A Systematic Approach to the Evaluation of RCRA Disposal Facilities under Future Climate-induced Events

by

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DEDICATION

This work is dedicated to my loving husband, Richard,
who has never ceased in his support of me,
regardless of the sacrifice. Thank you for helping me
to reach my dreams.

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CHAPTER I

INTRODUCTION

The Department of Energy (DOE) is responsible for the cleanup of hazardous chemical and radioactive waste at former nuclear weapons sites across the United States (U.S.). These sites produced nuclear weapons components and assembled nuclear weapons from the 1940s through the end of the Cold War (EPA 1989). The agency's Office of Environmental Management currently oversees environmental restoration activities at more than 80 of these sites. Cleanup activities include decontamination and demolition of buildings, management of contaminated soils and groundwater, containment of radioactive and hazardous chemical waste materials in near surface disposal facilities (e.g., landfills, trenches and vaults), treatment and stabilization of liquid radioactive wastes, and management of nuclear materials (EPA 1989).

In 1999 the DOE promulgated DOE Order 435.1, *Radioactive Waste Management*. The purpose of the order was to establish guidelines for the management of DOE high-level waste, transuranic waste, low-level waste, and the radioactive component of mixed waste (DOE 1999). A manual was created to catalog procedural requirements and existing practices that would ensure that all DOE elements and contractors managed DOE's radioactive waste in a manner that was protective of worker and public health and safety, and the environment. DOE Order 435.1 also states that performance objectives should be evaluated for a 1,000-year period to determine potential risk impacts to the public and environment. As defined by the manual, a performance assessment is, “an analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives established for the long-term protection of the public and the environment will be achieved following closure of the facility” (DOE 1999). While the manual requires uncertainty analyses, no mention was made of requirements to address important features, events, and processes at sites that may contribute to the long-term risk of groundwater contamination and human exposure (Arnold 2001). One long-term event that has risen to the forefront in the research community is potential climate change effects that stem from naturally occurring climatic mechanisms as well as anthropogenic forcing.

Overarching Climate Change Effects

Elevated concentrations of greenhouse gases are believed to have produced significant climate changes that include elevations and variations in patterns for temperature and precipitation (Solomon 2007). Early stages of these effects are already being experienced.

While the entire U.S. could be impacted by climate change, the extent to which certain effects are prevalent will occur on a regional basis. Therefore, any approach to understanding how climate change will affect environmental performance must be conducted at a regional level using numerical models that assess the design integrity of disposal facilities as well as their performance and post-closure monitoring. These models require input parameters such as temperature and precipitation that will be directly impacted by climate change effects. While temperature and precipitation represent direct impacts of climate change, it is also important to identify and explore model input parameters that may be indirectly affected by climate change (see Figure 1). These parameters encompass not only hydrological components but also design related features (e.g., hydraulic parameters).

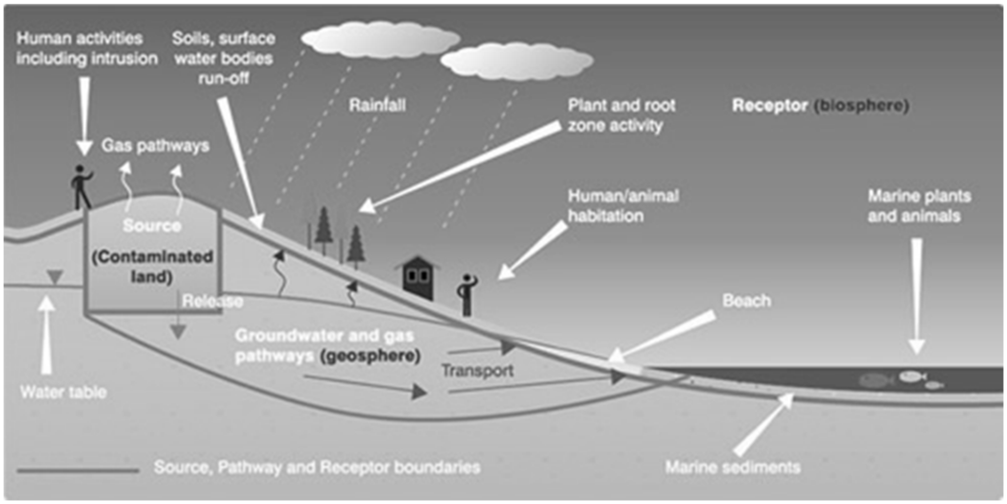


Figure 1: Conceptual Model of Contaminated Site

Problem Statement

Currently, regulations require the use of mathematical models of flow and transport processes to validate the effectiveness of near surface disposal facility designs. There is a need to build confidence in the predictive nature of long-term cover performance models, particularly when considering that disposal facility covers must be able to perform over long periods of time when significant climate change effects, such as variations in temperature and precipitation patterns, are anticipated.

However, the effects of increases in average temperature and precipitation and the occurrence of more frequent and extreme weather conditions are not being considered. This is particularly troubling since we are already witnessing, through field observations and reports, compromised cover systems and, in some cases, resulting groundwater contamination.

The presence of regulations alone to evaluate the proficiency of disposal facilities does not give proper guidance in addressing important long-term features, events, and processes, such as climate change. While currently used hydrological models are capable of evaluating these long-term features, a systematic approach for doing so has been absent.

Research Objectives

The objective of this research is to develop a systematic approach to assessing the long-term performance of near surface disposal facilities under potential climate change impacts. The ultimate goal is to establish an approach that can lead to safe and prudent design strategies, by incorporating reasonably foreseeable climatic changes of the future.

More specifically, the objectives of this research are to:

- Define a methodology that will establish an understanding of how historical climate patterns of precipitation and temperature affect near surface disposal facility water balance mechanisms (e.g., percolation);
- Use a Monte Carlo approach to conduct performance assessment of various near surface disposal facility designs based on historical climate events;
- Develop future climate change scenarios and assess landfill cover performance relative to percolation thresholds.

For reasons explained in the body of this dissertation, HELP was selected as the most appropriate hydrological model for this research.

Background and Pertinent Literature

Disposal Facility Cover Designs

Alternative final cover systems, such as ET covers, are becoming more popular for use at waste disposal sites. While ET covers have not been accepted for widespread use by regulatory bodies, agencies have allowed for their use when it can be demonstrated that their performance is equivalent to the EPA prescribed RCRA cover (Arnold 2001). Conventional cover system designs employ materials with low hydraulic permeability, like geomembranes and compacted clay, to minimize the downward migration of water from the cover to the waste (DOE 2009). In contrast, ET cover systems utilize the properties of soil to store water until it is either transpired through vegetation or evaporated from the soil surface, thus minimizing percolation (DOE 2009). Despite the fact that ET cover systems are being recommended, evaluated or placed in service at several waste disposal sites, field performance data and design guidance for these cover systems are limited (Benson 2007).

Hydrological Parameters Impacted by Climate Change

Disposal facility cover systems, including ET and conventional covers, rely on plants to remove water from the soil profile. Plants differ in their critical temperature range for life cycle development (Allan 2008). There is a base temperature where growth commences and an optimum temperature where the plant develops as fast as possible. Increasing temperature can accelerate the progression of a plant through its life cycle phases (Barnett 2008). This ultimately will cause plant growth to plateau at the optimum temperature, rather quickly, and development slows subsequently. Scientists have predicted the warming of "air" temperatures, which is not synonymous with plant temperatures. Solar radiation, wind speed, relative humidity and plant stomatal conductance are all variables that affect the difference in temperatures between plants and air (Goodrich 2008). These variables must be altered in conjunction with increased air temperatures to replicate changes in the critical temperature range for plant life cycle development. The easiest approach is to alter input parameters associated with the estimation of potential ET. Several hydrological models exist with the capabilities to implement these changes.

DOE 435.1 Modeling Approaches

As previously noted, traditional design guidelines for disposal facility covers often rely on deterministic models of flow and transport processes that neglect the effects of increases in average temperature or the occurrence of more frequent and extreme weather conditions (Arnold 2001). This research will explore and compare model results of long-term disposal facility cover performance (100+ years) using selected scenarios with respect to temperature and precipitation values.

Instrumentally-based analogues are often used in deterministic modeling. Typically, records are examined from initial instrumentation recording until the present. Common weather patterns are identified as well as extreme occurrences (e.g., wettest year). These extreme events serve as a worst case scenario and are used as "Design Year" conditions.

A disadvantage of using solely historical data is that past changes in climate may not have been caused by mechanisms (e.g., anthropogenic causes) expected to affect the future (Carter 2007). Furthermore, the historical record time period is relatively small compared to the forecast period (1,000 years). Palaeoclimatic changes from earlier time periods (e.g., the last Interglacial period) were most likely caused by changes in the Earth's orbit around the sun, while more recent palaeoclimatic changes are presumably related to naturally occurring changes in atmospheric circulation, as are changes in the earlier part of the instrumental record. Because anthropogenic climate changes are not accounted for in this record, if solely historical data is used, the future climate will resemble that of a past climate.

An alternative approach is to use historical records in conjunction with atmospheric models to produce synthetic analogues. General circulation models (GCMs), representing physical processes in the atmosphere, ocean, cryosphere and land surface, are the most advanced tools available to produce synthetic analogues (Carter 2007). While simpler models have also been used to provide globally or regionally averaged estimates of future climate conditions, only GCMs, often in conjunction with nested regional models or other downscaling methods, have the potential to provide geographically and physically consistent estimates of regional climate change data. GCMs depict the climate using a three dimensional grid over the globe. Many physical processes, such as those related to clouds, also occur at smaller scales and cannot be properly modeled. As an alternative, their known properties must be averaged over the larger scale in a technique known as parameterization. This is one source of uncertainty in GCM-based simulations of future climate.

Commonly Used Hydrological Deterministic Models

Hydrologic Evaluation of Landfill Performance (HELP) Model

The HELP model requires the input of weather, soil and design data. It provides estimates of runoff, evapotranspiration, lateral drainage, vertical percolation (i.e., infiltration), hydraulic head and water storage for the evaluation of various landfill designs. United States Army Corps of Engineers (USACE) personnel at the Waterways Experiment Station (WES) in Vicksburg, Mississippi developed the HELP model, under an interagency agreement with the Environmental Protection Agency (EPA) (Shroeder 1994). As such, HELP is an EPA sanctioned model for conducting landfill water balance analyses. HELP model version 3.07, issued on November 1, 1997, is the latest version of the model.

UNSAT-H

UNSAT-H is a finite difference numerical model that is based on Richard’s Equation. UNSAT-H is a one-dimensional unsaturated soil-water and heat flow model that contains transpiration, thermal and isothermal vapor flow models in addition to a range of hydraulic functions (Fayer 2000). The UNSAT-H model was developed at Pacific Northwest National Laboratory (PNNL) to assess the water dynamics of arid sites and, in particular, estimate recharge fluxes for scenarios pertinent to waste disposal facilities (Fayer 2000).

Hydrus-1D

Hydrus-1D is a public domain model that is used for the analysis of water flow and solute transport in variably saturated porous media (Šimůnek 2009). The model is a one-dimensional finite element model of its predecessor, HYDRUS. It was developed by the U.S. Salinity

Laboratory in cooperation with the International Groundwater Modeling Center (IGWMC), the University of California Riverside and PC-Progress, Inc. (Šimůnek 2009).

Previous Studies Evaluating Deterministic Model Validity

Fayer et al. (1992) and Fayer and Gee (1997) compared water balance data from eight non-vegetated lysimeters located in semiarid southeastern Washington state, to predictions made with UNSAT-H. The cover design consisted of 1.5 m of silt, 0.1 m of sand and 1.33 m of gravel. Soil–water storage was under-predicted during winter months and over-predicted during summer months. Differences between measured and predicted soil–water storage were due to over-predictions in evaporation during the winter and under-predictions of evaporation during the summer. Fayer et al. (1992) and Fayer and Gee (1997) indicate that water-balance codes can be calibrated to improve predictions by focusing on multiple performance variables (i.e., soil–water storage and percolation). They also noted that the hydraulic conductivity function, snow cover, hysteresis, and the calculation of potential evaporation can affect the accuracy of water-balance predictions.

Khire et al. (1997) compared predictions made using the HELP and UNSAT-H with lysimeter water balance data for two resistive barrier covers located in Georgia and the state of Washington. The cover design for both sites consisted of a vegetated surface layer overlying a compacted fine-grained layer. Both codes were able to capture the seasonal trends in surface runoff, ET, and soil–water storage, but the predictions from UNSAT-H were in better agreement with the measured water balance than those from HELP. Percolation was over-predicted by HELP and slightly under-predicted by UNSAT-H. Snowmelt and frozen ground prediction errors significantly affected runoff predictions during the winter months. These errors affected all other water-balance quantities.

Khire et al. (1999) compared predictions made using UNSAT-H with field data from a capillary barrier test section consisting of a 150-mm-thick layer of silt overlying a 750-mm-thick layer of sand. UNSAT-H predicted the water balance of the capillary barrier conservatively, with runoff being under-predicted within 100 mm and percolation being over-predicted by as much as 50 mm. Much of the over-prediction of percolation was attributed to the under-prediction of runoff. Soil–water storage, generally, was predicted within 30 mm of measured soil–water storage.

Scanlon et al. (2002, 2005) compared predictions made with HELP, HYDRUS, and UNSAT-H, to water-balance data from covers in semiarid Texas, New Mexico and Idaho, over a period ranging from one to three years. For the cover in New Mexico, the field data were compared only to predictions from UNSAT-H. The cover design at the Texas site consisted of (from top to bottom) 0.3 m of sandy clay blended with 15% gravel, 1.7 m of compacted sandy clay, and 1 m of sandy gravel. A 1.07-m-thick monolithic cover of silty sand was evaluated at the New Mexico site and a 3-m-thick monolithic cover of sandy silt was evaluated at the Idaho site. Codes employing Richards' equation (e.g., UNSAT-H and HYDRUS) predicted the water balance more accurately than codes employs a water routing approach. Scanlon et al. (2005) also suggest that the relationship between abundance of vegetation, evapotranspiration, and water availability is an important factor affecting the accuracy of water-balance predictions, and that most codes being used today do not account for this interaction explicitly.

Benson et al. (2004, 2005) compared water-balance data from a monolithic cover at a semiarid site to predictions made with UNSAT-H. Surface runoff was largely over-predicted by UNSAT-H, which had a direct effect on all subsurface hydraulic processes. The model was unable to predict percolation accurately. Differences in the method used to simulate precipitation intensity were attributed to the differences in the accuracy of predicted surface runoff.

Orgorzalek et al. (2008) compared predictions made with UNSAT-H and HYDRUS to water-balance data from a capillary barrier located in sub-humid western Montana. Both codes captured the seasonal variations in the water balance observed in the field. HYDRUS predicted total runoff with reasonable accuracy (timing of predicted and observed runoff events was different), while UNSAT-H over-predicted runoff. Soil-water storage generally was under-predicted by all three codes and predicted and measured percolation was in good agreement, except during the first year. Orgorzalek et al. (2008) suggest that cover modelers scrutinize runoff predictions for reasonableness and carefully account for snow accumulation, snowmelt, and ET during snow cover.

Bohnhoff et al. (2009) compared predictions made with UNSAT-H and HYDRUS to water-balance data from a test section of a monolithic cover in semiarid northern California. Inaccuracies associated with runoff predictions were found to affect the accuracy of all other water-balance quantities for both codes. When precipitation was applied uniformly throughout the day, runoff was predicted more accurately. Both codes predicted ET and soil-water storage reasonably well when runoff was predicted accurately. Percolation, however, was consistently under-predicted even when ET and soil-water storage were predicted reliably for both codes.

Organization and Content of Dissertation

Chapters 2, 3, and 4 of this dissertation consist of a series of research papers, each prepared as a separate manuscript for publication consideration in a refereed journal. Although the papers consecutively build upon each other, they can be read as stand-alone documents. This format may encumber the more knowledgeable reader with repeated introductory material, but it may also be useful to readers that prefer to review chapters as independent contributions. An overview of the contents of each chapter is provided in the following paragraphs.

In Chapter 2, a probabilistic approach is adopted that uses the Exponential Dispersion Model family to determine a preferred distribution for precipitation and temperature using observed data from two sites whose climate environments are quite different. Ultimately, the approach can support uncertainty analysis by establishing a probability of experiencing climatic events as opposed to using discrete values as a repetition of what has occurred in the past.

Chapter 3 presents the results of the method described in the previous chapter used as inputs for water balance predictions evaluated using the HELP model. Several variations of degradation were employed in a traditional RCRA disposal facility cover design over a 100-year simulation period. Analysis results were evaluated relative to two different thresholds for annual percolation thresholds (1 mm and 3 mm). These results demonstrate the importance of considering degradation in designing near surface disposal facilities, especially given the very long performance periods desired by different regulators.

Chapter 4 introduces an approach for evaluating anthropogenic climate change scenarios applicable for hydrological modeling of disposal facilities. The scenarios are characterized by changes in both precipitation and temperature, representing plausible future conditions. The analysis results are displayed using a mapping tool to support interpretation of DOE 435.1 performance assessments. Of particular interest is the extent to which precipitation effects are offset by increases in average temperature increases.

Chapter 5 provides a summary of major findings from this research as well as policy implications. Additionally, recommendations for future research are suggested.

CHAPTER II

MODELING PRECIPITATION AND TEMPERATURE IN VARIOUS CLIMATE ENVIRONMENTS

Abstract

A more stable and extensive analysis of climate is necessary to simulate long-term impacts associated with climate change. The Exponential Dispersion Model (EDM) family of distributions, a popular choice when characterizing precipitation levels and temperature in different climate environments, is being considered for its applicability to near-surface disposal performance assessments. In this study, the EDM family is examined to determine if there is a preferred distributional form within the family for these parameters using data from two sites whose climate environments are quite different. One site is in a semi-arid environment and the other is in a humid environment. In addition, the merit of selecting a different distributional form to represent each calendar month of precipitation and temperature data is explored.

Results show that the Gamma distribution was most often determined to be the best fit to recorded precipitation data. When considering temperature, however, the Weibull distribution proved to be a better fit. These results suggest that greater precision may be possible when temperature and precipitation serve as inputs to modeling activities, if these parameters are allowed to be represented by different distributions and derived by calendar month. Ultimately, the approach provides a more far-reaching examination of historical records and provides an

increase in confidence, when used in the evaluation of long-term climate impacts associated with near surface disposal facilities.

Introduction

The Department of Energy (DOE) is responsible for the cleanup of nuclear waste at former nuclear weapons sites across the United States (U.S.). Cleanup activities include the containment of radioactive and hazardous chemical waste materials in near surface disposal facilities, such as landfills, trenches, and vaults (EPA 1989). With the abundance of sites across the U.S. and the variability in operational management at each site, DOE introduced DOE Order 435.1, Radioactive Waste Management, in 1999 to assess the performance of these facilities. While the order requires uncertainty analyses, it may be unclear to users with respect to whether these requirements address important long-term features associated with climate (Ho 2001). Also, since the entire U.S. may be impacted by a changing climate, the extent to which certain effects are prevalent should be determined on a regional basis. Therefore, any approach to understanding how long-term features will affect environmental performance must be performed at a regional level using numerical models that assess the design integrity and performance of disposal facilities. Since these models require temperature and precipitation inputs, they are directly impacted by climate change.

Traditional approaches to evaluating near surface facility performance neglect the effects of increases in average temperatures or the occurrence of more frequent and extreme weather conditions (Ho 2001). Typically, records are examined from earliest records to the present. Common weather patterns are identified, as well as extreme occurrences (e.g., wettest year).

These extreme events are taken to be a worst-case scenario and are used as “design year” conditions. A disadvantage of using solely historical data is that the lengths of recorded time periods are typically small relative to the forecast period. In addition, worst case scenarios are developed based on precipitation, ignoring extreme temperature episodes, such as hotter than normal months. Research has shown that near surface disposal facility cover systems rely on plants to remove water from the soil profile. Plants differ in their critical temperature range for life cycle development (Allan 2008). There is a base temperature where growth commences and an optimum temperature where the plant develops as fast as possible. Increasing temperature can accelerate the progression of a plant through its life cycle phases (Barnett 2008). This ultimately will cause plant growth to plateau at the optimum temperature, rather quickly, and development slows subsequently. Scientists have predicted the warming of “air” temperatures, which is not synonymous with plant temperatures. Solar radiation, wind speed, relative humidity, and plant stomatal conductance are all variables that affect the difference in temperatures between plants and air (Goodrich 2008). These variables are critical in hydrological modeling and must be considered along with air temperatures to replicate changes in the critical temperature range for plant life cycle development. However, having confidence in the air temperatures used in hydrological modeling, alone, will increase the certainty in predictions.

An alternative approach to the traditional methods discussed above, is to use historical records in conjunction with statistical methods to produce observations of precipitation and temperature based on Monte Carlo approaches using probability distributions. This approach enables a more stable and extensive analysis of the climate probabilities than would be available using the raw data directly (Husak 2007). In addition, the inclusion of temperature in this approach will address concerns associated with a changing climate (e.g., increases in average temperatures).

There is little difference between many of the commonly used distributions when estimating climate parameters based on a limited number of data points (Husak 2007). The exponential dispersion model (EDM) family of distributions includes the response distributions for generalized linear models (GLMs), which have been utilized by several researchers to fit models to input climatological data, such as precipitation (Coe and Stern 1982; Wilks 1999; Chandler 2005; Hasan and Dunn 2011). Recently, there has been a growing interest in developing monthly climate distributions. Hasan and Dunn (2011) concluded that not only is this reasonable approach, but also recommend using the EDM family of distributions for this purpose.

In this paper, we present an approach for generating precipitation and temperature inputs to models used to assess near surface disposal performance assessment, on a monthly timescale, using the EDM family of distributions. As previously discussed, current methods rely on historical records, alone, to represent climate in the future. By evaluating the recordings and establishing a probability of occurrence for both temperature and precipitation, we attempt to create an approach that not only enables the ability to alter changes in average temperatures or increases in precipitation, but also is capable of producing data inputs for at least 100+ years. The approach is applied to two sites whose climate environments are very different, one semi-arid and the other humid. We discuss available empirical data and introduce the distributions used and their properties. The results and discussion are followed by concluding remarks.

Methodology

To study the different features of climatological distribution, the monthly precipitation and temperature data from two weather stations, in proximity to existing near-term surface disposal sites, were considered (Figure 2). Monticello, Utah is semi-arid, with an average annual precipitation of 412 mm and an average annual temperature of 7.8°C (Ho 2001). By contrast, New Brunswick, New Jersey is humid, with an average annual precipitation of 1,240 mm and an average annual temperature of 11.4°C (Rutgers University 2013). Table 1 shows other climate information for the two sites.

Figure 2: Station Location for Study Sites.

Table 1: Climate Summary for Sites Studied.

Statistic	New Brunswick, NJ	Monticello, UT
Annual average high temperature (°C)	16.9	14.7
Annual average low temperature (°C)	5.8	0.5
Average temperature (°C)	11.4	7.8
Average annual precipitation (mm)	1237	412

Sixty years (1950 to 2011) of daily precipitation and temperature data, maintained by the Utah State University Climate Center (weather station: Monticello 2E), and data collected from an onsite monitoring station at the Monticello near-surface disposal facility, provided the basis for generating monthly precipitation totals and average temperatures at the first site. Forty-four years (1968 to 2012) of daily precipitation and temperature, provided by Rutgers University (weather station: New Brunswick 3 SE NJ US), were utilized to generate monthly precipitation totals and average temperatures for the second site. Figures 3 and 4 display the results for the Monticello site; Figures 5 and 6 provide similar information for New Brunswick.

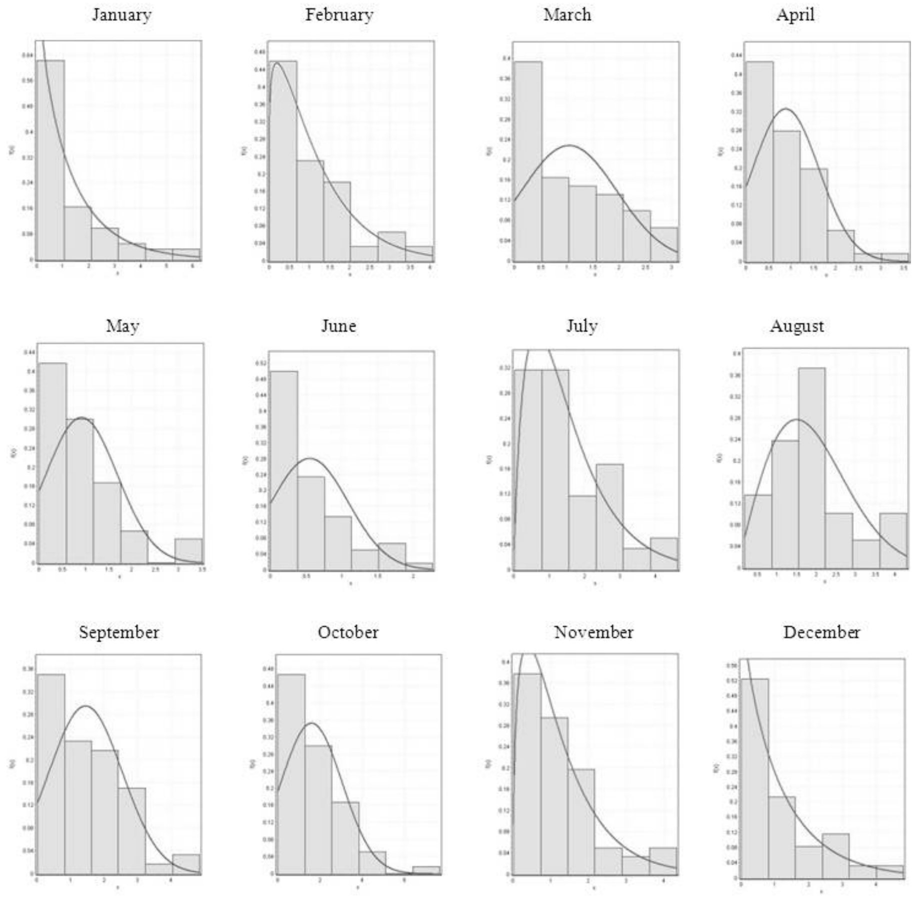


Figure 3: Monthly Precipitation Distribution for Monticello, Utah.

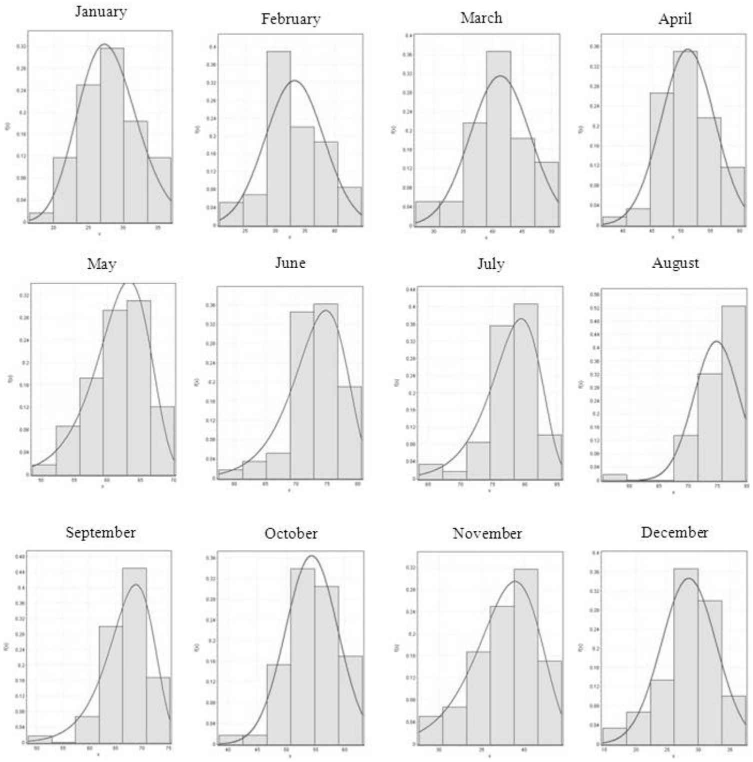


Figure 4: Monthly Temperature Distribution for Monticello, Utah.

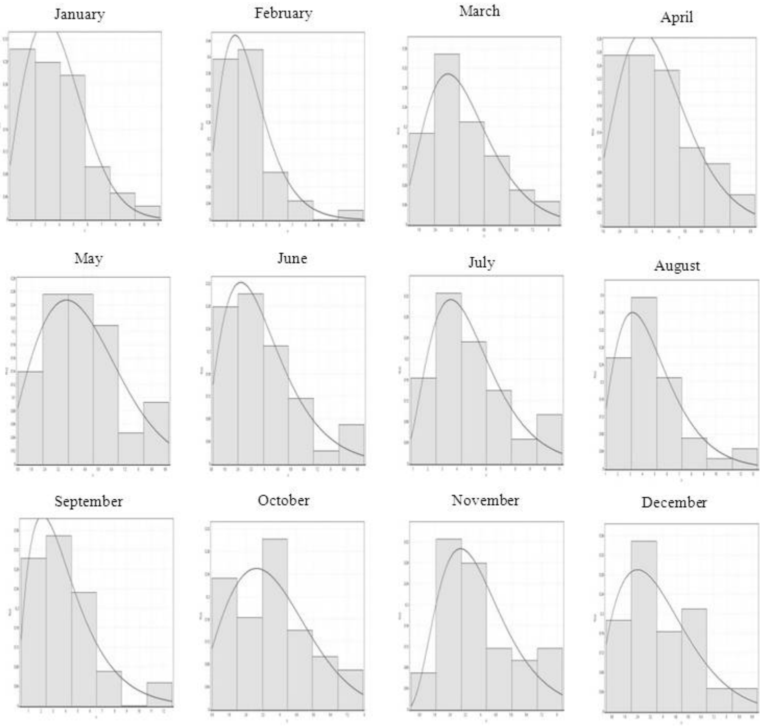


Figure 5: Monthly Precipitation Distribution for New Brunswick, New Jersey.

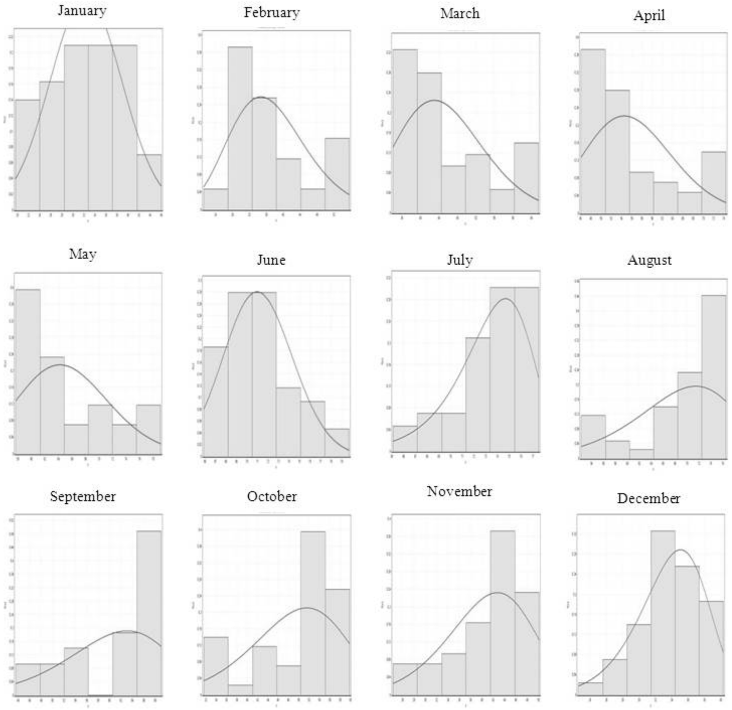


Figure 6: Monthly Temperature Distribution for New Brunswick, New Jersey.

EDM Distribution Properties

The EDM family includes the normal, gamma, exponential, chi-squared, Rayleigh, and Weibull distributions. This group provides a convenient general framework for which many statistical techniques can be applied (Jorgenson 1997). EDM probability functions have the following form:

$$f(y;\mu,\varphi) = a(y,\varphi)exp\left[\frac{1}{\varphi}\{y\theta - \kappa(\theta)\}\right]$$

where μ is the mean of the distribution, $\varphi > 0$ and the functions θ and $\kappa(\theta)$ are known. When considering EDMs, the mean is $\mu = d\kappa(\theta)/d\theta$ and the variance is $Var[y] = \varphi\ d^2\ \kappa\ (\theta)/d\theta^2$. The variance function characterizes the distribution in the class of EDMs.

Results and Discussion

Easy Fit, Version 5.5 was utilized to determine the best-fit distribution for monthly precipitation and temperature, Easy Fit provides data analysis and simulation software that enables the user to fit probability distributions to sample data, select the best model based on statistical fit, and apply analysis tools (e.g., a random number generator) to support further investigation (Mathwave Technologies 2010). The results for Monticello and New Brunswick are shown in Tables 7 and 8 for precipitation and temperature, respectively.

Table 2: Precipitation Probability Distribution Best Fit Results.

Month	**Probability Distribution Function** *Monticello, Utah*	**Probability Distribution Function** *New Brunswick, New Jersey*
January	Gamma	Rayleigh
February	Weibull	Gamma
March	Weibull	Gamma
April	Weibull	Gamma
May	Weibull	Rayleigh
June	Exponential	Gamma
July	Gamma	Gamma
August	Rayleigh	Gamma
September	Gamma	Gamma
October	Exponential	Rayleigh
November	Gamma	Gamma
December	Gamma	Weibull

Table 3: Temperature Probability Distribution Best Fit Results.

Month	**Probability Distribution Function** *Monticello, Utah*	**Probability Distribution Function** *New Brunswick, New Jersey*
January	Gamma	Weibull
February	Normal	Gamma
March	Normal	Chi-Squared
April	Normal	Gamma
May	Weibull	Gamma
June	Weibull	Gamma
July	Weibull	Weibull
August	Normal	Weibull
September	Weibull	Weibull
October	Normal	Weibull
November	Weibull	Weibull
December	Normal	Weibull

Easy Fit employs goodness-of-fit (GOF) tests to measure how well each candidate distribution fits the observed data and subsequently establishes rankings based on compatibility. While the Kolmogorov-Smirnov, Anderson-Darling, and Chi-Squared tests are supported, the Anderson-Darling test was selected for this analysis due to the small sample size (N=60) (Scholz 1987).

On the basis of the results from the two sites studied, the following observations are made. The Gamma distribution was selected as the best fit to the recorded data for the semi-arid and humid climates studied. The humid study site (New Brunswick) had the greatest variation in distributional forms for precipitation for each month (see Table 3). Both sites required at least three different distributional forms to characterize the precipitation data. When considering temperature for the semi-arid and humid climates studied, the Weibull distributional form was selected as the best fit (see Table 4). The semi-arid study site (Monticello) was the only location where temperature data fit best to the normal distributional form. This was seen in the months of

February, March, April, August, October, and December. Similar to precipitation data, both sites required three different distributional forms to characterize the monthly temperature data.

Concluding Remarks

The EDM family of distributions was considered for modeling monthly precipitation and temperature data in two different climate regions of the U.S. An approach was adopted to consider different distributions for each month. Under these conditions, it was shown that, when considering precipitation, the Gamma distribution fit the data most often at both sites. For temperature, the Weibull distribution was the best fit. It should be noted that in all cases, whether considering precipitation or temperature, at least three distributional forms were necessary to describe the data.

Our results indicate that the Gamma distribution is a logical distribution to select when modeling precipitation data in virtually any climate, a conclusion supported by previous studies. While research is limited in its support of the Weibull distribution as a logical choice in modeling temperature data, other studies indicate that temperature typically follows a normal distribution, that is quite similar in shape to the Weibull distribution (Negri 2005). The results also indicated that semi-arid climates with variable weather patterns experienced greater monthly variations in distribution fits. This evidence supports the idea that humid climates can be modeled using the same distribution for each month, while more arid climates may require multiple distributions. Additional research is needed to determine whether these findings are validated by studies of other semi-arid and humid sites.

The method presented in this paper establishes a probability of occurrence for both temperature and precipitation. Changes in average temperatures and increases in precipitation, important long-term features associated with climate, can be implemented by altering parameters of the selected probability distributions. In addition, the use of probability functions provides the ability to use random number generation which can produce data inputs of at least 100+ years. This approach will be used in future work that will apply hydrological modeling to simulate 100 years of near-surface disposal facility performance at a humid site.

CHAPTER III

SIMULATING COVER DEGRADATION ON RCRA LANDFILL PERFORMANCE

Abstract

The ability of near surface disposal facility cover designs to meet percolation performance criteria is influenced by degradation occurring over long periods of time. This study was conducted to determine the effect of degradation on percolation based on probabilistic distributions derived from historical climate data. Water balance predictions were evaluated using the HELP model, employing several variations of degradation in a traditional Resource Conservation and Recovery Act (RCRA) disposal facility cover design over a 100-year simulation period. Analysis results were evaluated relative to two different selected thresholds for annual percolation (1 mm and 3 mm). Approximately 20 percent of the results did not exceed both the 1 mm and 3 mm thresholds, while 10 percent of the realizations exceeded the 1 mm threshold but not the 3 mm threshold, with remaining cases exceeding the 3 mm threshold. These results demonstrate the importance of considering degradation in designing near surface disposal facilities, especially given the very long performance periods desired by different regulators.

Introduction

Performance Assessments

The Department of Energy (DOE) is responsible for the cleanup of nuclear waste at former nuclear weapons sites across the United States (U.S.). The sites actively produced nuclear weapons components and assembled nuclear weapons from the 1940s through the end of the Cold War (U.S. Environmental Protection Agency [EPA] 1989). The Agency's Office of Environmental Management currently oversees environmental restoration activities at more than 80 of these sites. Cleanup activities include decontamination and demolition of buildings, management of contaminated soils and groundwater, containment of radioactive and hazardous chemical waste materials in near surface disposal facilities (e.g., landfills, trenches and vaults), treatment and stabilization of liquid radioactive wastes, and disposal of nuclear materials (EPA 1989).

Given the abundance of sites across the U.S. and the potential variability in operational management at each location, DOE introduced Order 435.1, *Radioactive Waste Management*, in 1999. The order established guidelines for the management of DOE high-level waste, transuranic waste, low-level waste, and the radioactive component of mixed waste (DOE 1999). A manual was created to catalog procedural requirements and existing practices that would ensure that all DOE entities and contractors managed DOE's radioactive waste in a manner that was protective of worker and public health and safety, and the environment. DOE Order 435.1 also states that performance objectives should be evaluated for a 1,000-year period to determine potential risk impacts to the public and environment. As defined by the manual, a performance assessment is, "an analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives established for the long-term protection of the public and the environment will not be exceeded following closure of the facility" (DOE 1999). While the performance assessment requires uncertainty analyses, it is unclear whether there are requirements to address important long-term features, events, and processes at sites that may contribute to the risk of groundwater contamination and human exposure (Arnold 2001). One long-term event that has risen to the forefront in the research community is climate change effects that stem from anthropogenic forcing and naturally occurring climatic mechanisms.

Modeling Approaches

Traditional design guidelines for disposal facility covers often rely on deterministic models of flow and transport processes that neglect the effects of increases in average temperatures or the occurrence of more frequent and extreme weather conditions (Arnold 2001). While it is impossible to validate the long-term disposal facility cover performance (100+ years) of existing models at this time, this research explores and compares model results when climate change effects are considered over a 100-year period.

Instrumentally-based analogues are used most often in deterministic modeling. Typically, records are examined from initial instrumentation recording until the present. Common weather patterns are identified as well as extreme occurrences (e.g., wettest year). These extreme events serve as a worst case scenario and are used as "design year" conditions. While altering the soil hydraulic properties to resemble effects from extreme occurrences may provide a glimpse into the performance of the disposal facility, modeling only one year of worst-case scenario conditions is unrealistic in determining the long-term performance of a facility.

Research Objectives

This paper explores methods to implement degradation in a cover designed in accordance with RCRA requirements. Precipitation and temperature input data are created using a Monte Carlo approach that considers various weather conditions. In addition, cover performance is evaluated based on percolation rates achieved over a 100-year simulation period. Of particular concern is degradation in the synthetic geomembrane layer as well as degradation in the compacted soil liner, since these layers provide limited opportunity, if any, for repair after closure.

Methodology

Monte Carlo Method

Monte Carlo methods are designed to generate random inputs from a probability distribution over a domain of possible values. Figure 7 displays a process diagram utilizing a Monte Carlo approach. Below is a discussion of how this method was employed.

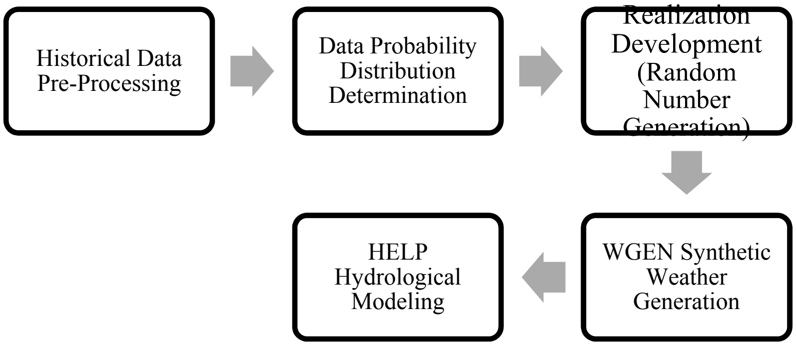


Figure 7: Analysis Methodology.

Historical Meteorological Data

To study the different features of climatological distribution, monthly precipitation and temperature data from New Brunswick, New Jersey were taken as a case study. Climate at this location is humid, with an average annual precipitation of 1,240 mm and an average annual temperature of 11.4 °C (Rutgers University 2013). Forty-four years (1968 to 2012) of daily precipitation and temperature data from the New Brunswick weather station (New Brunswick 3 SE NJ US) were aggregated into monthly sums and averages. Figures 8 and 9 display examples of these distributions for precipitation and temperature, respectively, for the month of January.

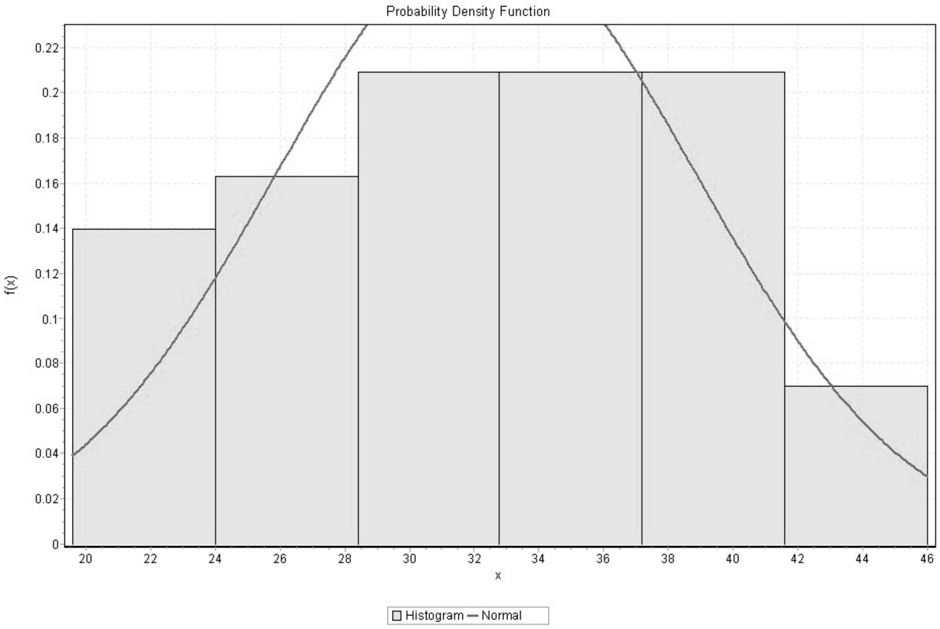


Figure 8: New Brunswick, NJ Precipitation Histogram – January.

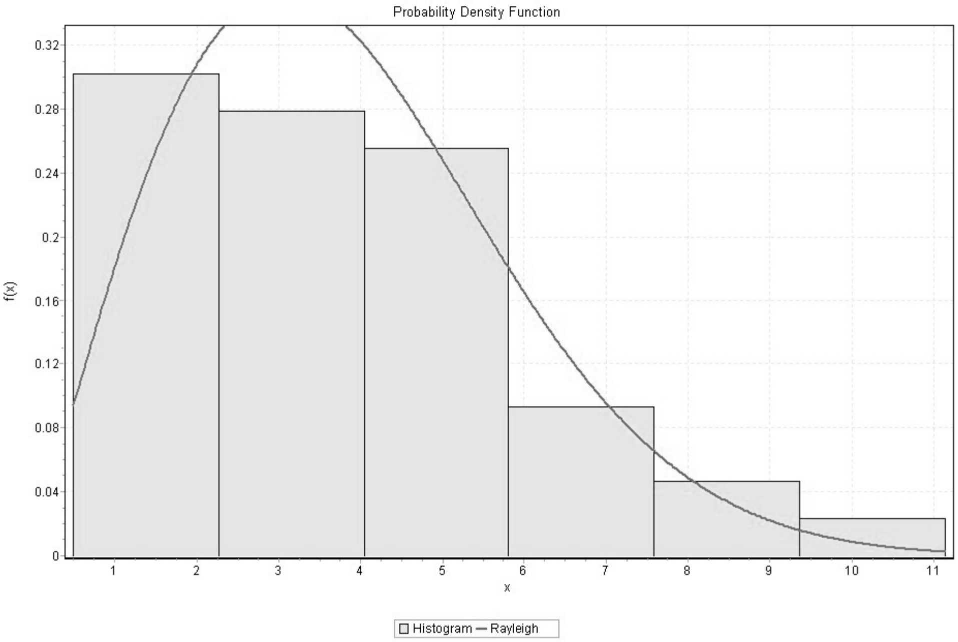


Figure 9: New Brunswick, NJ Temperature Histogram - January.

Probability Distribution Determination

There are several probability distributions that can be considered in parameterizing rainfall distributions, when estimating parameters based on a limited number of data points (Husak 2007). Many studies have suggested that when considering monthly data, a special class of distributions, the exponential dispersion model (EDM) family, should be used (Hasan and Dunn 2011). EDMs are the response distributions for generalized linear models (GLMs) that have been utilized by numerous researchers to fit models to climatological data such as rainfall (Coe and Stern 1982; Wilks 1999; Chandler 2005; Worthy et al. 2013). In addition, different approaches have incorporated the fitting of particular distributions for each month. Hasan and Dunn (2011) explored the possibility that different distributions are appropriate for each month, and concluded that this is a reasonable approach. The approach adopted herein is to fit the data to the EDM family of distributions, while allowing a different form for each month of precipitation and temperature.

Using Easy Fit 5.5, each of the 24 precipitation and temperature frequency histograms were fit to the normal, gamma, exponential, chi-squared, Rayleigh and Weibull distributions. Easy Fit 5.5 is a data analysis and simulation application that enables the user to fit probability distributions to sample data, select the best model based on statistical criterion, and apply analysis tools (e.g., Random Number Generator) to further investigate data characteristics (Mathwave Technologies 2010). Easy Fit implores goodness of fit (GOF) tests to measure the compatibility of the precipitation and temperature data with several theoretical probability distribution functions. The following GOF tests are supported: Kolmogorov-Smirnov, Anderson-Darling, and Chi-Squared. In this analysis, the Anderson-Darling test was selected due to the small sample size (n=44). Exhibit 4 lists the probability distribution that demonstrates the best fit for each month for both precipitation and temperature, respectively.

Table 4: Best Fit Probability Distribution Functions

Month	**Probability Distribution Function** *Precipitation*	**Probability Distribution Function** *Temperature*
January	Rayleigh	Weibull
February	Gamma	Gamma
March	Gamma	Chi-Squared
April	Gamma	Gamma
May	Rayleigh	Gamma
June	Gamma	Gamma
July	Gamma	Weibull
August	Gamma	Weibull
September	Gamma	Weibull
October	Rayleigh	Weibull
November	Gamma	Weibull
December	Weibull	Weibull

Realization Development

Parameters describing each respective distribution were fed into the Easy Fit random number generator function. One hundred random numbers were generated for average temperature and total precipitation for each month, creating 100 realizations. A synthetic weather generator was applied to generate 100 years of daily inputs from these values. This resulted in the creation of 100 realizations, each comprised of a simulation covering a 100-year performance period.

WGEN Synthetic Weather Generation

A stochastic weather generator is a numerical model that generates a synthetic daily time series of a set of climate variables (e.g., precipitation, temperature, and solar radiation) with specific statistical properties (Richardson 1981, Richardson and Wright 1984, Racsko et al. 1991). Weather Generator (WGEN), used in this research, generates daily values of temperature, precipitation, and solar radiation by analyzing certain statistical properties of observed monthly weather data for a selected site and uses these properties, along with a pseudo-random number generator, to produce daily simulated weather data. The generator specifies daily probability distributions for each weather variable as well as statistical relationships between the variables. The observed weather data are used to define the parameters of the probability distributions and the correlation coefficients between the variables. Semenov et al. (1998) evaluated the use of WGEN at 18 sites in the US, Europe, and Asia. Statistical tests were performed to compare different weather characteristics of the observed and synthetic weather data (e.g., length of wet and dry series, distribution of precipitation, and length of frost spells). While WGEN did not use complex distributions for weather variables that would have matched the observed data more closely, it performed as well as other available generators. The study also noted that the accuracy required for each variable will vary according to the sensitivity of the application in which the data are used, making confidence in observed inputs important.

Hydrological Modeling

Many hydrologic models exist that are used to determine the performance of disposal facility cover systems. UNSAT-H is a one-dimensional, unsaturated soil-water and heat flow model based on Richard's Equation that contains transpiration, thermal, and isothermal vapor flow models in addition to a range of hydraulic functions. The UNSAT-H model was developed at Pacific Northwest National Laboratory to assess the water dynamics of arid sites and, in particular, estimate recharge fluxes for scenarios pertinent to waste disposal facilities (Fayer 2000). Hydrus-1D is a one-dimensional finite element model based on Richard's Equation that is used for the analysis of water flow and solute transport in variably saturated porous media (Simuek et al. 2009). Like UNSAT-H, Hydrus-1D accounts for transpiration and permits various hydraulic functions. Further discussion of these models can be found in Orgorzalek et al. (2008) and Bohnhoff et al. (2009).

In this work, predictions from the Hydrologic Evaluation of Landfill Performance (HELP) model were used to study percolation rates at a hypothetical RCRA landfill in the study area (New Brunswick, New Jersey). HELP was chosen because of its specificity to landfills, as well as its capability to simulate hydrological processes repetitively for many years. HYDRUS-1D and UNSAT-H are limited in this regard. HELP, a water routing model, requires the input of meteorological, vegetation and landfill design data, and provides estimates of runoff, evapotranspiration (ET), lateral drainage, vertical percolation (i.e., infiltration), hydraulic head, and water storage for the evaluation of various landfill designs. Additional inputs for HELP include the Soil Conservation Service curve number, which is used to estimate runoff. A detailed discussion of HELP water balance calculation methods can be found in Shroeder et al. (1994). A traditional RCRA design was evaluated in this study (Figure 10) and Table 5 shows values for vegetative input used to calculate ET estimates obtained from the model.

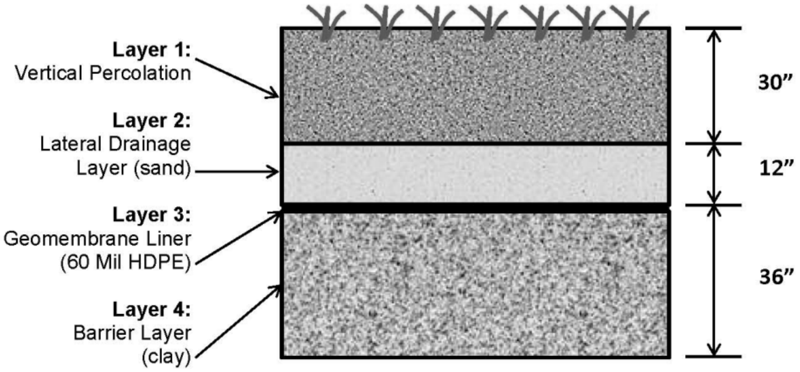


Figure 10: RCRA Landfill Design.

Table 5: HELP Vegetative Properties

Input Parameter		Value
Evaporative Zone Depth (in)		18
Max Leaf Area Index (LAI)		1.00
Growing Season	Start - DOY	109
	End - DOY	299
Average Wind Speed (mph)		10.2
Average Relative Humidity (%)	1st Quarter	64
	2nd Quarter	61
	3rd Quarter	66
	4th Quarter	68

Degradation of Saturated Hydraulic Conductivity

Shroeder et al. (1994) note that HELP assumes Darcian flow for vertical drainage through homogeneous, temporally uniform soil and waste layers. HELP does not consider preferential flow through channels such as cracks, root holes, or animal burrows. As such, the model will tend to overestimate the storage of water during the early part of the simulation. However, the effects of these limitations can be minimized by modifying various hydraulic inputs. In this research, a larger effective saturated hydraulic conductivity was used to simulate the degradation previously described. Layers of particular concern are the geomembrane synthetic liner (layer 3) and the compacted soil liner (layer 4).

Eight variations in saturated hydraulic conductivity for layers 3 and 4 were created by successively increasing the baseline values by four orders of magnitude. These values are consistent with hydraulic conductivities present in the natural environment (see Figure 11). Table 6 shows the eight values as well as the baseline value. A total of 25 design combinations were possible when varying each saturated hydraulic conductivity (including the baseline design), creating a total of 2,500 realizations of 100 years.

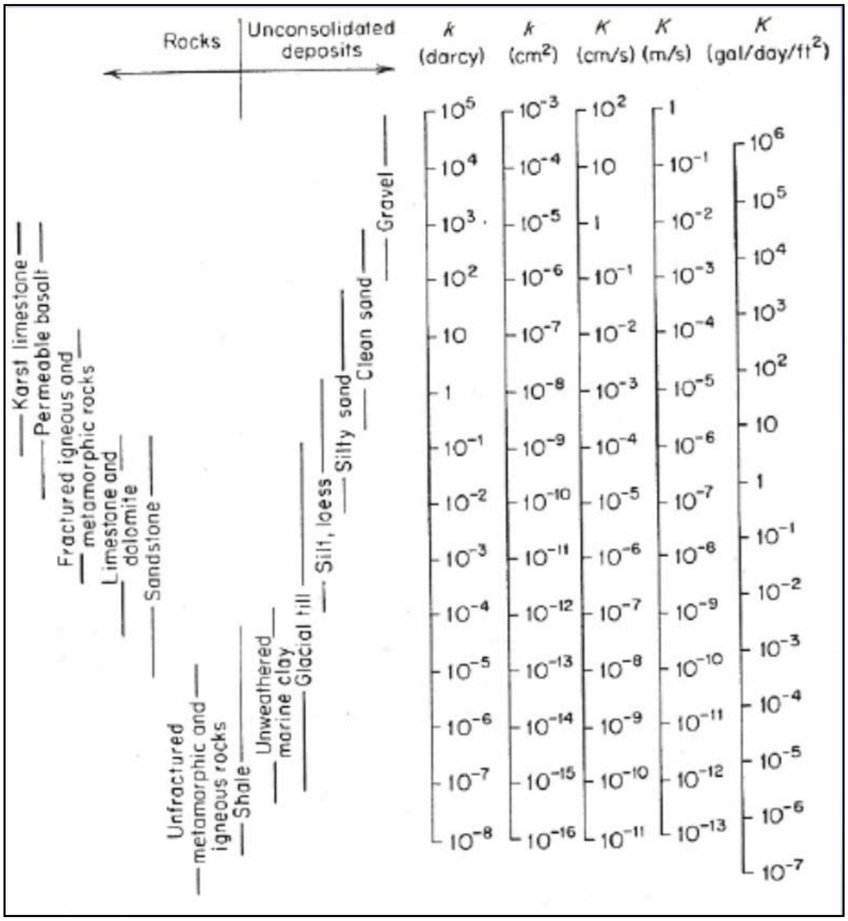


Figure 11: Hydraulic Conductivity and Permeability (Freeze and Cherry 1979).

Table 6: Saturated Hydraulic Conductivity Values (cm/sec).

	Layer 3	Layer 4
Baseline Value	2.00E-13	1.00E-07
Step 1	2.00E-12	1.00E-06
Step 2	2.00E-11	1.00E-05
Step 3	2.00E-10	1.00E-04
Step 4	2.00E-09	1.00E-03

Results and Discussion

Each 100-year realization was examined to determine the average annual percolation for the simulation period. This included an assessment of whether percolation met or exceeded a 1 mm and 3 mm threshold, respectively. Below is a detailed discussion of the analysis results.

P-P Plot

Figure 12 presents a probability-probability (P-P) plot of the percolation results. This graph plots the empirical cumulative distribution function (CDF) values against theoretical CDF values. It is used to determine how well a specific distribution fits to the observed data. This plot will be approximately linear if the specified theoretical distribution is the correct model. The theoretical distributions examined are the normal, gamma, and Weibull distributions. As seen, the data are approximately linear for all three distributions, but the normal distribution follows more closely to the empirical values.

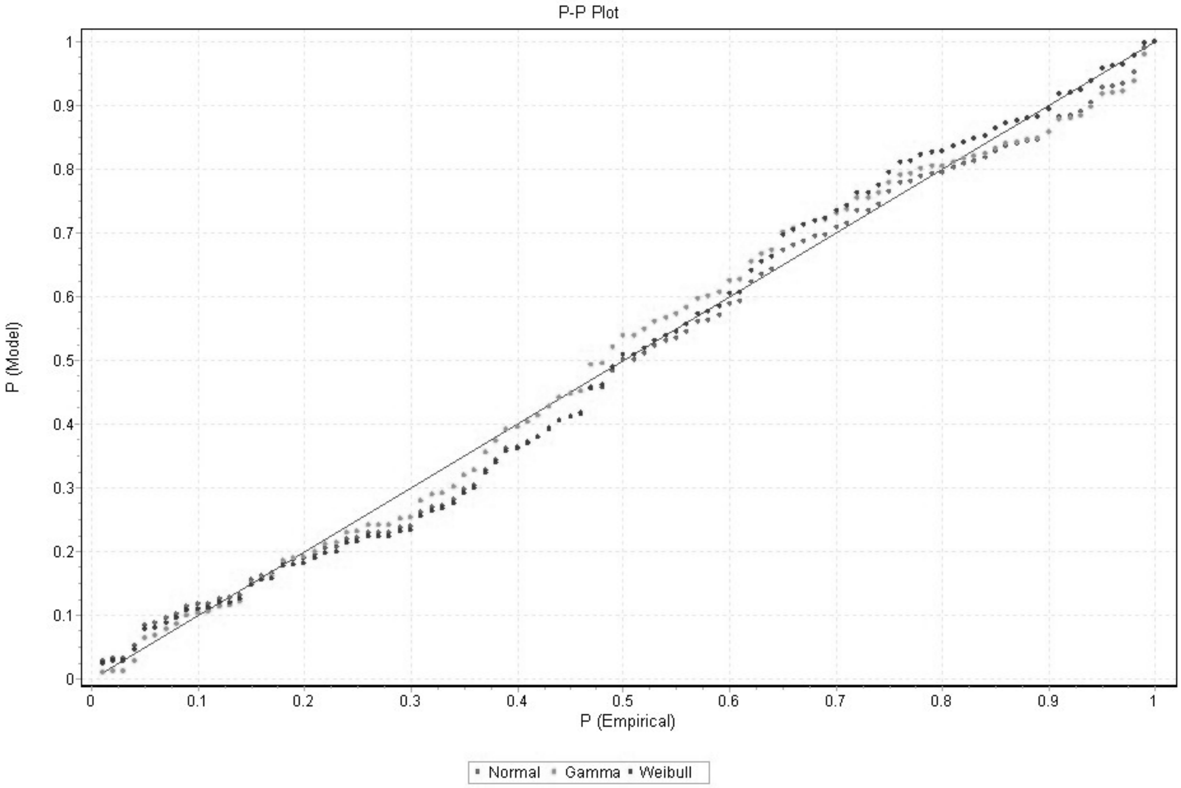


Figure 12: P-P Plot of Percolation Results.

Exceedance Thresholds

As previously mentioned, a total of 2,500 realizations were simulated, producing average annual percolation results for each realization. Approximately 20 percent of the results did not exceed both the 1 mm and 3 mm thresholds, 10 percent exceeded the 1 mm threshold but did not exceed the 3 mm threshold, and the remainder exceeded the 3 mm threshold. In addition to evaluating threshold exceedance, this criterion was examined to determine the effects of degradation in Layers 3 and 4. Figures 13 and 14 show the percentage of realizations exceeding both thresholds for Layers 3 and 4 baseline conditions, respectively, at various points of degradation. By contrast, Figures 15 and 16 show these results at the other end of the analysis spectrum. Note that Figure 15 shows percolation exceedance at the 1 mm and 3 mm thresholds when Layer 3 is constant at the 10^{-9} centimeters per second (cm/sec) saturated hydraulic conductivity. All results exceed both thresholds, indicating that regardless of the condition of the other design layers, when the geomembrane liner reaches that specified saturated hydraulic conductivity, the performance of the entire cover design system is compromised. This finding also applies when Layer 4, the compacted soil liner, reaches 10^{-3} cm/sec (Figure 16).

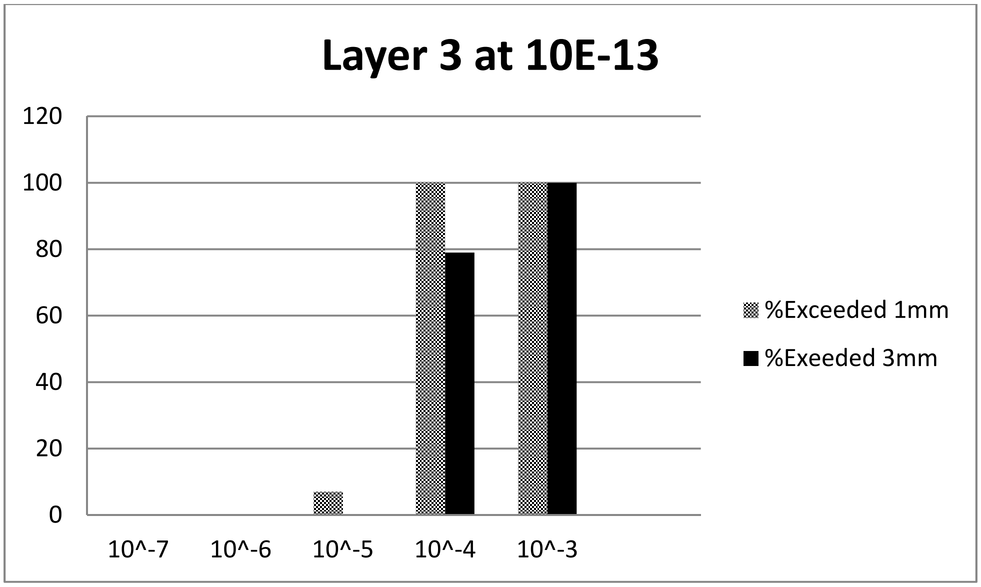


Figure 13: Layer 3 Constant at 10E-13.

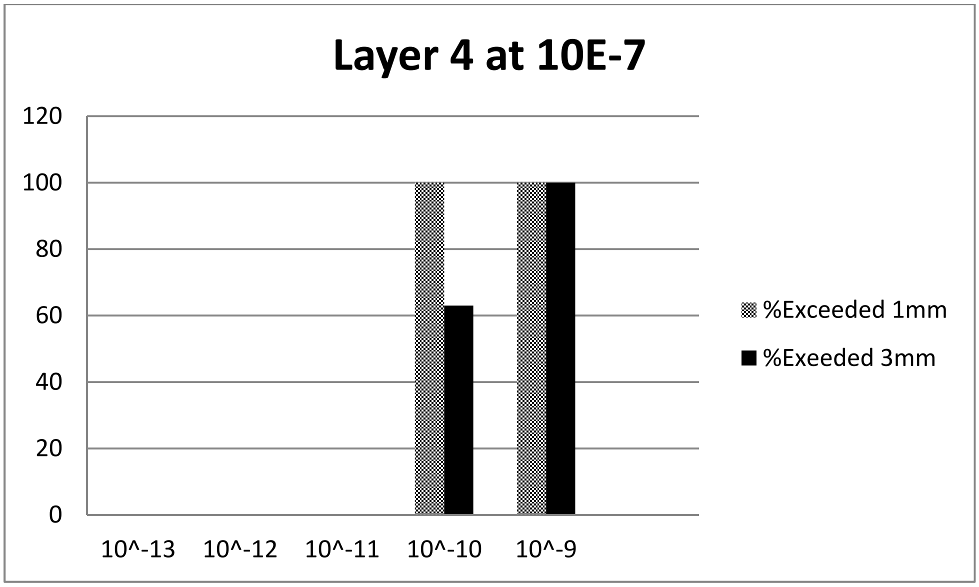


Figure 14: Layer 4 Constant at 10E-7.

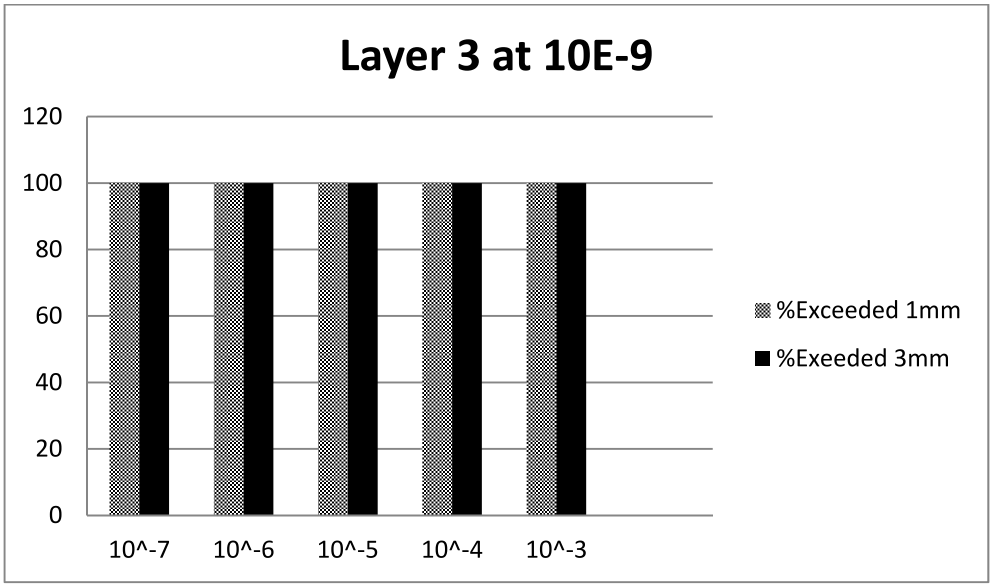


Figure 15: Layer 3 Constant at 10E-9.

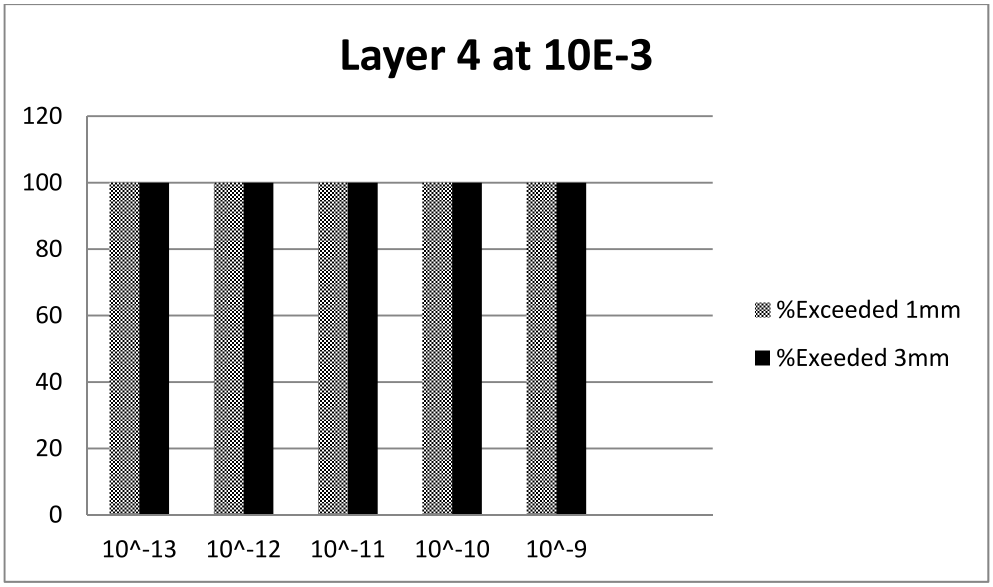
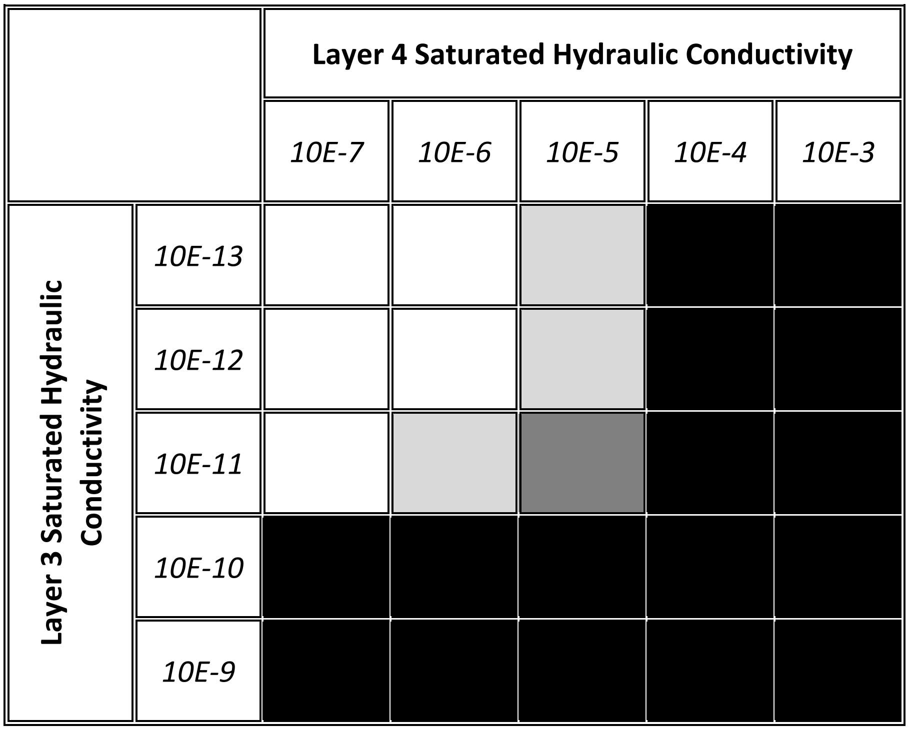


Figure 16: Layer 4 Constant at 10E-3.

Performance Threshold Heat Maps

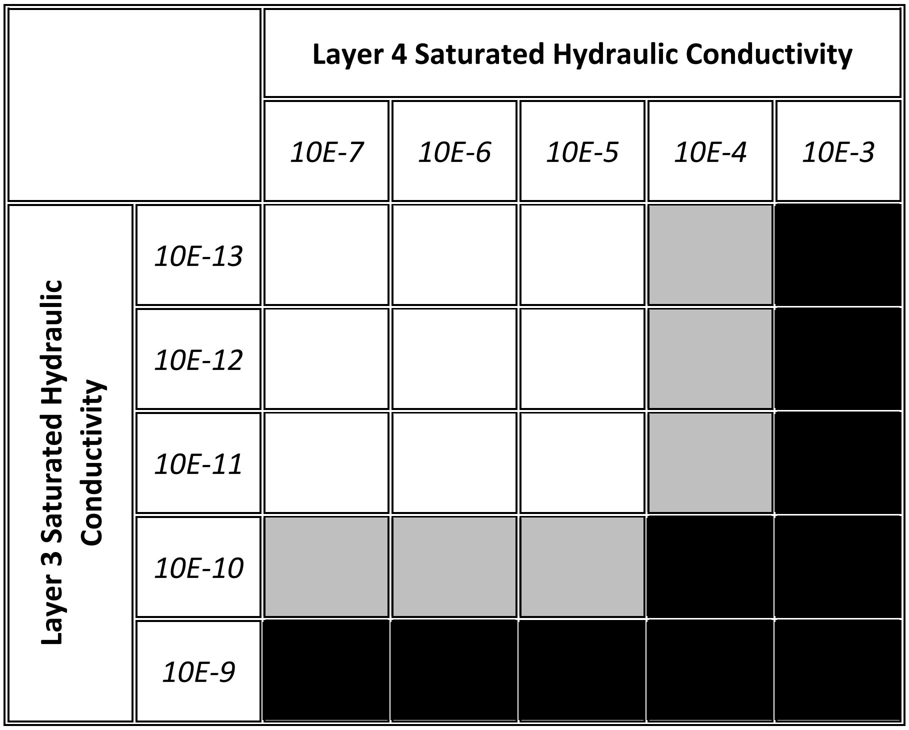
Establishing the previously presented performance thresholds can be beneficial when saturated hydraulic conductivities are considered. Figures 17 (1 mm) and 18 (3 mm) are “heat” maps constructed from the results of this study. Saturated hydraulic conductivities producing 100 percent of percolation results less than both thresholds are denoted in “white”. If less than 50 percent of the percolation rates exceeded the designated threshold the mapping is “light gray”. If greater than 50 percent of the percolation rates exceeded the designated threshold the mapping is “dark gray”. Designs where 100 percent of percolation results exceed the designated threshold are denoted in “black”. As previously discussed, the majority of the percolation results are within the “black” mapping region. These charts help identify where the saturated hydraulic conductivities for the specified layers approach the brink of exceedance. For example, the results suggest that designers should be cautious when using a saturated hydraulic conductivity of 10^{-11}

cm/sec for Layer 3 and 10^{-5} cm/sec for Layer 4 when considering the 1 mm threshold and 10^{-10} cm/sec for Layer 3 and 10^{-4} for Layer 4 when considering the 3 mm threshold.



		Layer 4 Saturated Hydraulic Conductivity				
		10E-7	*10E-6*	*10E-5*	*10E-4*	*10E-3*
Layer 3 Saturated Hydraulic Conductivity	*10E-13*	⬜	⬜	░	⬛	⬛
	10E-12	⬜	⬜	░	⬛	⬛
	10E-11	⬜	░	▓	⬛	⬛
	10E-10	⬛	⬛	⬛	⬛	⬛
	10E-9	⬛	⬛	⬛	⬛	⬛

Figure 17: 1 mm Performance Threshold Heat Map



		Layer 4 Saturated Hydraulic Conductivity				
		10E-7	*10E-6*	*10E-5*	*10E-4*	*10E-3*
Layer 3 Saturated Hydraulic Conductivity	*10E-13*	□	□	□	▨	■
	10E-12	□	□	□	▨	■
	10E-11	□	□	□	▨	■
	10E-10	▨	▨	▨	■	■
	10E-9	■	■	■	■	■

Figure 18: 3 mm Performance Threshold Heat Map

Concluding Remarks

Numerical modeling of landfill performance over long periods of time has demonstrated that incorporating degradation into the modeling methodology can have significant impacts on percolation rates. The methodology itself has created a process by which near surface design can more appropriately consider saturated hydraulic conductivities and performance thresholds. These developments and findings can have important implications on future regulatory policies and performance assessment guidelines.

CHAPTER IV

DEVELOPMENT OF ANTHROPOGENIC CLIMATE CHANGE SCENARIOS

Abstract

The ability of near surface disposal facility cover designs to meet percolation performance criteria can be influenced by naturally occurring climatic mechanisms as well as anthropogenic forcing. This study was conducted to determine the effect of climate-induced events on percolation based on probabilistic distributions derived from historical climate data. Water balance predictions were evaluated using the HELP model, employing several variations of degradation in a traditional RCRA disposal facility cover design over a 100-year simulation period. Results demonstrated that changes in precipitation and temperature can influence performance. The analysis also revealed that when both precipitation and temperature are increased, warmer temperatures tend to offset some of the impact from greater precipitation.

Introduction

The Department of Energy (DOE) is responsible for the environmental restoration at former nuclear weapons sites across the United States (U.S.). Given the abundance of sites across the U.S. and the potential variability in waste and site specific environments at each location, DOE requires an uncertainty analysis in which important long-term features, events, and processes can be assessed to determine applicable risks associated with groundwater contamination and potential human exposure. One long-term event that has risen to the forefront of consideration is climate change effects that stem from naturally occurring climatic mechanisms as well as anthropogenic forcing.

Significant climate changes that include rises in temperature and variation in precipitation patterns are anticipated (Solomon 2007). Early stages of these effects are already being experienced. While the entire U.S. could be impacted by climate change, the extent to which certain effects are prevalent will occur on a regional basis. Therefore, any approach to understanding how climate change will affect environmental performance must be performed at a regional level using numerical models that assess the design integrity of disposal facilities, as well as their performance and post-closure monitoring. These models include parameters representing temperature and precipitation. This research described herein explores the extent to which temperature and precipitation are important to disposal facility cover performance.

Traditional design guidelines for disposal facility covers often rely on deterministic models of flow and transport processes that neglect the effects of increases in average temperatures or the occurrence of more frequent and extreme weather conditions (Arnold 2001). Instrumentally-based historical data is used most often in deterministic modeling. Typically, records are examined from initial instrumentation recording until the present. Common weather patterns are identified as well as extreme occurrences (e.g., wettest year). These extreme events serve as worst case scenarios and are used as “design year” conditions. While altering the soil hydraulic properties to simulate effects from extreme occurrences may provide a glimpse into the performance of the disposal facility, we believe that modeling only one year of worst case scenario conditions is unrealistic in determining the long-term performance of a facility.

Worthy et al. (2013) adopted a Monte Carlo approach that not only varies soil hydraulic properties, but also uses a probabilistic method that creates 100 years of climate data. In this study, water balance predictions were evaluated using the Hydrologic Evaluation of Landfill Performance (HELP) model, employing several variations of degradation in a traditional RCRA disposal facility cover design over a 100-year simulation period. The exponential dispersion model (EDM) family of distributions was used to categorize precipitation and temperature. EDMs are the response distributions for generalized linear models (GLMs) that have been utilized by several researchers to fit models to climatological data such as rainfall (Coe and Stern 1982; Wilks 1999; Chandler 2005; Worthy et al. 2013). Parameters describing each respective distribution were used to create 100 random values of average temperature and total precipitation for each month, creating 100 realizations. A synthetic weather generator was applied to produce 100 years of daily inputs from these values. This resulted in the creation of 100 realizations, each comprised of a simulation covering a 100-year performance period. Predictions using the HELP model were used to study percolation rates at a hypothetical RCRA landfill located in the northeast climate region of the U.S. (Shroeder 1994). These realizations were then applied to eight variations in saturated hydraulic conductivity, creating a total of 2,500 realizations of 100 years. Each 100-year realization was examined to determine whether average annual percolation met or exceeded a 1 mm and 3 mm threshold[1]. Results demonstrated the importance of considering degradation in designing near surface disposal facilities, especially given the very long performance periods desired by regulatory agencies (Benson 2011).

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[1] The 1 mm threshold was selected based on Draft EPA cover system guidance for municipal solid waste landfills, which states that maximum cover system percolation rates of 0.1 to 1 mm/yr should prevent the bathtub effect. The 3 mm threshold was selected arbitrarily as an alternative to the EPA guidance.

This paper is an extension of the aforementioned study. We explore methods to evaluate the effects of future climate change by altering the fitting parameters of probability distributions used for temperature and precipitation. Cover performance is evaluated based on percolation rates achieved over a 100-year simulation period. Percolation threshold exceedances are measured to assess performance as different climate scenarios are evaluated.

Methodology

Data

Monthly precipitation and temperature data were used as input to a hypothetical near surface disposal facility located in New Brunswick, New Jersey[2]. The model facility featured the EPA RCRA design. Climate at this location is humid, with an average annual precipitation of 1,240 mm and an average annual temperature of 11.4 °C (Rutgers University 2013). Forty-four years (1968–2012) of daily precipitation and temperature data from the New Brunswick weather station (New Brunswick 3 SE NJ US) were aggregated into monthly totals and averages, respectively, creating twenty-four precipitation and temperature frequency histograms. The monthly data was fit to the normal, gamma, exponential, chi-squared, Rayleigh and Weibull distributions, where the Anderson-Darling Goodness of fit test was used due to the small sample size (n=44). These distributions, for both precipitation and temperature, were employed to generate 100 random monthly values for each of the months in a calendar year. These values served as the basis for input into selected scenarios

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[2] New Brunswick, New Jersey is located in the northeastern region of the U.S., where climate is characterized by humid, warm summers and cold winters with moderate to considerable rainfall throughout the year.

Scenario Development

When establishing future temperature and precipitation scenarios to consider, it is important to investigate how climate will be impacted by anthropogenic forcing. The *Global Climate Change Impacts in the United States* report was used for this analysis and projections are discussed below (Karl 2009).

The annual average temperature in the Northeast region has increased by 2°F since 1970. Winter temperatures have risen by twice this amount. The Northeast is projected to face other climate-related changes, such as more frequent days with temperatures above 90°F, more frequent and intense precipitation, and winter precipitation falling less as snow and more as rain. In order to replicate these conditions in a hydrological modeling environment, our methodology utilized an approach that altered averages, obtained from probability distributions, for both temperature and precipitation. This had the effect of changing fitting parameters and consequently the randomly generated values. Five specific future climate scenarios were defined according to this approach (see Table 7).

Table 7: Climate Change Scenario Descriptions

Scenario	**Precipitation**	**Temperature**	**Realizations**
Base Case	Precipitation conditions representative of past 44 years.	Temperature conditions representative of past 44 years.	2,500
Scenario 1	Similar to base case.	10% increase in average temperatures over base case.	2,500
Scenario 2	10% increase in precipitation averages over base case.	Similar to Scenario 1.	2,500
Scenario 3	Similar to Scenario 2.	Similar to base case.	2,500
Scenario 4	25% increase in precipitation averages over base case.	Similar to base case.	2,500
Scenario 5	Similar to Scenario 4.	Similar to Scenario 1.	2,500

It should be noted that no scenarios were developed involving large increases (25%) in temperature. Such an increase would create values outside of the range of the aforementioned

2°F increase over a 40 year period. No decreases in precipitation or temperature were considered due to the absence of such climate change forecasts in the study area. Percentage increases were arbitrarily selected to test the sensitivity of the approach adopted. A more refined analysis would require use of more regionally specific general circulation models that provide projections for increases in both temperature and precipitation (Solomon 2007).

Hydrological Modeling

In this work, predictions from the HELP model were used to study percolation rates at a hypothetical RCRA landfill in the study area. HELP was selected because of its specificity to landfills, as well as its capability to simulate hydrological processes repetitively for many years. A water routing model, HELP requires the input of meteorological, vegetation and landfill design data, and provides estimates of runoff, evapotranspiration, lateral drainage, vertical percolation (i.e., infiltration), hydraulic head and water storage relative to a specified landfill design. An additional input for HELP is the Soil Conservation Service curve number, which is used to estimate runoff. A detailed discussion of HELP water balance calculation methods can be found in Shroeder et al. (1994).

A traditional RCRA design was evaluated in this study (Figure 19) and Table 8 shows values for vegetative input used to calculate evapotranspiration (ET) estimates. Because HELP does not consider preferential flow through channels such as cracks, root holes or animal burrows, eight variations in saturated hydraulic conductivity for Layers 3 and 4 were defined by successively increasing the baseline values by four orders of magnitude, respectively.

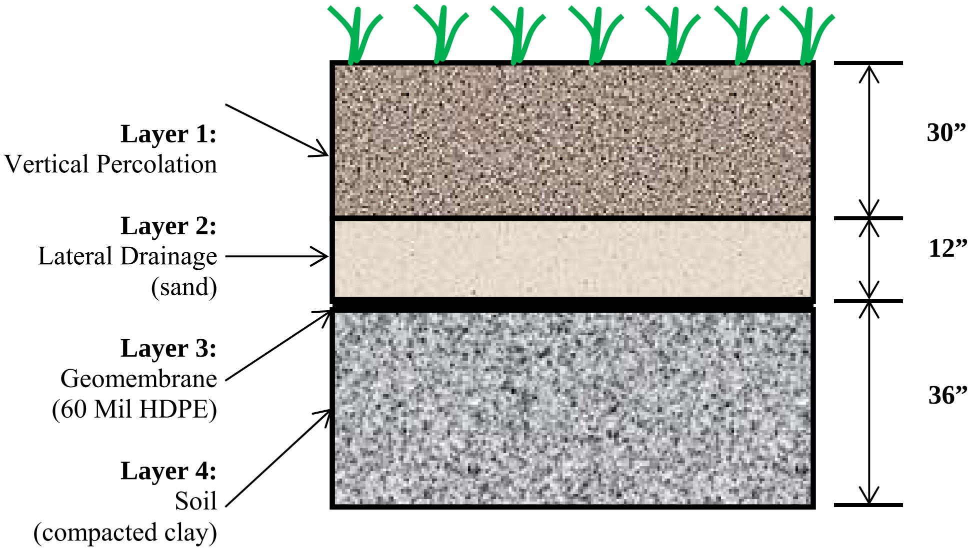


Figure 19: RCRA Disposal Facility Design

Table 8: HELP Input Specific to the Vegetated Soil Cover Layer (the top of the cover)

Input Parameter		Value
Evaporative Zone Depth (in)		18
Max Leaf Area Index (LAI)		1.00
Growing Season	Start – day-of-year	109
	End – day-of-year	299
Average Wind Speed (mph)		10.2
Average Relative Humidity (%)	1st Quarter	64
	2nd Quarter	61
	3rd Quarter	66
	4th Quarter	68

Results and Discussion

All 2,500 realizations for each scenario were examined to determine the average annual percolation for the simulation period (Table 9). Results were found to be statistically significant when compared to the base case (two sample t-test, p=0.0025). The least amount of percolation was predicted (1.08E-03 inches) when Layer 3 saturated hydraulic conductivity was modeled at 2.00 E-13 cm/sec and Layer 4 at 1.00E-07 cm/sec under Base Case conditions. The greatest amount of percolation occurred (2.48 inches) when the saturated hydraulic conductivity of Layer 3 was modeled at 2.00E-09 cm/sec and Layer 4 at 1.00E-03 cm/sec under Scenario 4 conditions. Generally, as precipitation increased, average annual percolation increased. In some instances, when both precipitation and temperature increased, warmer temperatures tended to offset some of the impact from greater precipitation. An assessment of whether percolation met or exceeded 1 mm and 3 mm thresholds, respectively, is the subject of a separate discussion to follow.

Table 9: Average Annual Percolation Results

Saturated Hydraulic Conductivity (cm/sec)		**Average Annual Percolation (inches)**					
Layer 3	**Layer 4**	**Base Case**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
2.00E-13	1.00E-06	5.32E-03	5.34E-03	5.88E-03	5.79E-03	7.49E-03	7.43E-03
2.00E-12	1.00E-06	6.53E-03	6.57E-03	7.24E-03	7.13E-03	9.25E-03	9.17E-03
2.00E-11	1.00E-06	1.87E-02	1.88E-02	2.08E-02	2.04E-02	2.68E-02	2.65E-02
2.00E-10	1.00E-06	1.38E-01	1.39E-01	1.54E-01	1.51E-01	1.99E-01	1.97E-01
2.00E-09	1.00E-06	1.17E+00	1.17E+00	1.30E+00	1.28E+00	1.66E+00	1.65E+00
2.00E-13	1.00E-05	2.86E-02	2.87E-02	3.16E-02	3.11E-02	4.02E-02	3.99E-02
2.00E-13	1.00E-04	1.54E-01	1.55E-01	1.71E-01	1.68E-01	2.17E-01	2.15E-01
2.00E-13	1.00E-03	7.90E-01	7.90E-01	8.70E-01	8.59E-01	1.10E+00	1.10E+00
2.00E-13	1.00E-07	1.08E-03	1.08E-03	1.19E-03	1.17E-03	1.52E-03	1.51E-03
2.00E-12	1.00E-05	2.98E-02	2.99E-02	3.30E-02	3.24E-02	4.20E-02	4.16E-02
2.00E-12	1.00E-04	1.56E-01	1.56E-01	1.72E-01	1.69E-01	2.19E-01	2.17E-01
2.00E-12	1.00E-03	7.92E-01	7.91E-01	8.71E-01	8.61E-01	1.10E+00	1.10E+00
2.00E-12	1.00E-07	2.29E-03	2.31E-03	2.56E-03	2.51E-03	3.28E-03	3.25E-03
2.00E-11	1.00E-05	4.19E-02	4.22E-02	4.65E-02	4.57E-02	5.94E-02	5.89E-02
2.00E-11	1.00E-04	1.67E-01	1.68E-01	1.85E-01	1.82E-01	2.36E-01	2.34E-01
2.00E-11	1.00E-03	8.01E-01	8.01E-01	8.82E-01	8.72E-01	1.12E+00	1.11E+00
2.00E-11	1.00E-07	1.44E-02	1.46E-02	1.61E-02	1.67E-02	2.09E-02	2.06E-02
2.00E-10	1.00E-05	1.61E-01	1.62E-01	1.79E-01	1.85E-01	2.31E-01	2.29E-01
2.00E-10	1.00E-04	2.83E-01	2.84E-01	3.14E-01	3.25E-01	4.02E-01	3.98E-01
2.00E-10	1.00E-03	9.01E-01	9.01E-01	9.92E-01	1.02E+00	1.26E+00	1.25E+00
2.00E-10	1.00E-07	1.34E-02	1.35E-01	1.50E-01	1.55E-01	1.93E-01	1.91E-01
2.00E-09	1.00E-05	1.18E-03	1.19E+00	1.32E+00	1.36E+00	1.68E+00	1.68E+00
2.00E-09	1.00E-04	1.28E-03	1.29E+00	1.42E+00	1.47E+00	1.81E+00	1.81E+00
2.00E-09	1.00E-03	1.76E-01	1.77E+00	1.96E+00	2.02E+00	2.48E+00	2.47E+00
2.00E-09	1.00E-07	7.36E-01	7.37E-01	7.94E-01	8.09E-01	9.35E-01	9.43E-01

Performance Threshold Heat Maps

Worthy et al. 2013 utilized a graphical method of evaluating performance, referred to as a saturated hydraulic conductivity “heat map.” This chart was used to identify those cases in which the saturated hydraulic conductivities for the specified layers approach values that will cause an exceedance of the percolation limits considered (i.e., 1 and 3 mm). Saturated hydraulic conductivities that produced percolation results below the threshold 100% of the time are denoted in green. If less than 50% of the percolation rates exceeded the specified threshold, the result is shaded in yellow. If greater than 50% of the percolation rates exceeded the designated threshold, the mapping is orange. Designs where 100% of percolation results exceeded the specified threshold are shaded in red. Figures 20 and 21 provide a comparison of heat maps for the 1 mm and 3 mm thresholds, respectively. The specific exceedance percentages also appear in each cell of these figures.

1 mm Threshold

Base Case		Layer 4 Saturated Hydraulic Conductivity				
		1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03
Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	7%	100%	100%
	1.00E-12	0%	0%	10%	100%	100%
	1.00E-11	0%	1%	55%	100%	100%
	1.00E-10	100%	100%	100%	100%	100%
	1.00E-09	100%	100%	100%	100%	100%

10% Temperature Increase		Layer 4 Saturated Hydraulic Conductivity				
		1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03
Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	13%	100%	100%
	1.00E-12	0%	0%	16%	100%	100%
	1.00E-11	0%	2%	51%	100%	100%
	1.00E-10	100%	100%	100%	100%	100%
	1.00E-09	100%	100%	100%	100%	100%

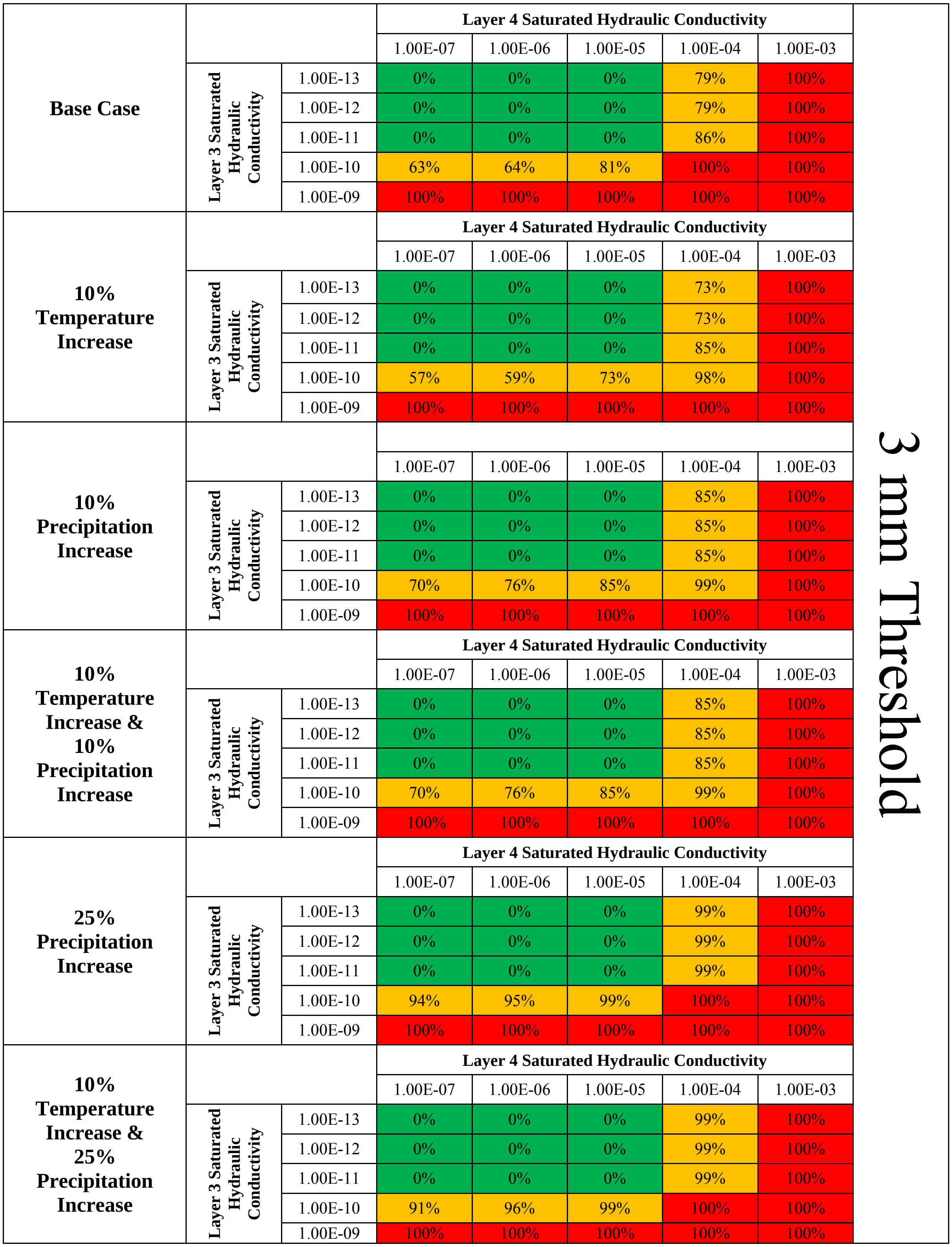
10% Precipitation Increase		Layer 4 Saturated Hydraulic Conductivity				
		1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03
Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	20%	100%	100%
	1.00E-12	0%	0%	24%	100%	100%
	1.00E-11	0%	1%	51%	100%	100%
	1.00E-10	100%	100%	100%	100%	100%
	1.00E-09	100%	100%	100%	100%	100%

10% Temperature Increase & 10% Precipitation Increase		Layer 4 Saturated Hydraulic Conductivity				
		1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03
Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	20%	100%	100%
	1.00E-12	0%	0%	24%	100%	100%
	1.00E-11	0%	1%	51%	100%	100%
	1.00E-10	100%	100%	100%	100%	100%
	1.00E-09	100%	100%	100%	100%	100%

25% Precipitation Increase		Layer 4 Saturated Hydraulic Conductivity				
		1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03
Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	52%	100%	100%
	1.00E-12	0%	0%	57%	100%	100%
	1.00E-11	2%	7%	92%	100%	100%
	1.00E-10	100%	100%	100%	100%	100%
	1.00E-09	100%	100%	100%	100%	100%

10% Temperature Increase & 25% Precipitation Increase		Layer 4 Saturated Hydraulic Conductivity				
		1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03
Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	46%	100%	100%
	1.00E-12	0%	0%	52%	100%	100%
	1.00E-11	1%	7%	88%	100%	100%
	1.00E-10	100%	100%	100%	100%	100%
	1.00E-09	100%	100%	100%	100%	100%

Figure 20: 1 mm Threshold Saturated Hydraulic Conductivity Heat Maps



			Layer 4 Saturated Hydraulic Conductivity					3 mm Threshold
Base Case			1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03	
	Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	0%	79%	100%	
		1.00E-12	0%	0%	0%	79%	100%	
		1.00E-11	0%	0%	0%	86%	100%	
		1.00E-10	63%	64%	81%	100%	100%	
		1.00E-09	100%	100%	100%	100%	100%	
10% Temperature Increase			**Layer 4 Saturated Hydraulic Conductivity**					
			1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03	
	Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	0%	73%	100%	
		1.00E-12	0%	0%	0%	73%	100%	
		1.00E-11	0%	0%	0%	85%	100%	
		1.00E-10	57%	59%	73%	98%	100%	
		1.00E-09	100%	100%	100%	100%	100%	
10% Precipitation Increase								
			1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03	
	Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	0%	85%	100%	
		1.00E-12	0%	0%	0%	85%	100%	
		1.00E-11	0%	0%	0%	85%	100%	
		1.00E-10	70%	76%	85%	99%	100%	
		1.00E-09	100%	100%	100%	100%	100%	
10% Temperature Increase & 10% Precipitation Increase			**Layer 4 Saturated Hydraulic Conductivity**					
			1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03	
	Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	0%	85%	100%	
		1.00E-12	0%	0%	0%	85%	100%	
		1.00E-11	0%	0%	0%	85%	100%	
		1.00E-10	70%	76%	85%	99%	100%	
		1.00E-09	100%	100%	100%	100%	100%	
25% Precipitation Increase			**Layer 4 Saturated Hydraulic Conductivity**					
			1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03	
	Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	0%	99%	100%	
		1.00E-12	0%	0%	0%	99%	100%	
		1.00E-11	0%	0%	0%	99%	100%	
		1.00E-10	94%	95%	99%	100%	100%	
		1.00E-09	100%	100%	100%	100%	100%	
10% Temperature Increase & 25% Precipitation Increase			**Layer 4 Saturated Hydraulic Conductivity**					
			1.00E-07	1.00E-06	1.00E-05	1.00E-04	1.00E-03	
	Layer 3 Saturated Hydraulic Conductivity	1.00E-13	0%	0%	0%	99%	100%	
		1.00E-12	0%	0%	0%	99%	100%	
		1.00E-11	0%	0%	0%	99%	100%	
		1.00E-10	91%	96%	99%	100%	100%	
		1.00E-09	100%	100%	100%	100%	100%	

Figure 21: 3 mm Threshold Saturated Hydraulic Conductivity Heat Maps

1 mm Threshold Results

With a 10% increase in temperature, the most significant performance changes were observed when Layer 4 was at a saturated hydraulic conductivity of 1.00E-05. Simulations exceeding the 1 mm threshold increased as much as 6% when Layer 3 had conductivities of 1.00E-13 and 1.00E-12. In contrast, when Layer 3 reached a conductivity of 1.00E-11, threshold exceedances decreased by 4%. These results are therefore inconclusive with respect to the effect of such an increase in temperature on cover performance.

When a 10% increase in precipitation occurs, a slight degradation in performance is observed at the 1 mm percolation threshold. When Layer 4 reaches a conductivity of 1.00E-05, as much as a 14% increase in exceedances occur, more than double the 10% temperature increase scenario. In other instances, however, the results are mixed, making it difficult to draw any immediate conclusions as to how the 10% increase in precipitation would impact performance.

The results for the scenario in which both precipitation and temperature increase by 10% did not vary from results obtained from the 10% increase in precipitation scenario. It was anticipated that increases in precipitation would be mitigated by the rise in temperature as the additional availability of energy from higher temperatures can increase surface evaporation, a component of evapotranspiration, in the soil profile. It is possible that the unchanged results are “model-induced” and not necessarily reflective of behaviors caused by changes in model input values. Several studies indicate that the water routing algorithms in HELP possess an inability to simulate the complex hydrodynamics associated with evapotranspiration (Scanlon, B.R., et al.

2002; Feddes and H. Zaradny, 1978). At such a small relative temperature increase, the model may have been unable to capture the possible benefits of increased evapotranspiration.

Exceedance rates change noticeably for Scenario 4, however. The 1 mm threshold exceedances rose considerably when compared to the base case, supporting the argument that degradation is exacerbated when average annual precipitation amounts are increased by 25%. Scenario 5 (25% increase in precipitation and 10% increase in temperature) shows some mitigating behavior in the results, presumably due to evapotranspiration effects that HELP was able to capture when more substantial changes in precipitation are considered.

3 mm Threshold Results

When the exceedance threshold is increased to 3 mm, a 10% increase in temperature scenario results in a performance improvement when compared to the base case. The larger threshold amount is less stringent and consequently performance under all scenarios is improved compared to the 1 mm threshold outcomes.

Results for the 10% increase in precipitation scenario generally show degradation in performance when compared to the base case. Exceedances increased by as much as 12%, compared to the 10% increase in temperature scenario. When the precipitation was increased by 25%, results for the 3 mm threshold were not as compelling as the 1 mm threshold but still showed decreases in performance.

Concluding Remarks

While many evaluations of landfill cover performance have focused almost exclusively on changes in precipitation, the research described herein has demonstrated that changes in both precipitation and temperature can influence landfill cover performance over extended time periods. The analysis also revealed that when both precipitation and temperature are increased, warmer temperatures tend to offset some of the impact from greater precipitation. These observations can have important implications in the development of future regulatory policies and performance assessment guidelines when long-term features that stem from naturally occurring climatic mechanisms as well as anthropogenic forcing are considered.

While the hydraulic conductivity heat mapping approach proved to be a worthwhile tool in assessing performance, the sensitivity of the maps to capture small changes in results may be a disadvantage to using this method. A potential remedy would be to increase the number of colors in the map, thereby creating more evaluation levels (e.g., 0-10%, 10-20%, etc.) to better capture smaller changes in values. Alternatively, a model other than HELP could be utilized if it can capture some of the sensitivities that are not inherent in the HELP design.

CHAPTER V

SUMMARY

This research aimed to develop a systematic approach to assessing the long-term performance of near surface disposal facilities under anthropogenic climate change impacts. This was accomplished by: (1) defining a methodology that evaluated historical climate patterns of precipitation and temperature; (2) using a Monte Carlo approach to conduct a performance assessment of a near surface disposal facility design based on historical climate events; (3) performing a proof of concept application; and (4) developing future anthropogenic climate change scenarios and assessing performance of the design relative to percolation thresholds.

Research objectives were achieved by employing a probabilistic approach to evaluating precipitation and temperature data on a monthly basis. These distributions were subsequently used to generate random values of monthly precipitation and average temperature for 100 years. Significant climate change effects, such as variations in precipitation patterns and the effects of increases in average temperatures were considered by changing the distributional means to reflect plausible future climate scenarios. By creating a stepwise process that included a proof of concept exercise, a systematic approach was developed that can be replicated for various disposal sites located in different geographic regions.

Conclusions

The major conclusions stemming from this research are as follows:

- The EDM family of distributions is an appropriate selection when modeling monthly precipitation and temperature data.
- Within this family, the Gamma distribution is a logical distribution to select when modeling precipitation data in virtually any climate, a conclusion supported by previous studies.
- While the research provided limited support of the Weibull distribution as a desirable choice in modeling temperature data, other studies have suggested that temperature typically follows a normal distribution, which is similar in shape to the Weibull distribution.
- Semi-arid climates with variable weather patterns experienced greater monthly variations in distribution fits. This implies that humid climates may be modeled using the same distribution for each month, while more arid climates may require multiple distributions.
- The HELP model is a useful tool to assess the hydrological performance of near surface disposal facilities in humid climates when degradation of designs is considered by modifying various hydraulic inputs.
- Changes in both precipitation and temperature have been found to influence landfill cover performance.
- In many cases, the potential negative effects of additional precipitation on landfill cover performance can be offset by warmer temperatures.

These developments and findings can have meaningful implications on future regulatory policies and performance assessment guidelines when considering long-term features that stem from naturally occurring climatic change as well as anthropogenic forcing.

Recommendations for Future Research

The following activities are recommended for continuing research:

- Develop a similar methodology for evaluating landfill cover performance for an arid climate. Previous work indicated that arid climates produced different probabilistic precipitation and temperature results when compared to humid climates.
- Conduct performance assessments for longer time periods (e.g., 1,000 years). Since HELP is unable to simulate hydrological modeling beyond 100 years, this would require developing a method using HELP or another hydrological model that utilizes results from the previous simulation of 100 years to establish a new simulation period.
- Investigate ways to incorporate plausible changes in vegetative properties associated with climate change (e.g., stomata conductance, leaf area index) into the development of anthropogenic climate change scenarios.
- Assess the performance of an alternatively designed near surface disposal facility (e.g., ET cover). While HELP is unable to model the complex hydrodynamics of ET covers, other models exist with the appropriate capabilities.
- Conduct additional research that evaluates a wider range of future temperature and precipitation scenarios.

This additional research would establish a more widespread understanding of how climate change can impact near surface disposal facilities. In doing so, safer and more prudent design strategies can emerge, ones that take into consideration plausible future climatic changes.

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