
99th	0.22	2.018	7.10	6.92	3.39

5.0 ADDRESSING THE IMPORTANCE OF PRECIPITATION TIMING AND STORM MAGNITUDE

In section 4.0, it is shown that beyond the 9 parameters addressed in the sensitivity analysis the importance of the timing of precipitation events as well as the magnitude of individual events on cover performance is visually demonstrated. In this section the importance of these factors is mathematically demonstrated. The timing of PET over the modeled years is fairly consistent, with PET generally reaching a maximum in the summer months correlating with the timing of the growing season. Therefore the timing of PET will be ignored in this analysis. That is, the timing of precipitation in relation with PET is what is important, and thus the only parameter that needs to be adjusted is the timing of precipitation events.

5.1 Methods For Addressing Precipitation Timing

To mathematically demonstrate the importance of the timing of precipitation events on cover performance, a new variable or set of variables needs to be added to the sensitivity analysis that represents this timing. Thus, a lag parameter is added to the python parameter script. This lag parameter adjusts the starting date for the precipitation data array and thus changes the relative timing of the precipitation events for the year. 365 data points are entered for the time series, which is lagged for specified number of days. For example, setting the lag to 90 days would represent changing day 91 to January 1st and day 90 to December 31st. As discussed in section 3, UCODE perturbs each parameter in two directions. The sensitivity is calculated by running the model with the precipitation lagged twice, once forward with day 1 being the 91st day and then lagging the array backward such that day 1 becomes day 274. Each perturbation is changing the relative timing of the precipitation compared to the periods of high PET. Through this method UCODE will be able to calculate the sensitivity of cover performance to lag, which is representative of precipitation timing.

Using the lag parameter it is possible to estimate how percolation rates may vary as precipitation is lagged. A forward model run will be conducted using the initial values outlined in the previous section for the definition of the growing season, LAI and soil parameters. The precipitation and PET for Colorado Springs(2007) will be used. The model will be run starting with a lag of 0. During each consequent run the lag will be increased by 7 days until the lag reaches 365. This will result in a distribution of percolation values as a function of lag from 0 to 365. By observing how percolation rates change as the precipitation event is lagged it is possible to evaluate the effect of precipitation timing on cover performance.

5.2 Methods For Addressing The Impact of Large Magnitude Storms

To test the impact of individual large magnitude storms and the timing of these events, artificial large storms will be placed into the observed precipitation data at various periods over the year. Three new model runs will be conducted with the addition of a 25-year return period storm at three different times; the first day of the growing season, the middle of the growing season and the last day of the growing season. The lag parameter is included in each of the five sensitivity model runs conducted in the Front Range. The addition of an artificial precipitation event will increase the total yearly rainfall and a constant P/PET ratio should be maintained from the simulation without the addition of the 25-year event to insure that the perceived calculated sensitivities do not represent the impact of the increased P/PET ratio. The PET data is scaled to account for the increased precipitation. This can be done be changing the start value in UCODE for the PET factor to a value that will maintain the P/PET ratio. These simulation results will then be compared to the results for the Longmont (2006) simulation. The relative sensitivities at the two sites will provide insight into the impact that a single storm event has on cover effectiveness.

Along with adding 25-year events, a 2-year, 5-year and 10-year event will be added to the middle of the growing season and run 3 additional times. This will be done to address the relative importance of the timing of large storm events compared to the magnitude of the event. Again the PET data will be scaled up to account for the increased precipitation. Through these methods it will be possible to directly address the importance of large storms on cover performance.

5.3 Sensitivity of Cover Performance

For all the five sites in the Front Range, the lag variable tends to have a high impact on cover performance. The composite scaled sensitivities for 4 of the 5 sites with a lag set at 91 days were greater than 1.0. Physically this means that by lagging the precipitation by 90 days there is a greater than 25% increase in percolation rates. These results can be seen in figure 5-1. For Colorado Springs and Trinidad the timing of the precipitation had the highest impact of the 10 parameters on percolation rates. The sensitivities to lag are also very similar for the DIA and Longmont sites. Despite this, the cover appears to be relatively more sensitive to a variety of other parameters at DIA and Longmont. This is due to the way UCODE operates. Each parameter is adjusted individually with all other parameters remaining constant between runs as discussed in section 3, therefore the cover will be more sensitive to other parameters for DIA and Longmont because the initial precipitation record has storms of significant magnitude before and/or after the growing season. Because of this, the sensitivity to these parameters is expected to be high as explained in section 6.0. This demonstrates that the sensitivity of cover performance to climate, vegetation and soil parameters are correlated to the timing of precipitation events. The consistency in the sensitivities to lag shows that the impact of precipitation patterns on cover performance is unique from the other climate, vegetation and soil parameters.

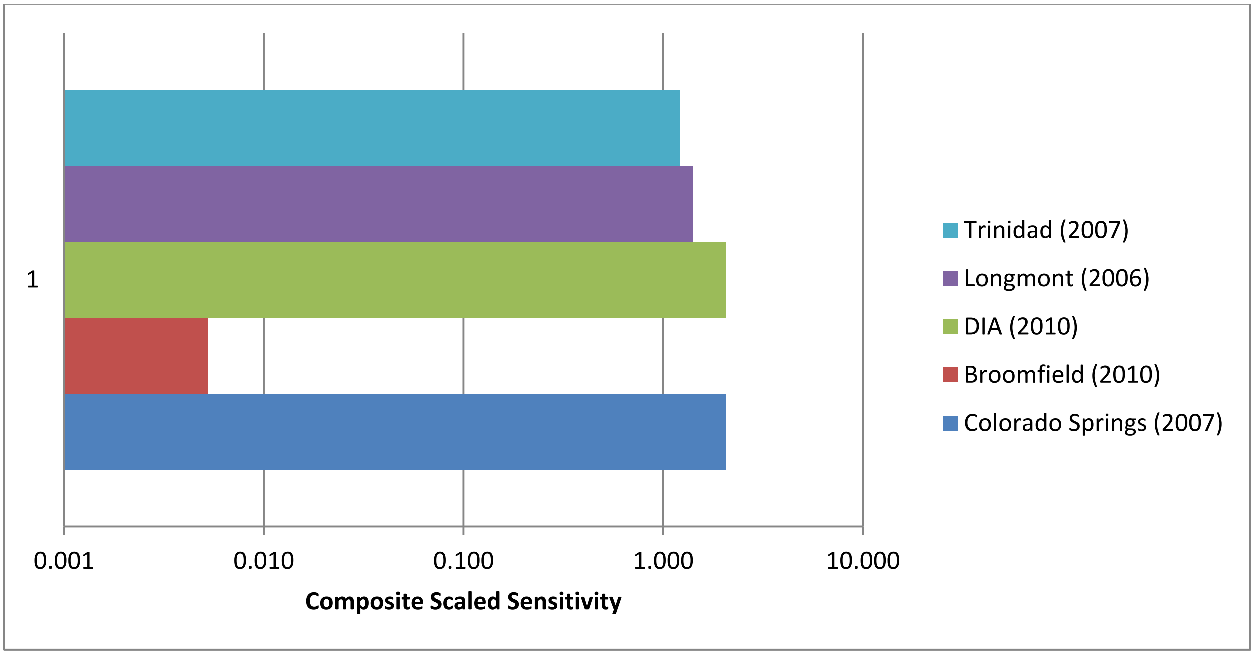

Figure 5-1: Sensitivity of cover performance to lag, representative of precipitation timing.

The sensitivity to lagging the precipitation at the Broomfield site is significantly lower than the other 4 sites. This is likely due to the distribution of storm events at Broomfield. There were consistent storms between February and the end of August, such that when the distribution was lagged 91 days, the early year storms then took place during the growing season and the storms that took place originally in the middle of the growing season instead took place after PET peaks, as seen in figures 5-2 and 5-3. Therefore if the lag is changed to 200 days, then the dry period between September and January takes place in the summer months while generally the precipitation takes place during the winter months. As a result the sensitivity to lag increases by two factors to 0.346192 which is similar to the sensitivities found for the other 4 sites. This demonstrates a weakness in the lag parameter, that the sensitivity to lag may change as the perturbation amount for lag set in UCODE varies. Despite this, the lag parameter numerically demonstrates the importance of precipitation timing on cover performance.

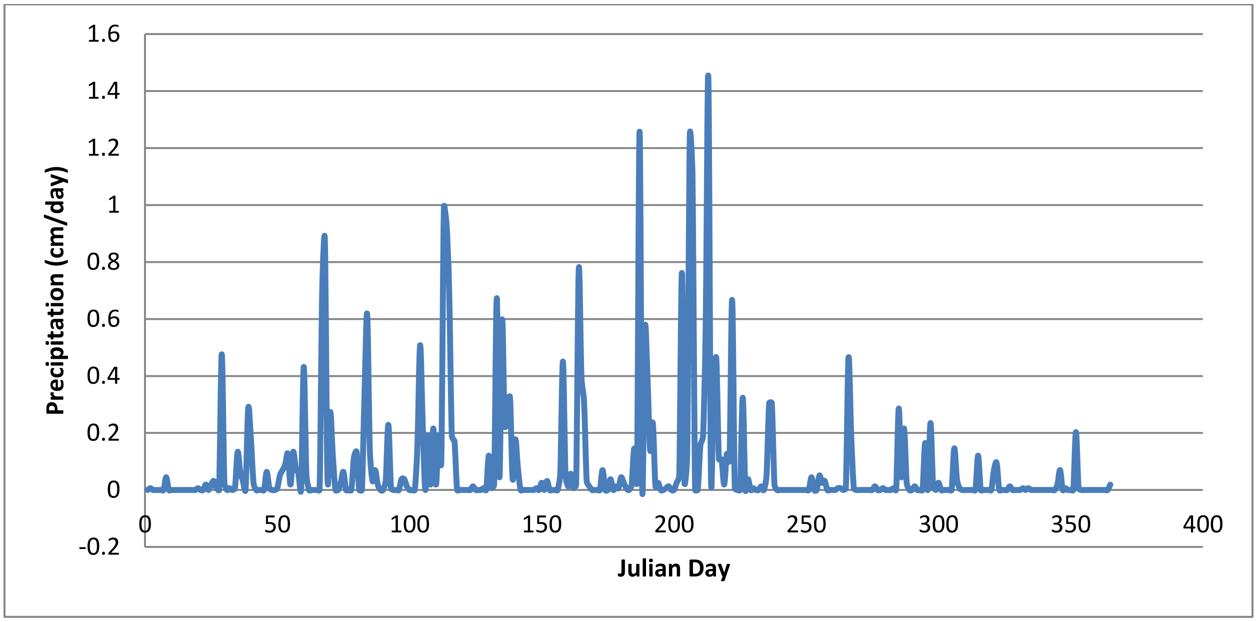

Figure 5-2: Observed precipitation for the Broomfield data set. The precipitation tends to be concentrated between February and August, before and during periods of high PET.

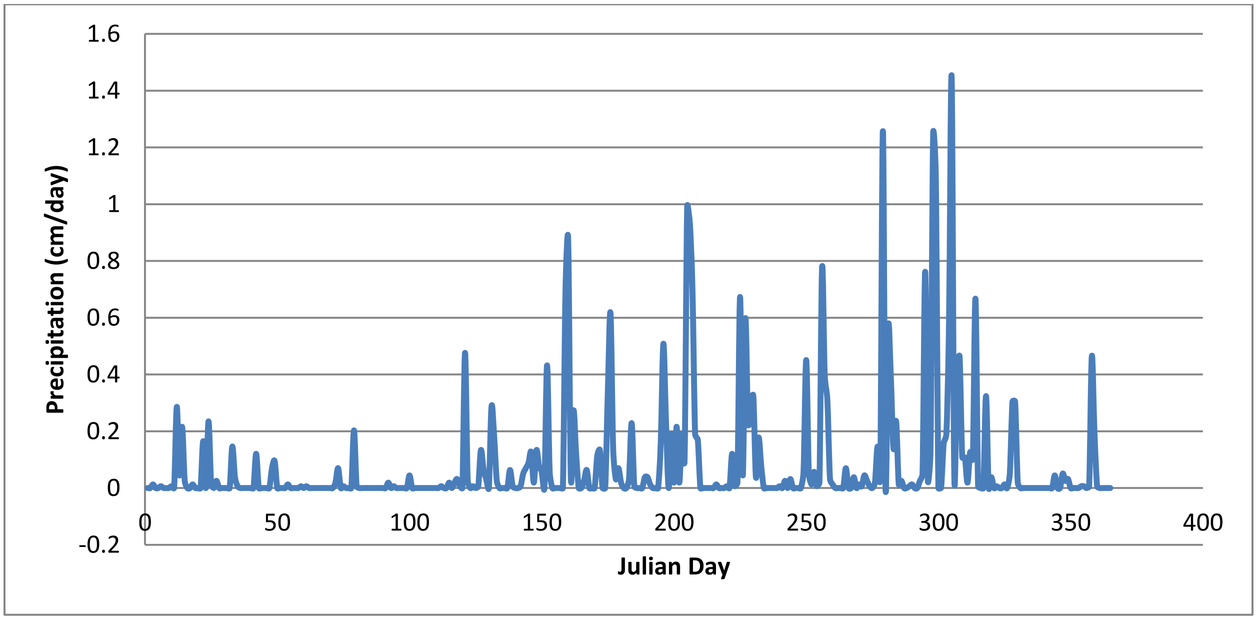

Figure 5-3: Broomfield precipitation record from figure 5-2 lagged forward 91 days. After this lag the precipitation is concentrated between April and November, during and after the growing season.

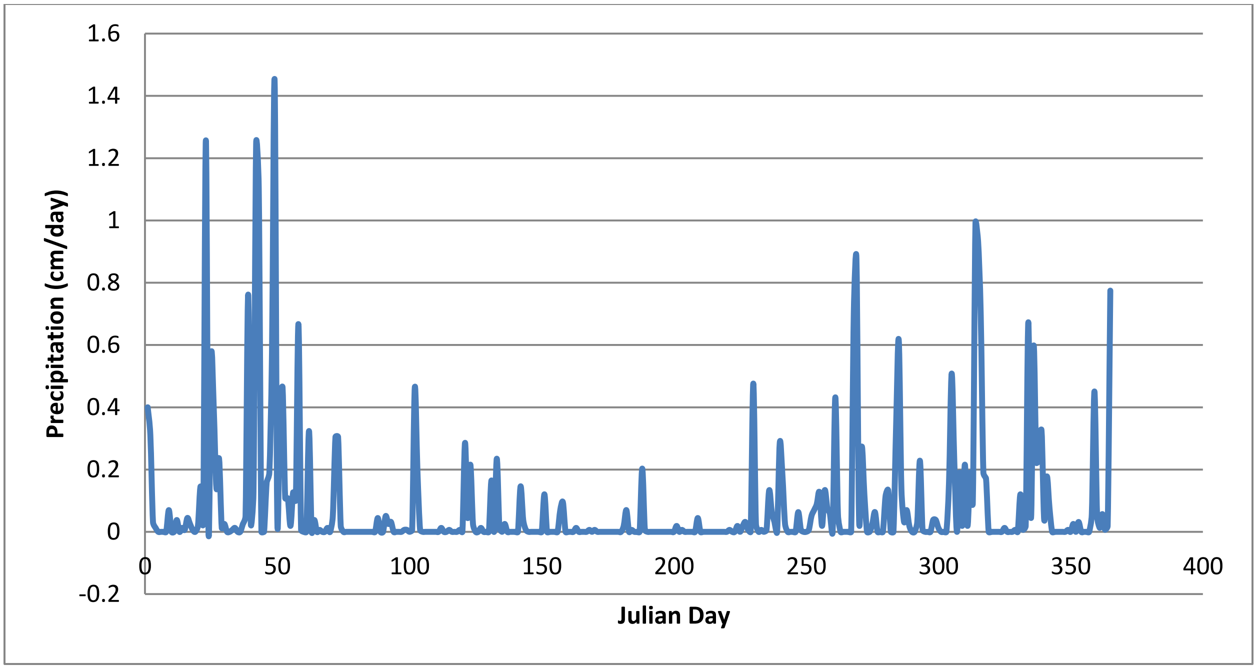

Figure 5-4: Broomfield precipitation record lagged 200 days. Adjusting the lag to 200 days creates a precipitation pattern where rain fall occurs during the winter months, while during the growing season and periods of high PET precipitation is very low.

5.4 Sensitivity to Large Magnitude Precipitation Events

With the addition of large magnitude precipitation events to the observed precipitation at the Colorado Springs site there are significant increases in model sensitivity. For Colorado Springs a 25-year event is 9.56 cm (Miller et al. [1973]). This storm was added at day 124, 199 and 274 corresponding to the average last frost, middle of the growing season and first frost. The new starting value for the PET factor in the sensitivity analysis is set at 1.34 to scale the PET, maintaining a P/PET ratio of 0.318.

The simulations demonstrate a significant increase in cover sensitivity to a multitude of parameters for all three simulations compared to the initial simulation, see figure 5-5. The climate parameters precipitation factor and PET factor demonstrate the largest increase in sensitivities with a 3 order and 4 order of magnitude increase respectively. Generally the results of these simulations are in line with the results of the simulation at the Longmont site. This shows that the 100-year event that took place at the Longmont site dominates the effectiveness of the cover. It also shows a strong correlation of the modeled parameters to individual large precipitation events. Because Sensitivities increase for all parameters no matter when the precipitation event was added it may indicate that the actually timing of this event is less important than the magnitude.

Figure 6-6 shows how the additions of various size storm events during the middle of the growing season effect cover sensitivities. Generally as the magnitude of the storm event increases the cover becomes increasingly more sensitive to the definition of the growing season. The soil parameters α and k_s generally demonstrate this pattern as well, with the exception of the 25-year event which the sensitivities begin to decrease slightly. The sensitivity to *n* increases with the addition of the storm but maintains fairly constant with increases in storm magnitude. This is representative of correlated parameters, such that the sensitivity of cover performance to the definition of the growing season is correlated to the magnitude of an individual large storm event. The greatest increase in sensitivity is to the precipitation factor, which is expected because a percentage increase to a large storm is a greater increase in magnitude than the same factor increase in a smaller event. Therefore the cover is subject to marginally more precipitation over a short period with the major storm additions. It is important to note that the sensitivity to the lag is generally high for all model simulations and fairly constant for all model runs. This shows that sensitivity to storm magnitude and timing are independent.

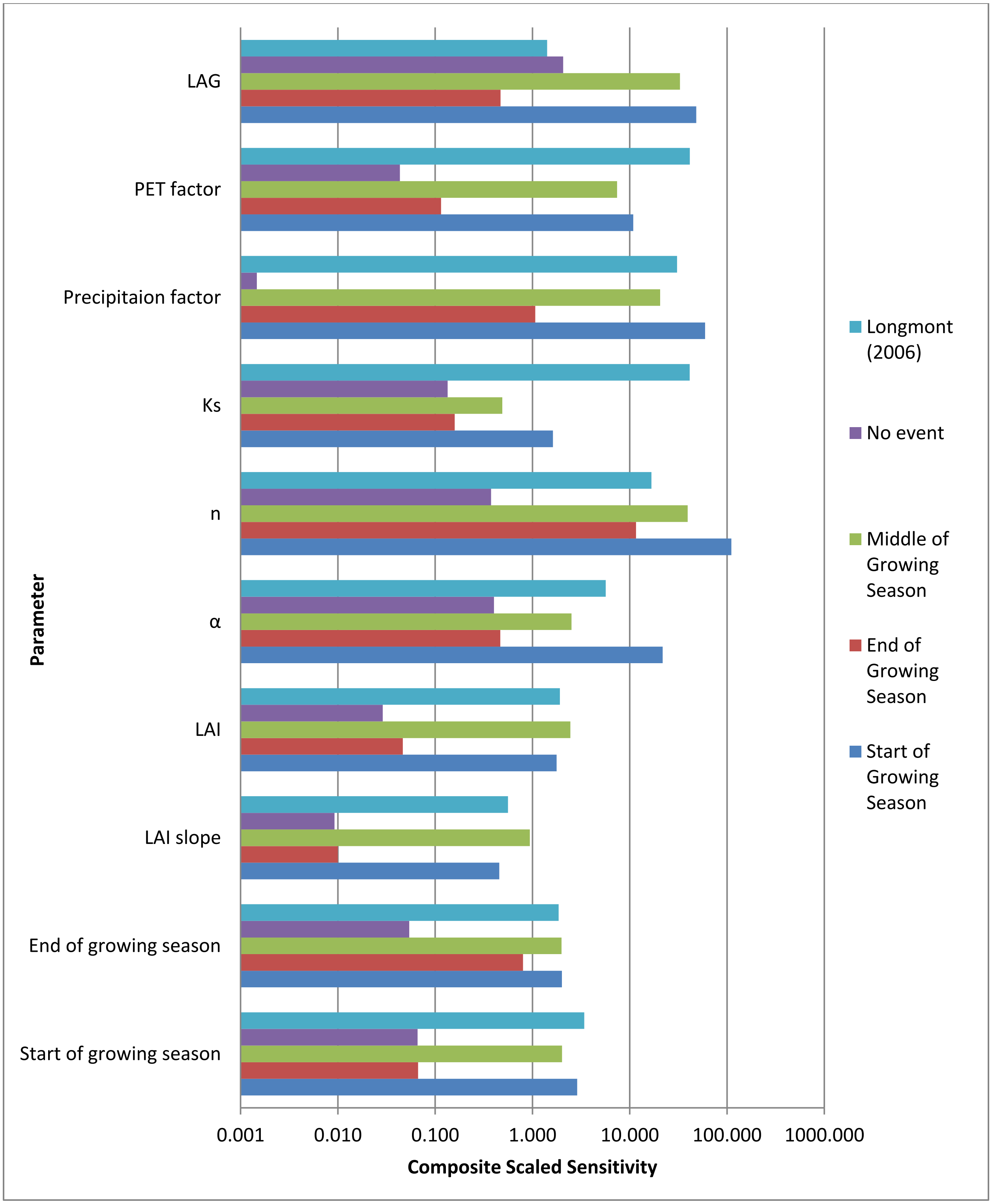

Figure 5-5: Changes in sensitivity results with the addition of 25-year storm events at three points during the year. Generally sensitivities to the climate, vegetation and soil parameters increase with the addition of these events.

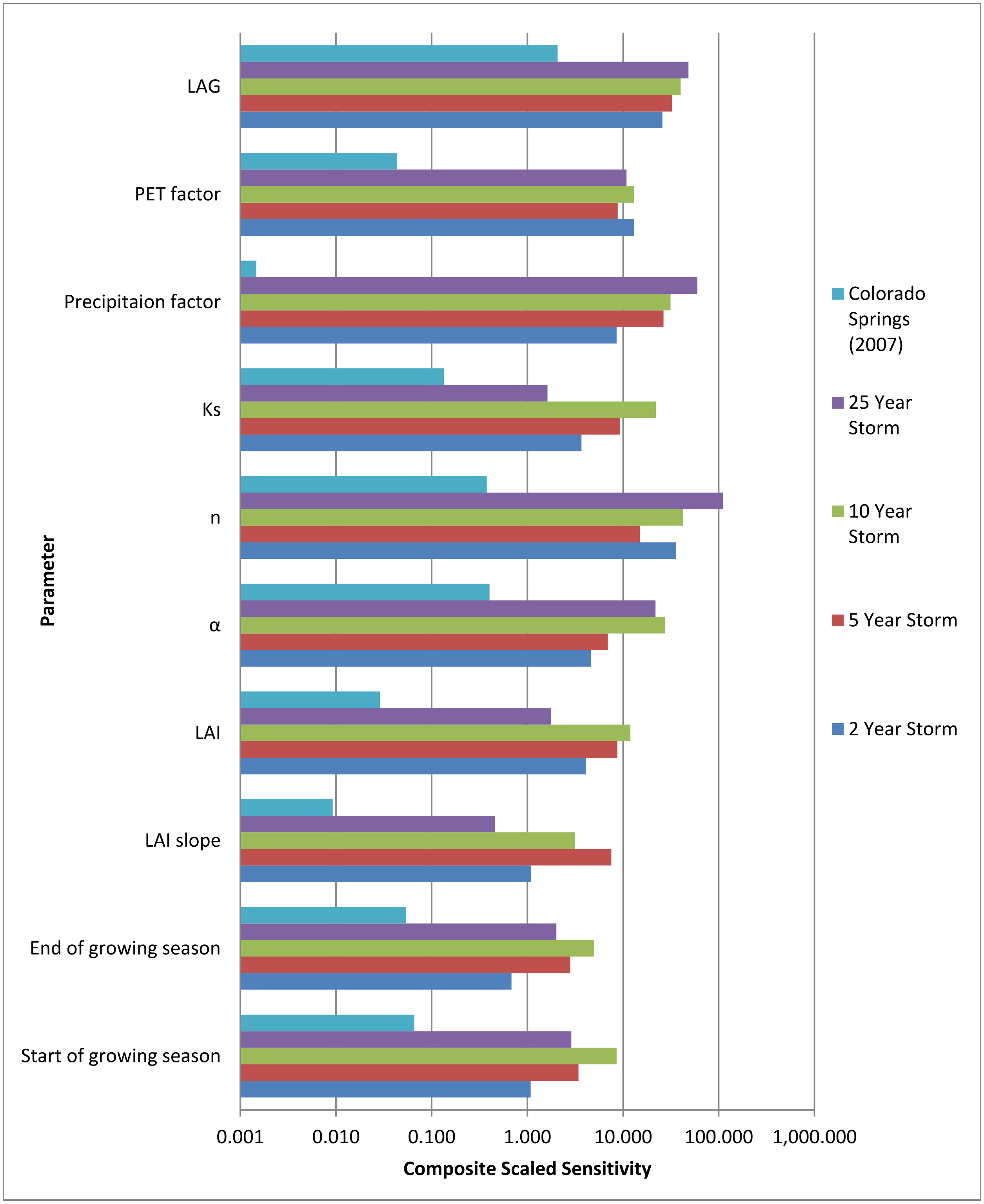

Figure 5-6: Changes in cover sensitivities due to the addition of a large magnitude storm event. As the magnitude of the precipitation event increases so does the sensitivity to various parameters. This indicates that the sensitivities are correlated to storm magnitude.

5.5 Distribution of Percolation Rates As a Function of Lag

The results of the series of forward model runs with varying periods of lag in the Colorado Springs (2007) precipitation record are shown in figure 5-7. It can be seen that there are two peaks in percolation rates as lag changes. Generally the estimated percolation is around 0.7 mm/year, such as when the base precipitation record is input into the model, lag = 0. At a lag of 91 days a maximum percolation of about 8.5 mm/year is estimated. This corresponds with the precipitation pattern displayed in figure 5-8, where the precipitation nearly entirely takes place during the late winter and early spring months when PET is low. With a lag of 197 days the percolation rates again peak. This estimated percolation rates correspond to the precipitation pattern shown in figure 5-9. Again precipitation is concentrated in the late fall and winter when PET is low. This demonstrates the sensitivity of cover performance to precipitation patterns and timing. While keeping all other climate, soil and vegetation parameters constant precipitation rates are shown to increase by a magnitude by simply changing the timing of events in relationship to periods of maximum PET.

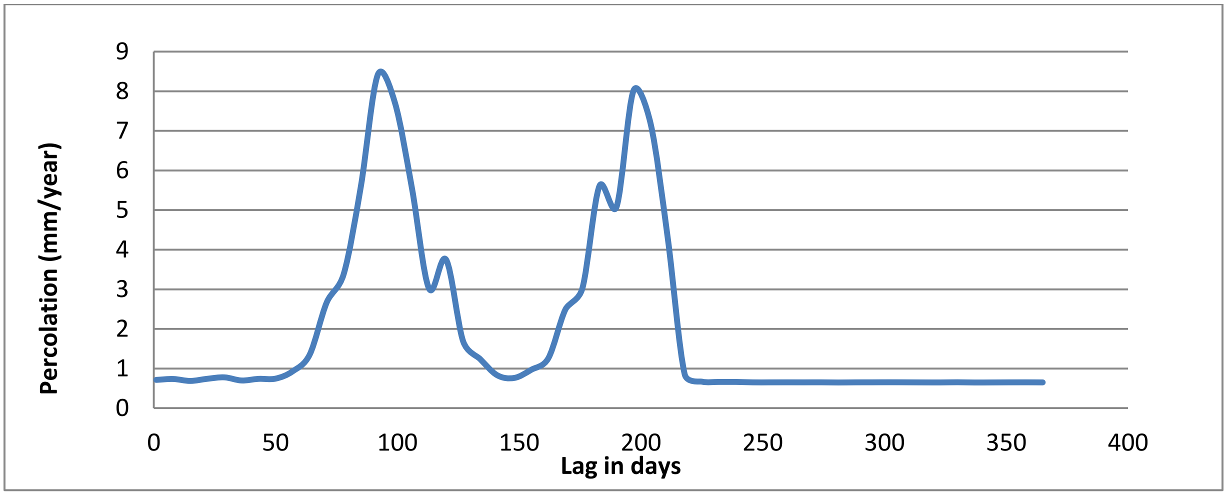

Figure 5-7: Distribution of percolation rates as a function of lag. The peaks indicate when precipitation is generally occurring outside periods of peak PET.

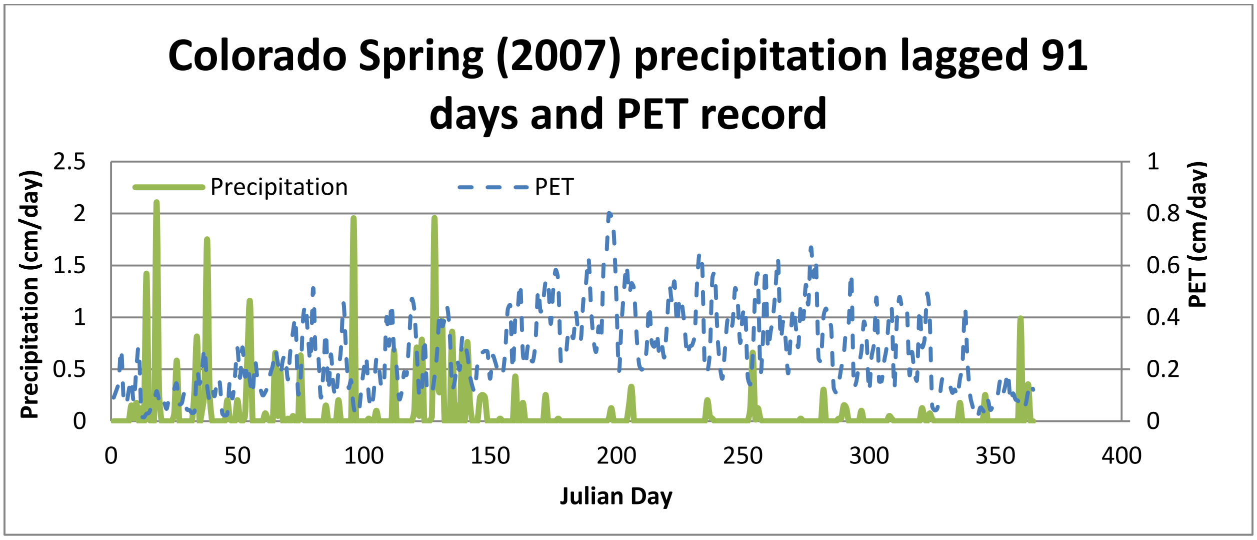

Figure 5-8: Colorado Springs (2007) precipitation lagged 91 days and PET record.

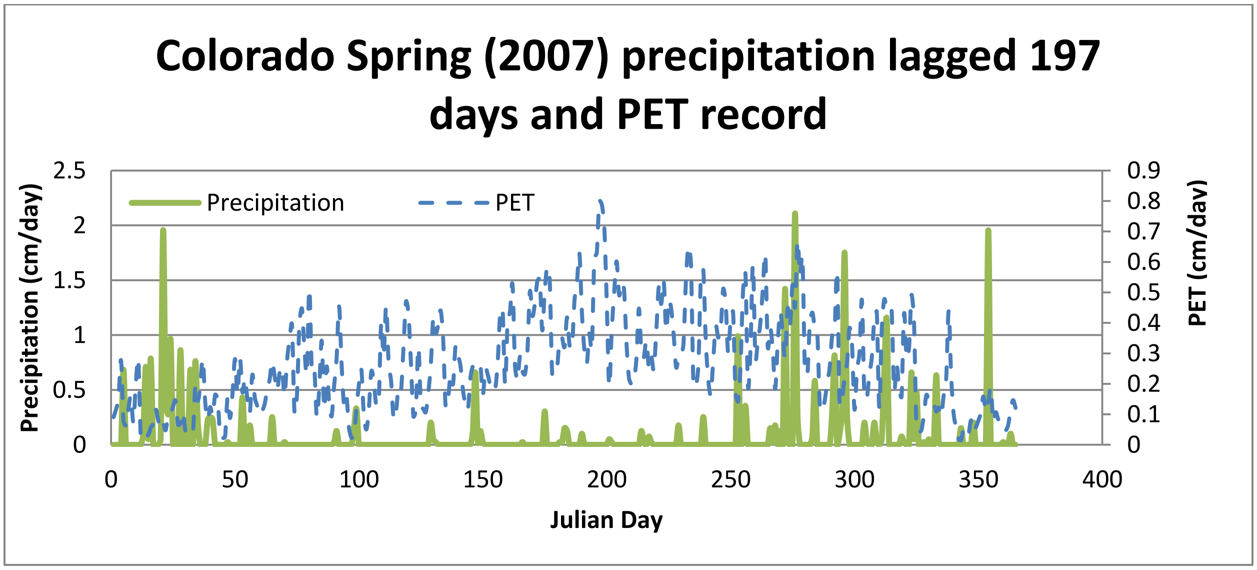

Figure 5-9: Colorado Springs (2007) precipitation lagged 197 days and PET record.

6.0 IMPLICATIONS ON GENERIC WATER BALANCE COVER DESIGN BASED ON ECOZONES AND OTHER INSIGHTS

Based on these model results, some insight can be made into the feasibility of designing water balance covers in a generic fashion based on ecozones. First, the initial sensitivity analysis results demonstrate the importance of soil parameters on the effectiveness of water balance covers. Changes in soil parameters consistently have a major impact on percolation rates. Soils are also highly variable at relatively small scales and therefore it is important that specific soil requirements are used in the generic cover design process. This does not inherently rule out generic cover methodologies. The available storage in a cover is controlled by the material properties as well as the cover thickness (equation 1-1). By setting strict cover thickness requirements that is dependent on on-site soil properties it may be feasible to implement generic covers despite the highly variable nature of soils. Limits on cover thickness are important because the capabilities of ET to remove water from the cover decrease with depth [Albright (2010)]. Although k_s does not represent available storage in a cover, it does describe the flow phenomena through the profile. Because it was found that cover effectiveness is generally sensitive to k_s, it is important that regulations also address the importance of this factor.

The relative sensitivities of cover effectiveness to each of the climate, vegetation and soil parameters have implication on the precision with which each parameter needs to be defined. The sensitivity to soil parameters tended to be 1 order of magnitude greater than the sensitivity to LAI, start of the growing season and the end of the growing season, and two oders of magnitude greater than LAI slope. Sensitivity to soil paraemters varied from 3 orders of magnitude greater than the precipitation factor to being equal to or 1 order of magnitude less. Magnitudinal increases in sensitivities can be interpreted as the need for increased precision in the definition of a parameter, such that an increase of one order of magnitude requires the parameter to be defined with 10 times precision, a 2 magnitude increase in precision demonstrating the need for 100 times precision, etc. As such it can be said that the soil parameters need to be defined with 10 times the precision of the vegetation parameters and 100 times the precision of the LAI slope. Sensitivities increased by 1 to 2 orders of magnitude depending on the timing of precipitation for the specific climate record for the site. For regions in which precipitation tends to occur outside periods of peak PET and the growing season, parameters need to be defined with 100 times the precision of the same parameters in a region when precipitation and peak PET coincide. This indicates the importance of precipitation timing on the implementation of generic cover designs and as such, ecozones need to be defined based on precipitation and PET patterns.

Ecozones must be specifically outlined based on the parameters that water balance covers are most sensitive to. Published ecozones that are outlined based on a mosaic of parameters are likely to be incapable of defining ecozones with sufficient precision to implement generic cover designs. Although, on the surface, two sites may be similar based on the total yearly precipitation and PET or a description of climate such a P/PET ratio, they may display different patterns of precipitation and PET. Cover effectiveness is shown to be highly sensitive to the timing of precipitation events relative to periods of high PET and the growing season. Ecozones should be defined primarily on these patterns. Predicting spatial patterns in precipitation is difficult and the feasibility of implementing generic covers based on ecozones is directly tied to the capabilities of defining the spatial distribution of precipitation patterns with accuracy. Therefore an ecozone used to design water balance covers in a generic fashion need to be outlined based on areas that demonstrate similar precipitation and PET patterns. The feasibility of outlining ecozones based on precipitation and PET timing is not addressed in this paper. It may be found that precipitation patterns are to variable to effectively implement generic cover designs, effectively eliminating the validity of the methodology. Only if the relative timing and magnitude of precipitation in relation to the region's growing season and periods of high PET is consistent will it be possible to implement generic cover designs.

The timing of precipitation has to be broken down into three aspects. First is the timing of PET during the season. If the period of maximum PET varies, then, even if precipitation patterns are consistent, they will vary with relation to the PET patterns. Because of this it is important that both precipitation and PET patterns are consistent throughout the region. The importance of individual storm magnitude and timing needs to be taken into account when developing ecozones. It was found that some of the climate, vegetation and soil parameters are correlated to a single storm event of significant magnitude. It was found that even a single 2-year event in the middle of the growing season can have a significant impact on cover performance. Therefore the magnitude of 2-year or greater return interval storms as well as the associated timing of these events should be consistent within an ecozone.

It is important to note that the importance of plant life in the design of water balance that is stressed in other studies does not fully concur with the results of this report (Albright, 2010). The specific plant parameters included in the modeling process tended to have a low impact on cover performance relative to soil and climate parameters. Despite this, the importance of plant life should not be ignored when regulating and designing generic cover design methodologies as vegetation is needed to efficiently remove water from the cover. Regulations may include specifications on LAI and root depth and distribution.

These conclusions have been combined into a decision matrix which can aid both current regulatory committees working on the implementation of generic cover design methods as well as further research. The goal of this matrix is to break down an ecozone based on the factors that are found to be most influential on cover performance, particularly precipitation and PET timing. This decision matrix is outlined in figure 6-1. The first step is to evaluate patterns of PET in the region in which generic covers are intended to be implemented. If PET patterns are consistent, then the next step is to look into the magnitude of major precipitation events for the region. If there is significant variation in PET patterns the region needs to be broken down into 2 or more regions, each with similar PET patterns. At what point consistency in data has been reached cannot be determined based on the results of this study alone and is a starting point for further research. If the magnitude of major events, such as a 2-year return rate storms, are consistent within the ecozone the next step is to evaluate precipitation patterns. If they are not, then reduce each zone into 2 or more zones until the magnitude and timing of major events are consistent. The evaluation of PET timing should include both large storm timing as well as general trends in precipitation. If these trends are consistent within the ecozone, it is then important to develop soil and vegetation requirements for the region as described above.

The question of consistency in a data set is important when going through this decision matrix. This question is out of the extent of the research and modeling conducted for this report. This decision matrix was outlined based on the assumption that PET and precipitation patterns are primarily spatially variable and that by reducing the size of the ecozone precipitation and PET patterns will become less variable. It should be focal point for future research to define at what point is there enough similarity in specific data sets that generic cover sill perform throughout the region.

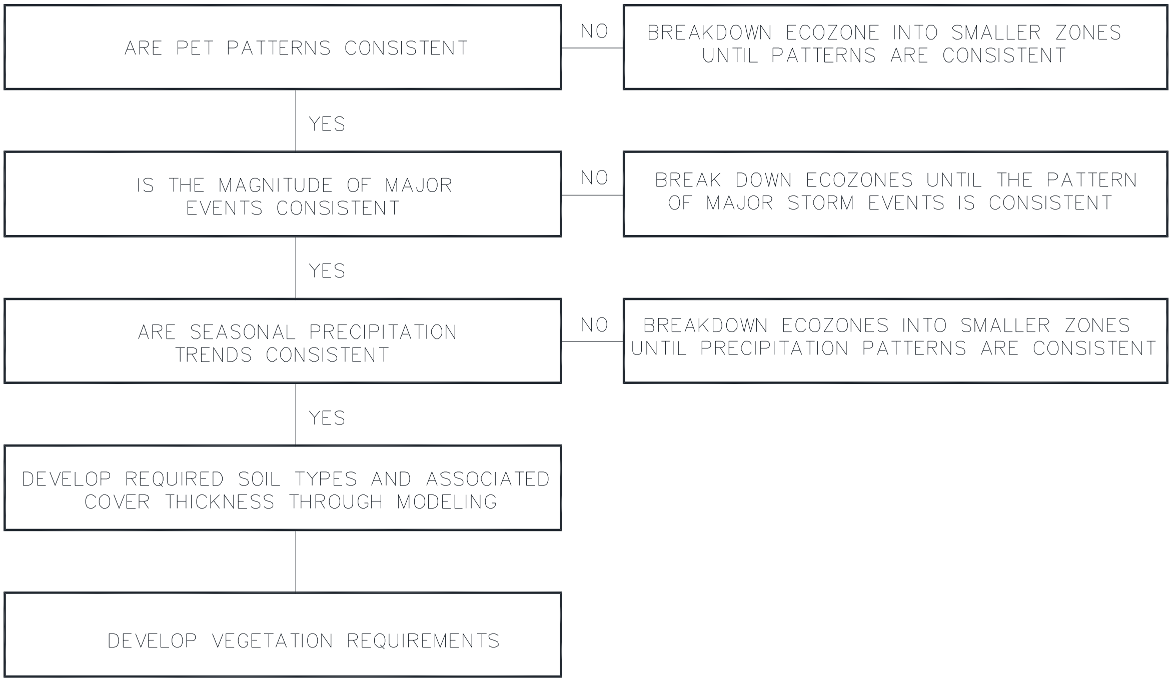

Figure 6-1: A possible decision matrix for breaking down a ecozone into small enough chunks to feasibly implement generic cover design.

These simulations were conducted on just two ecozones, both with arid to semi-arid climates and as such whether these results can be applied to other climates is uncertain. The range of P/PET for the 10 simulation years in this study is from 0.23 to 0.35. These results may not be applicable to regions that have a P/PET ratio that falls significantly outside of this range.

7.0 CONCLUSIONS

The purpose of this project was to evaluate the feasibility of generic water balance cover design methodologies by testing the sensitivity of cover performance as evaluated by estimated yearly percolation rates, to select climate vegetation and soil parameters. A series of simulations were conducted suing HYDRUS 1-D and UCODE_2005 at 10 hypothetical sites located in the Front Range of Colorado, USA and the Western Slope of Colorado, USA. Initial model runs suggest that the sensitivity of cover performance to the tested parameters (saturated hydraulic conductivity, van Genuchten fitting parameters, leaf area index, definition of the growing season, potential evapotranspiration and precipitation) are correlated to the relative timing of precipitation events during the year as well as the magnitude and timing of major storm events. It was shown that sites which have significant precipitation before or after the growing season, which corresponded with periods of high PET, also demonstrated relatively higher sensitivities to variations in climate, vegetation and soil parameters compared to sites where precipitation was concentrated during the summer months. It is observed that sites with single large magnitude storm events displayed higher sensitivities.

Consistent trends in the relative sensitivities between the climate, vegetation and soil parameters were noticed at the 10 sites. Generally the sensitivity of cover effectiveness to K_s, α and n were two to three orders of magnitude greater than that of the definition of the growing season and the LAI. The sensitivity the total yearly precipitation varied greatly from site to site, from being four magnitudes less than the sensitivities to K_s, α and n to being nearly equal to the sensitivity to these soil parameters. The sensitivity to PET also varied but to a smaller degree, from one order of magnitude less to equal to the sensitivity of cover performance to soil parameters. The sensitivity results shed some insight into the relative precision parameters need to be defined. Soil parameters were shown to require 10 times the precision of the definition of LAI, start of the growing season, and the end of the growing season and 100 times the precision of the definition of the rate of increase and decrease in LAI at the start and end of the growing season. The definition of all parameters where shown to require approximately 100 more times precision when precipitation occurred outside periods of maximum PET compared to the sites where precipitation and PET coincide.

Forward model runs demonstrated a large range of possible percolation rates within the front range and the western slope. For both regions variability in climate and vegetation parameters greatly affects percolation estimates. As such it was concluded that for the front range and the western slope variability within the ecozones is great enough to effectively rule out generic cover methodologies for these ecozones.

The impact of precipitation timing on cover performance was evaluated by lagging the precipitation record. It was determined that cover performance was consistently highly sensitive to precipitation timing. Forward model runs were also conducted on a data set with varying lags. It was found that the estimated percolation rate varied by one to two orders of magnitude as the precipitation data was lagged. It can be concluded based on this analysis that precipitation timing, relative to periods of maximum PET and the growing season, plays a vital role in the performance of water balance covers.

Individual large storm events were added to the simulations to evaluate the importance of large storm events on cover effectiveness. It was found that the timing of large events is impactful on cover effectiveness. It was also found that many of the climate, vegetation and soil parameters evaluated in these simulations are correlated to the magnitude and occurrence of a large magnitude storm event. Data sets without a 2-year event tended to demonstrate relatively lower sensitivities to the input parameters than the simulations which included a 2-year return period event or larger. Through these simulations it was shown that the parameters that define the growing season and LAI are correlated to the magnitude of these events. As the magnitude of a major storm event increases so does the sensitivity of cover performance to the parameters that define the growing season.

A monte carlo analysis was conducted to evaluate a possible range of percolation rates for a generic cover for both the front range and the western slope. It was found that for a 3 ft monolithic cover composed of a slity loam material the 90th percentile percolation estimate ranged from 9.5 to 100 mm/year, both of which could be considered failing covers. For the western slope the range was 1.2 to 40 mm/year. Based on these estimations it was determined that the implementation of generic designs on a scale of the front range or the western slope is infeasible.

Based on these observations it was determined that the implementation of generic covers based on ecozones is only feasible if the ecozone is outlined based on the parameters that were determined to impact cover effectiveness. A framework was developed to aid future research and regulation committees on the factors that need to be focused on when implementing generic cover design methods. This framework stressed the importance of defining ecozones that are outlined based on precipitation and PET timing rather than a mosaic of parameters. Conclusions on the scale at which generic covers are feasible could not be made. Generic covers appear to be feasible if ecozones can be broken down sufficiently based on the precipitation timing relative to periods of maximum PET as well as the timing and magnitude of major storm events. Methods that define ecozones based on a mosaic of parameters are likely to be insufficient to effectively implement generic covers, and therefore site specific design should be used in replace of generic design methodologies that implement these broad definitions of ecozones.

Further work should focus on the possibility of outlining ecozones that have consistent precipitation and PET patterns. This project demonstrates the importance of outlining ecozones based on precipitation and PET patterns to effectively design a generic cover methodology. It may be determined that precipitation and PET patterns are too variable to break down into individual ecozones, in which case the generic cover methodologies are infeasible. On the other hand if ecozones can be broken down through the framework outlined in this paper generic design methodologies may be feasible. Further research is needed to look into the point at which variability in precipitation and PET timing is small enough that generic cover methodologies are feasible. This project identified that importance of timing, yet did not address the point at which patterns are consistent which is needed to implement generic covers. Research should also be conducted into the scale at which ecozones need to be defined to implement generic cover methodologies. It is possible that ecozones need to be extremely small to effectively outline areas that have similar precipitation and PET patterns, thus eliminating the feasibility of generic cover methodologies. On the other hand if these patterns can be outlined at a large scale, than generic cover methodologies may be feasible.

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APPENDIX A

Climate and vegetation parameters used for the simulations conducted in this report can be found in electronic supplements to this report. The name of each file and a brief description of the data for each file can be seen in table A-1

Table A-1: Description of supplemental files.

Data File	Description
PrecipitationData.xls	Precipitation data for the 5 sites in each the front range and western slope from 2006 to 2011. Also included is the low end and high end precipitation factors used in the parameter file script.
PETData.xls	PET data for the 5 sites in each the front range and western slope from 2006 to 2011. Also included is the low end and high end PET factors used in the parameter file script.
FrostDates.xls	Earliest, latest and mean frost dates for the 5 sites in each the front raRoonge and western slope from 2006 to 2011.
RootDensity.xls	Root density as a function of depth for the cheatgrass vegetation.