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Analysis of Factors that Influence Infiltration Rates using the HELP Model

J. C. Shipmon
J. A. Dyer
September 2017
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REVIEWS AND APPROVALS

AUTHORS:

J. C. Shipmon, Environmental Modeling, SRNL Date

J. A. Dyer, Environmental Modeling, SRNL Date

TECHNICAL REVIEW:

K. L. Dixon, Geosciences, SRNL Date

APPROVAL:

D. A. Crowley, Manager Date
Environmental Modeling, SRNL

L. T. Reid, Acting Director
Environmental Restoration Technology, SRNL Date

EXECUTIVE SUMMARY

The Hydrologic Evaluation of Landfill Performance (HELP) model is used by Savannah River National Laboratory (SRNL) in conjunction with PORFLOW groundwater flow simulation software to make long-term predictions of the fate and transport of radionuclides in the environment at radiological waste sites. The work summarized in this report supports preparation of the planned 2018 Performance Assessment for the E-Area Low-Level Waste Facility (LLWF) at the Savannah River Site (SRS). More specifically, this project focused on conducting a sensitivity analysis of infiltration (i.e., the rate at which water travels vertically in soil) through the proposed E-Area LLWF closure cap. A sensitivity analysis was completed using HELP v3.95D to identify the cap design and material property parameters that most impact infiltration rates through the proposed closure cap for a 10,000-year simulation period. The results of the sensitivity analysis indicate that saturated hydraulic conductivity (K_{sat}) for select cap layers, precipitation rate, surface vegetation type, and geomembrane layer defect density are dominant factors limiting infiltration rate. Interestingly, calculated infiltration rates were substantially influenced by changes in the saturated hydraulic conductivity of the Upper Foundation and Lateral Drainage layers. For example, an order-of-magnitude decrease in K_{sat} for the Upper Foundation layer lowered the maximum infiltration rate from a base-case 11 inches per year to only two inches per year. Conversely, an order-of-magnitude increase in K_{sat} led to an increase in infiltration rate from 11 to 15 inches per year. This work and its results provide a framework for quantifying uncertainty in the radionuclide transport and dose models for the planned 2018 E-Area Performance Assessment. Future work will focus on the development of a non-linear regression model for infiltration rate using Minitab 17® to facilitate execution of probabilistic simulations in the GoldSim® overall system model for the E-Area LLWF.

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LIST OF ABBREVIATIONS

CN	Curve number
DOE	Department of Energy
EPA	Environmental Protection Agency
GCL	Geosynthetic clay liner
GUI	Graphical User Interface
HDPE	High-density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
K_{sat}	Saturated Hydraulic Conductivity
LDL	Lateral Drainage Layer
LLWF	Low-Level Waste Facility
PA	Performance Assessment
SCS	Soil Conservation Service
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
UFL	Upper Foundation Layer
U.S.	United States

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1.0 HELP Model Background

The HELP model was developed originally by the United States (U.S.) Army Corps of Engineers (Schroeder et al. 1987) under the sponsorship of the U.S. Environmental Protection Agency (U.S. EPA). More recently, Klaus Berger, Professor at the University of Hamburg Allende-Platz, collaborated with Paul Schroeder to develop an improved version of the HELP model (version 3.95D) that is Microsoft Windows 7/8/10 compatible and eliminates several errors and limitations in the most recent U.S. version—HELP v3.07 (Schroeder et al. 1994a and 1994b). The primary use for the HELP model is to compare different landfill cover system design alternatives as judged by a water balance for the climatic conditions experienced at a particular geographical location (Berger et al. 2000). HELP is a quasi-two-dimensional layer model with the capability to estimate the water balance for both open and closed landfills and other solid-waste disposal systems (Berger et al. 2015). A Fortran-based program, HELP allows the user to input weather, soil property and cap design parameters, execute the program, and output the expected hydrologic performance of the landfill cover design to text files for post processing in Microsoft Excel. Currently, three versions of the model are available (HELP v3.07, Visual HELP v2.2, and HELP v3.95D). HELP v3.95D was chosen for the sensitivity analysis for several reasons:

- The v3.07 simulation module was updated in v3.95D to include a new graphical user interface (GUI) that is fully Windows 7/8/10 compatible (Berger et al. 2012).
- The software can be executed separately as either v3.07 or v3.95D, if desired.
- The synthetic weather generator functions in both its original version (v3.07) and the modified version (v3.95D) which fixes a problem with leap years. Version 3.95D of the weather generator gives slightly different results than the original version (Berger et al. 2012).

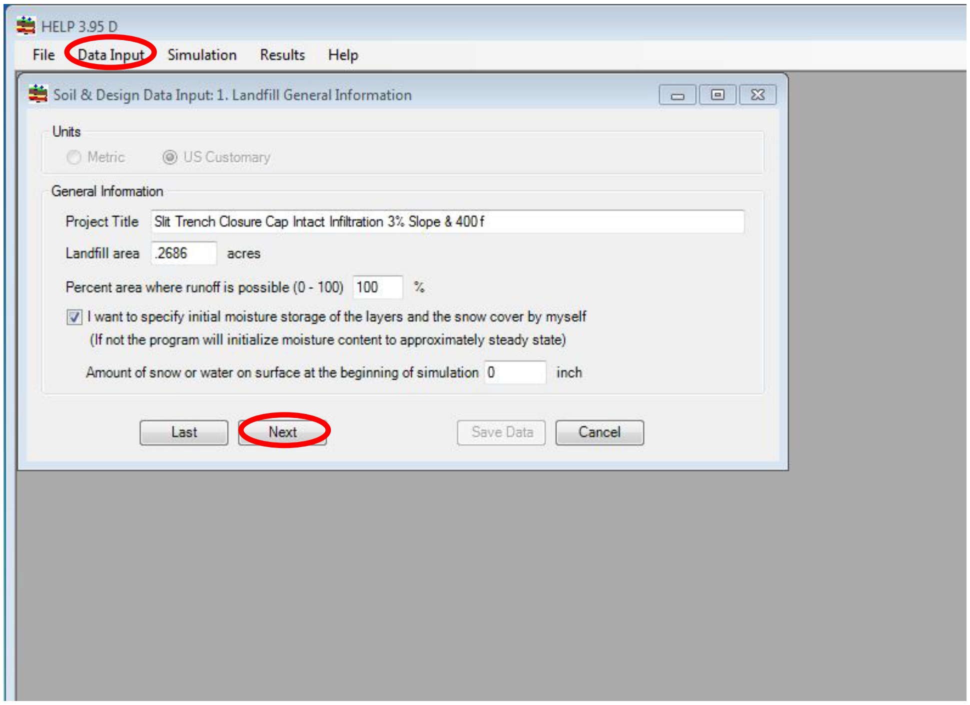
2.0 Model Representation

File management is particularly important when executing the HELP model. Initially, substantial effort was involved in subdirectory set up to organize input and output files for multiple-case runs. When working with the software, it is often desirable to vary the soil property, cap design, and/or weather input parameters. HELP v3.95D simplifies the process of editing input files through a user-friendly GUI. It is also possible to generate multiple sets of weather data within the software.

The Data Input tab on the HELP v3.95D menu bar provides the user access to the input files of choice for editing. HELP model data input files include a daily precipitation file (.d4), daily temperature file (.d7), daily solar radiation file (.d13), evapotranspiration file (.d11), soil and design file (.D10), and a simulation control file (.OPD). Figure 2-1, Figure 2-2, and Figure 2-3 display the three input screens for soil and design data. Once the necessary input files are created, the simulation control input dialog screen shown in Figure 2-4 allows the user to link the input files and execute the model.

When the simulation is complete, HELP generates a set of output text files containing the hydrologic data of interest for the specified cover system design. Four different output file formats can be generated by the HELP v3.95D software, including a:

- yearly subdivided data file (.YR),
- monthly subdivided file (.MON),
- daily subdivided file (.DAY), and
- summary file that consolidates all results in a single file (.OUT).



Soil & Design Data Input: 1. Landfill General Information

Units

○ Metric ● US Customary

General Information

Project Title: Slit Trench Closure Cap Intact Infiltration 3% Slope & 400 f

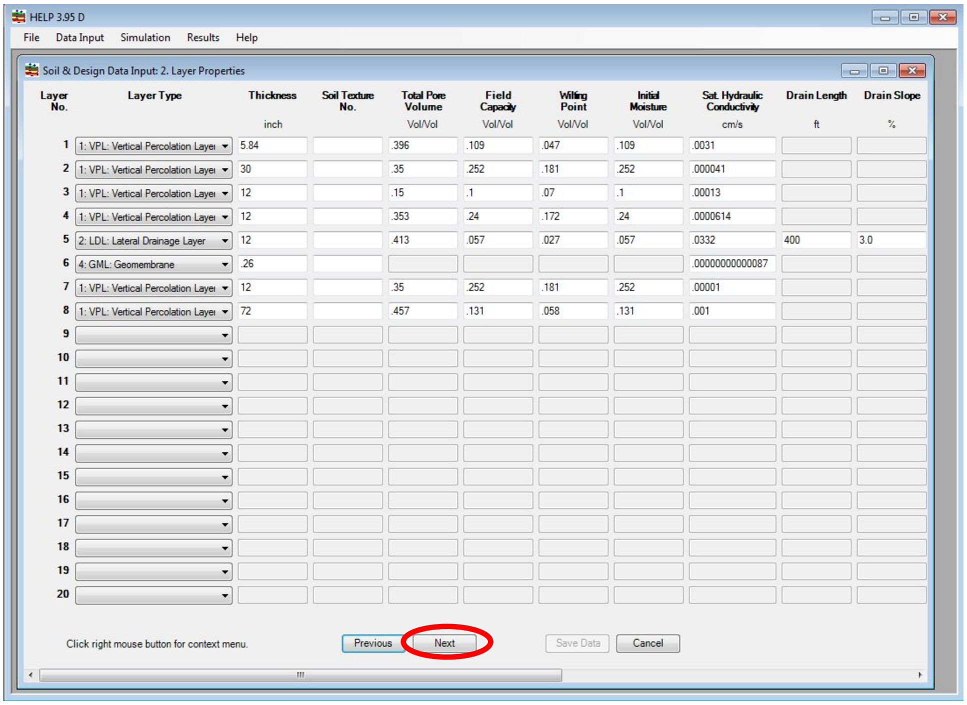
Landfill area: .2686 acres

Percent area where runoff is possible (0 - 100): 100 %

☑ I want to specify initial moisture storage of the layers and the snow cover by myself
(If not the program will initialize moisture content to approximately steady state)

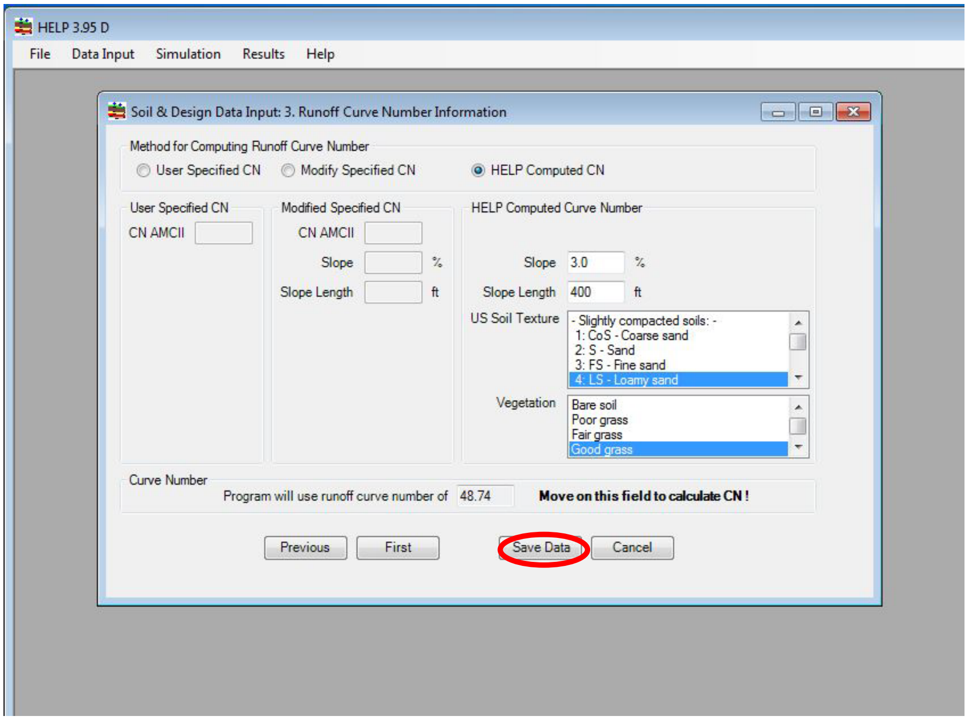
Amount of snow or water on surface at the beginning of simulation: 0 inch

Figure 2-1. Snapshot of Soil and Design Input Screen #1



Layer No.	Layer Type	Thickness inch	Soil Texture No.	Total Pore Volume Vol/Vol	Field Capacity Vol/Vol	Wilting Point Vol/Vol	Initial Moisture Vol/Vol	Sat. Hydraulic Conductivity cm/s	Drain Length ft	Drain Slope %
1	1: VPL: Vertical Percolation Layer	5.84		.396	.109	.047	.109	.0031		
2	1: VPL: Vertical Percolation Layer	30		.35	.252	.181	.252	.000041		
3	1: VPL: Vertical Percolation Layer	12		.15	.1	.07	.1	.00013		
4	1: VPL: Vertical Percolation Layer	12		.353	.24	.172	.24	.0000614		
5	2: LDL: Lateral Drainage Layer	12		.413	.057	.027	.057	.0332	400	3.0
6	4: GML: Geomembrane	.26						.00000000000087		
7	1: VPL: Vertical Percolation Layer	12		.35	.252	.181	.252	.00001		
8	1: VPL: Vertical Percolation Layer	72		.457	.131	.058	.131	.001		
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

Figure 2-2. Snapshot of Soil and Design Input Screen #2



Method for Computing Runoff Curve Number
○ User Specified CN ○ Modify Specified CN ● HELP Computed CN

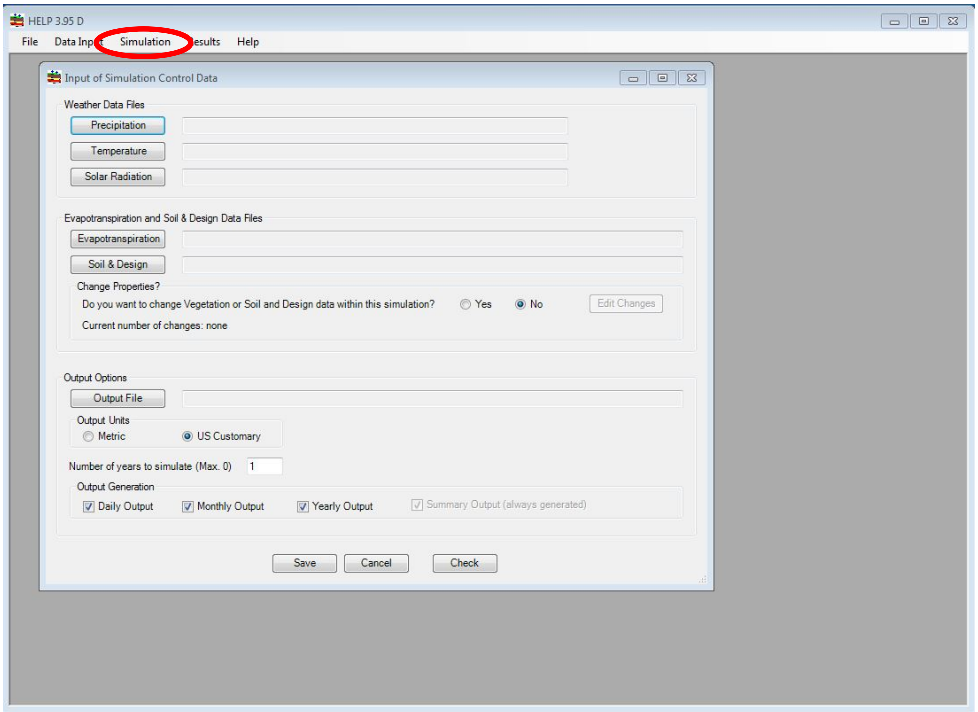
User Specified CN
CN AMCII

Modified Specified CN
CN AMCII
Slope %
Slope Length ft

HELP Computed Curve Number
Slope 3.0 %
Slope Length 400 ft
US Soil Texture: - Slightly compacted soils: -; 1: CoS - Coarse sand; 2: S - Sand; 3: FS - Fine sand; 4: LS - Loamy sand (selected)
Vegetation: Bare soil; Poor grass; Fair grass; Good grass (selected)

Curve Number
Program will use runoff curve number of 48.74 **Move on this field to calculate CN !**

Figure 2-3. Snapshot of Soil and Design Input Screen #3



Do you want to change Vegetation or Soil and Design data within this simulation? ○ Yes ● No

Current number of changes: none

○ Metric ● US Customary

Number of years to simulate (Max. 0) 1

☑ Daily Output ☑ Monthly Output ☑ Yearly Output ☑ Summary Output (always generated)

Figure 2-4. Simulation Control Input Dialog Screen

3.0 Proposed Cover System Design

The HELP model is used at SRS to simulate the expected long-term hydraulic performance of proposed waste cover system designs before they are installed. This report focuses on the proposed design of the final cover system for the SRS E-Area LLWF. Currently, E-Area comprises a system of slit and engineered trenches and other specially designed vaults and casks containing solid waste materials with various levels of radioactivity. To support completion of the planned 2018 E-Area Performance Assessment, an updated hydrologic model of the proposed final cover system using the HELP software is required to aid in estimating peak releases of radionuclides to the environment.

The proposed E-Area cover or cap is an engineered system designed to minimize the quantity (mass) of rainwater percolating vertically downward through the cap layers to the subsurface waste disposal zone where the water interacts with the various waste forms, and eventually enters the vadose zone and water table aquifer. Notable cover system design features that help minimize passage of water into the waste zone include the lateral drainage and geomembrane (barrier) layers. The lateral drainage layer removes a large fraction of the rainfall that does not evaporate or transpire at/near the surface of the cover system (upper ~24 inches) and transports it horizontally to the edges of the cap for collection.

A high-density polyethylene (HDPE) geomembrane, in combination with a geosynthetic clay liner (GCL) immediately below, functions as the cover system's final barrier layer. The geomembrane possesses an extremely low saturated hydraulic conductivity (K_{sat}) on the order of 10^{-13} cm/sec, meaning that the geomembrane allows minimal water to pass through it when properly installed and free of defects.

The proposed E-Area cover system design contains a total of nine soil/material layers at the time of installation (time zero). The layers are as follows (see Figure 3-1):

- Layer 1 - Topsoil
- Layer 2 - Upper Backfill
- Layer 3 - Erosion Barrier
- Layer 4 - Middle Backfill
- Layer 5 - Lateral Drainage Layer
- Layer 6 - Combined Geomembrane
- Layer 7 - Geotextile Clay Liner
- Layer 8 - Upper Foundation Layer
- Layer 9 - Lower Foundation Layer

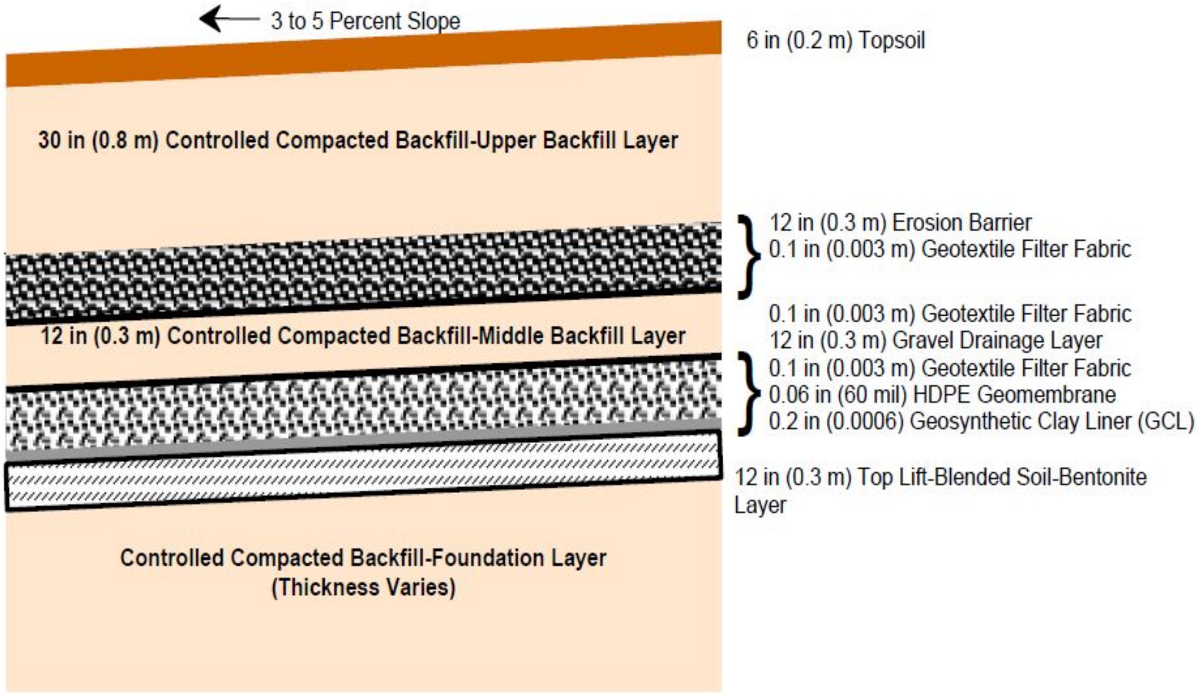


Figure 3-1. Proposed E-Area Waste Cover System Schematic

4.0 Sensitivity Analysis using HELP (Summer Intern Project)

The work described in this technical report was performed by Jacoby Shipmon, an undergraduate intern from North Carolina A&T, during summer 2017. The objective of the summer intern project was to assess the performance of the proposed E-Area LLWF cover system design as required for the completion of the planned 2018 E-Area Performance Assessment (PA). The purpose of the PA is to ensure with reasonable certainty that Department of Energy (DOE) performance objectives will be met so as to minimize the release and transport of radionuclides in the environment. To accomplish this task, a sensitivity analysis was performed on the factors that influence the infiltration rate into and through the proposed cover system. A sensitivity analysis is a study of how the uncertainty in the output of a mathematical model or system can be attributed to the uncertainty in its inputs, and is performed to gain an understanding of the relationship between input and output variables in a model (Saltelli et al. 2002).

Infiltration or percolation is the rate at which water moves through the pores of soil or rock (Richards et al. 1952). Understanding and quantifying this rate is important because it directly affects how much water interacts with the waste forms disposed under the final cover and thus the aqueous concentration of radionuclides released to groundwater. An objective of the PA is to quantify the magnitude and timing of the peak concentration of each radionuclide entering the vadose zone. In this sensitivity analysis, parameters that were varied included percent slope and slope length of the cap, Soil Conservation Service (SCS) curve number, number of geomembrane defects, saturated hydraulic conductivity of various cap layers, leaf area index, precipitation rate, and temperature. The SCS curve number is a function of soil texture and vegetation type for the surface soil layer, and directly impacts surface runoff. Leaf area index influences the calculated evapotranspiration rate from the upper approximately 24 inches of soil (i.e., the evapotranspiration zone).

The methodology employed in this sensitivity analysis consisted of independently varying individual climate, soil property, and cover design parameters, while holding all others constant, to quantify the effect of these parameter changes on the infiltration rate through the geomembrane/GCL layers. To accomplish this task, the following general approach was taken based on past HELP simulation studies:

- First, a set of four weather input files (i.e., .d4, .d7, .d11, and .d13) was generated by the HELP v3.95D weather generator for a 100-year time period using default climate data for Augusta, GA modified with SRS-specific monthly average precipitation and temperature data.

- Second, all soil property and design input parameters for the cover system age of interest (0 to 10,000 years) were entered into the model using the appropriate data input screens (see Figure 2-1 through Figure 2-3 and Appendix A).

- Third, the model was executed for the desired cover age, generating 100 years of hydrologic performance data for the specified cover system.

- Fourth, the output data was exported to Microsoft Excel for post processing and analysis.

HELP model input parameter data for the ten base-case simulations (ST00.D10, ST02.D10, ST04.D10, ST06.D10, ST07.D10, ST08.D10, ST09.D10, ST10.D10, ST11.D10, and ST13.D10) are included in Appendix B. A large number of the model input parameters (e.g., porosity, field capacity, wilting point, initial moisture, saturated hydraulic conductivity for specific cap layers, etc.) were unchanged from their base-case values because prescreening simulations showed that the infiltration rates were relatively insensitive to these parameters.

5.0 Improvements or Changes in Methods

To improve efficiency in execution and accuracy of the results, several additional steps were taken for this sensitivity analysis. A significant change compared to past HELP simulation studies was the use of the recently purchased HELP v3.95D software. The updated GUI in HELP v3.95D greatly improves the ease with which input files can be created and edited. A second method improvement was the decision to update past PA weather data files with the most current SRS-specific monthly average precipitation and temperature data provided by the Atmospheric Technologies Center at SRS. In addition, useful tools, such as WinMerge and Notepad++, were used to facilitate post processing of input and output files.

To take advantage of HELP v3.95D’s multiple-case simulation capability, however, the most significant change in methodology was the decision to transform the 100-year weather data files into files containing ten identical stacked ten-year data sets having the same monthly averages as the 100-year weather data input files (10 years weather data x 10 cases = 100 years total simulation time allowed by software). This change enabled an entire S-shaped cover-system degradation curve (infiltration rate vs. time) to be generated with a single execution of the HELP v3.95D model. For purposes of the sensitivity analysis, the loss in accuracy in using 10-year weather data sets instead of 100-year data sets was small compared to the gain in productivity (i.e., substantially decreased time to generate results for each sensitivity case).

By combining all of the aforementioned methods and improvements, a detailed sensitivity analysis of infiltration into the E-Area LLWF cover system was completed efficiently and effectively. Results are summarized below by sensitivity parameter.

6.0 Results

6.1 Percent Slope

Percent slope refers to the nominal percentage slope of the proposed cover. For example, 3% slope signifies 3 feet of vertical rise for every 100 feet of horizontal run (3 feet/100 feet x 100% = 3%). Percent slope will influence infiltration rate by impacting surface runoff and lateral drainage rate. Table 6-1, Figure 6-1, and Figure 6-2 present the results of the sensitivity analysis for percent slope at a fixed slope length of 400 feet. As shown in the figures below, a decrease in percent slope from the 3% base case to 2% results in an upward shift in the average annual infiltration rate vs. time curve. An increase in percent slope (5%), on the other hand, leads to a decrease in the annual average infiltration rate into the cap compared to the base case. Table 6-1 shows the percentage change in annual average infiltration rate relative to the base case as a function of time.

Table 6-1. Change in Infiltration Rate with Percent Slope at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)					
Time (years)	3% Slope (Base Case)	2% Slope	% Change (vs. base case)	5% Slope	% Change (vs. base case)
0	0.000154	0.000286	86	0.0000823	-47
180	0.00560	0.0106	89	0.00471	-16
300	0.0146	0.0368	153	0.0161[*]	10[*]
380	0.205	0.520	153	0.0498	-76
560	1.10	1.79	63	0.501	-54
1000	3.85	5.21	35	2.46	-36
1800	8.91	9.86	11	7.48	-16
2623	11.1	11.5	3.9	10.3	-6.9
3200	11.2	11.6	3.6	10.5	-6.2
10000	11.6	11.9	3.2	11.0	-4.5

[*] In all cases but one, infiltration rate decreases with increasing % slope as expected. This single case at 300 years and 5% slope appears to be an anomaly and cannot be explained. At 300 years, the geomembrane and GCL layers are combined into a single layer to account for pine tree root penetration.

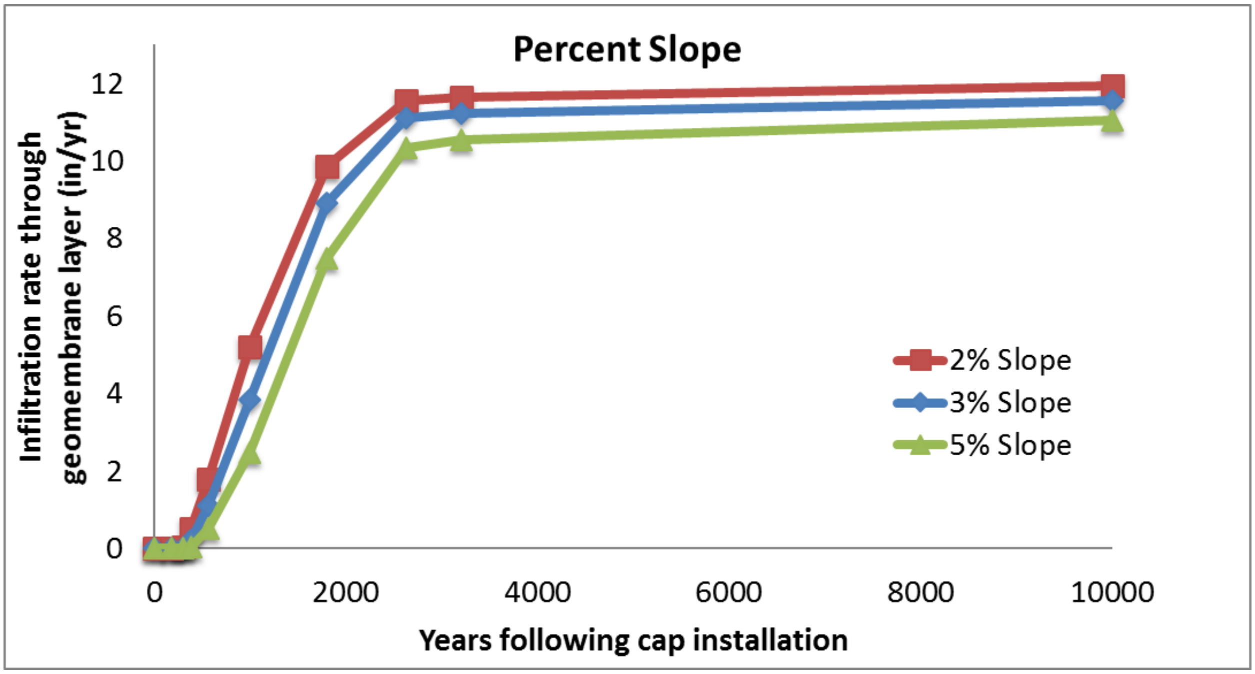


Figure 6-1. Impact of Percent Slope on Annual Avg. Infiltration Rate (0-10,000 Years)

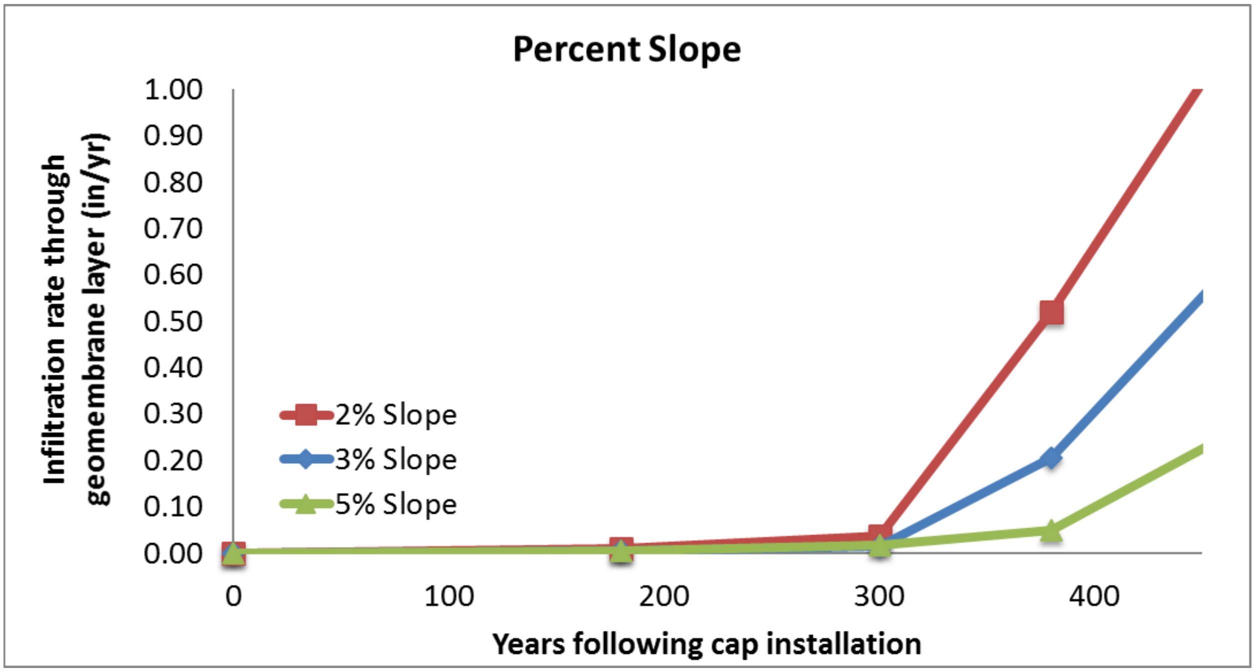


Figure 6-2. Impact of Percent Slope on Annual Avg. Infiltration Rate (0-400 Years)

6.2 SCS Curve Number

The SCS curve number (CN) is calculated internally within the HELP model and accounts for the effect of surface soil texture and vegetation type on surface runoff. A higher CN is indicative of increased runoff and, hence, a decrease in the infiltration rate. As shown in Figure 6-3 below for a slope length of 400 feet, the SCS CN has a only minor impact on annual average infiltration rate because surface runoff represents only a small fraction (1 to 5% of average annual rainfall) of the total water balance for SRS cap designs. Table 6-2 shows the percentage change in annual average infiltration rate relative to the base case as a function of time.

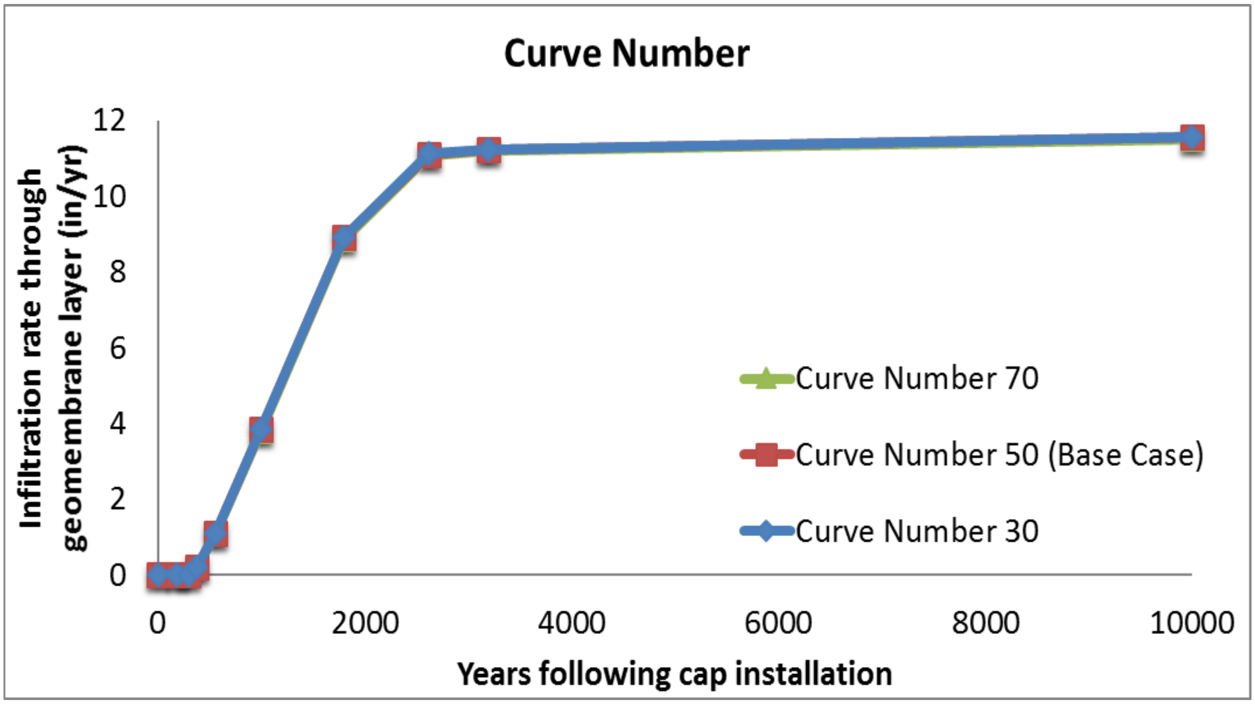


Figure 6-3. Impact of SCS Curve Number on Annual Avg. Infiltration Rate (0-10,000 Years)

Table 6-2. Change in Infiltration Rate with SCS Curve Number at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)					
Time (years)	CN = 50 (Base Case)	CN = 30	% Change (vs. base case)	CN = 70	% Change (vs. base case)
0	0.000150	0.000150	0.0	0.000120	-20
180	0.00560	0.00559	-0.18	0.00543	-2.9
300	0.0146	0.0145	-0.69	0.0144	-0.42
380	0.205	0.205	0.0049	0.199	-3.0
560	1.10	1.10	0.16	1.07	-2.7
1000	3.85	3.85	0.099	3.79	-1.5
1800	8.91	8.92	0.089	8.85	-0.74
2623	11.1	11.1	0.038	11.1	-0.44
3200	11.2	11.2	0.052	11.2	-0.49
10000	11.6	11.6	0.082	11.5	-0.71

6.3 Geomembrane Liner Defect Number

The geomembrane liner defect number equals the total assumed number of 1-cm^2 holes or defects in the geomembrane barrier layer. The geomembrane liner for the E-Area cover system is implemented in the HELP model as a separate 60-mil thick HDPE layer that allows minimal water to percolate through it in the absence of defects. In the sensitivity analysis, the effect of time on these layers is tested. As time progresses in the HELP model of the E-Area cover system, the geomembrane layer is assumed to “age” and develop holes or defects due to both physical and chemical degradation mechanisms. As shown in Figure 6-4 and Figure 6-5, doubling the geomembrane defect number relative to the base case results in a significant increase in the annual average infiltration rate, especially during the 300 to 1,000-year time period. Conversely, a 2X decrease in the defect number leads to a significant drop in the average annual infiltration rate over the same time period. Table 6-3 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time.

Table C-1 in Appendix C provides a summary of the geomembrane defect numbers assumed in the base case and two sensitivity analysis simulations.

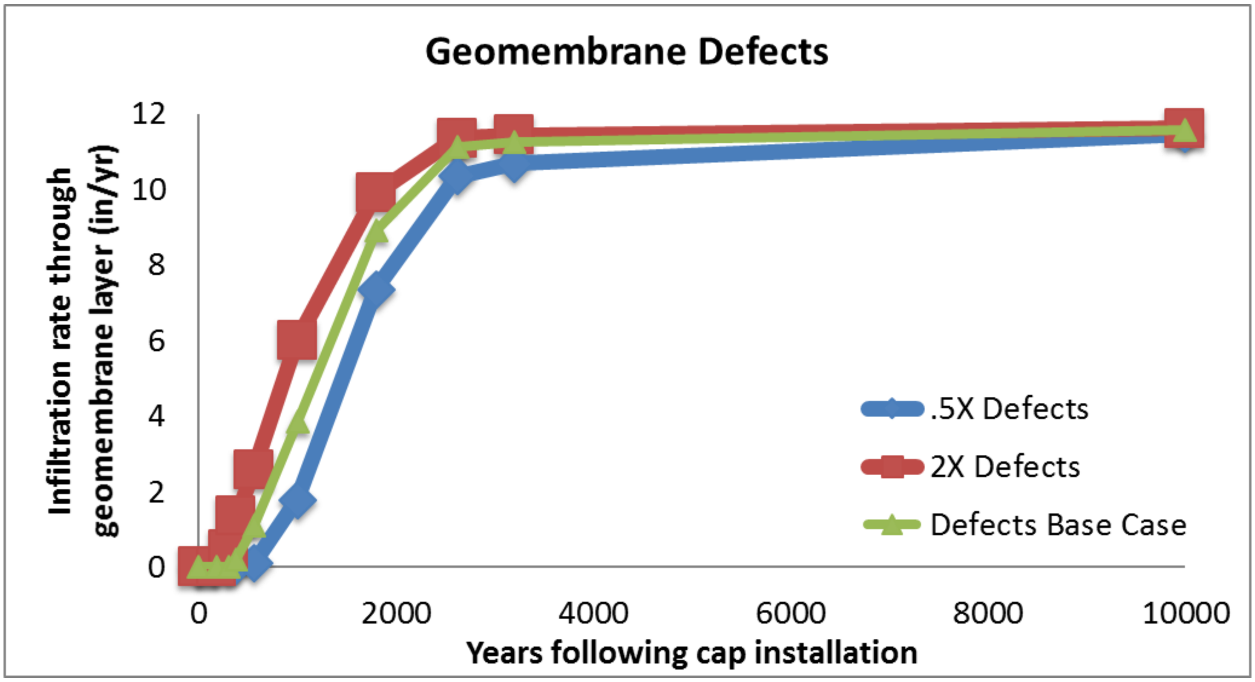


Figure 6-4. Impact of Geomembrane Defect Number on Annual Avg. Infiltration Rate (0-10,000 Years)

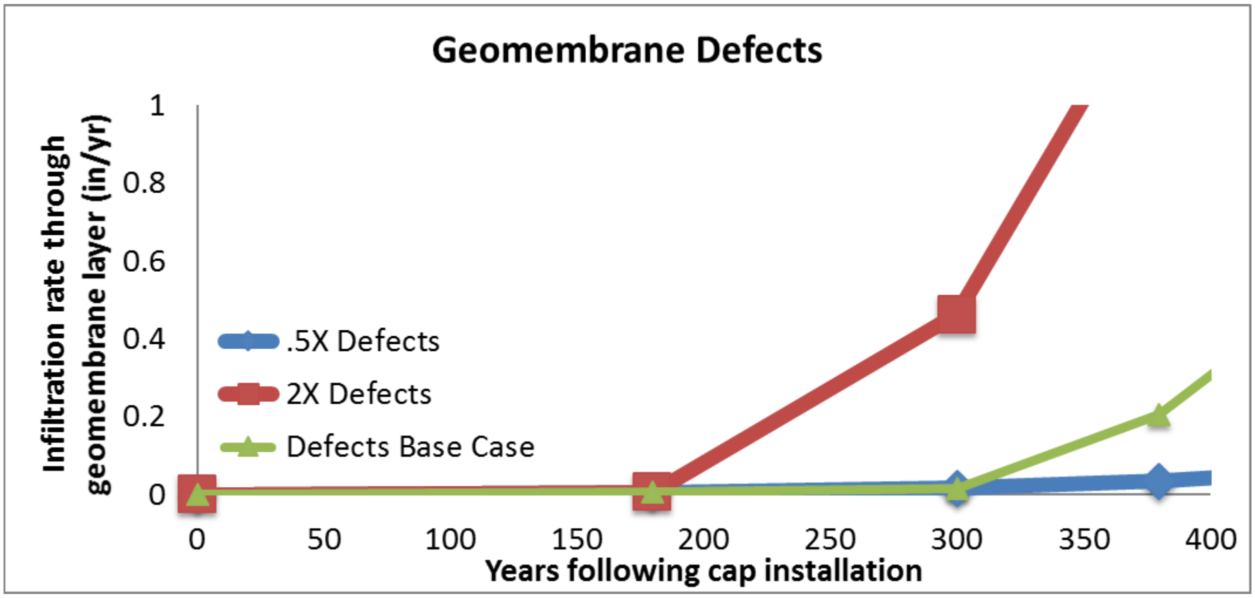


Figure 6-5. Impact of Geomembrane Defect Number on Annual Avg. Infiltration Rate (0-400 Years)

Table 6-3. Change in Infiltration Rate with Geomembrane Defect Number at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)					
Time (years)	Base Case	+0.5X Defect Number	% Change (vs. base case)	+2X Defect Number	% Change (vs. base case)
0	0.000150	0.000150	0.0	0.000150	0.0
180	0.00560	0.00560	0.0	0.00560	0.0
300	0.0146	0.0158	8.7	0.463	2800
380	0.205	0.035	-83	1.34	3300
560	1.10	0.105	-90	2.57	1400
1000	3.85	1.78	-54	6.02	120
1800	8.91	7.36	-17	9.90	13
2623	11.1	10.3	-6.9	11.4	2.3
3200	11.2	10.7	-5.0	11.4	1.9
10000	11.6	11.5	-0.82	11.6	0.37

6.4 Saturated Hydraulic Conductivity

6.4.1 Lateral Drainage Layer

Saturated hydraulic conductivity (K_{sat}) is a measure of a saturated soil column's ability to transmit water when subjected to a hydraulic gradient and has units of length per unit of time. As K_{sat} increases, so too does the mass flux of water through the soil or barrier material. In this step of the sensitivity analysis, K_{sat} values for the lateral drainage layer (LDL) were varied above and below the base-case values at each time step (0 to 10,000 years). As shown in Figure 6-6 and Figure 6-7, K_{sat} for the LDL has a strong negative correlation with annual average infiltration rate. The results for the LDL are particularly interesting when considering the onset time of steep increases in the infiltration rate. As seen in Figure 6-6 and Figure 6-7, the infiltration rate curves increase sharply from their baseline low values at much different times. For example, the annual average infiltration rate increases sharply almost immediately when K_{sat} equals 1/10 of the base-case value; however, it takes more than 1,000 years when K_{sat} equals 10X the base-case value. Table 6-4 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time.

Table C-3 in Appendix C reports K_{sat} values used in the base case and four sensitivity cases for the LDL.

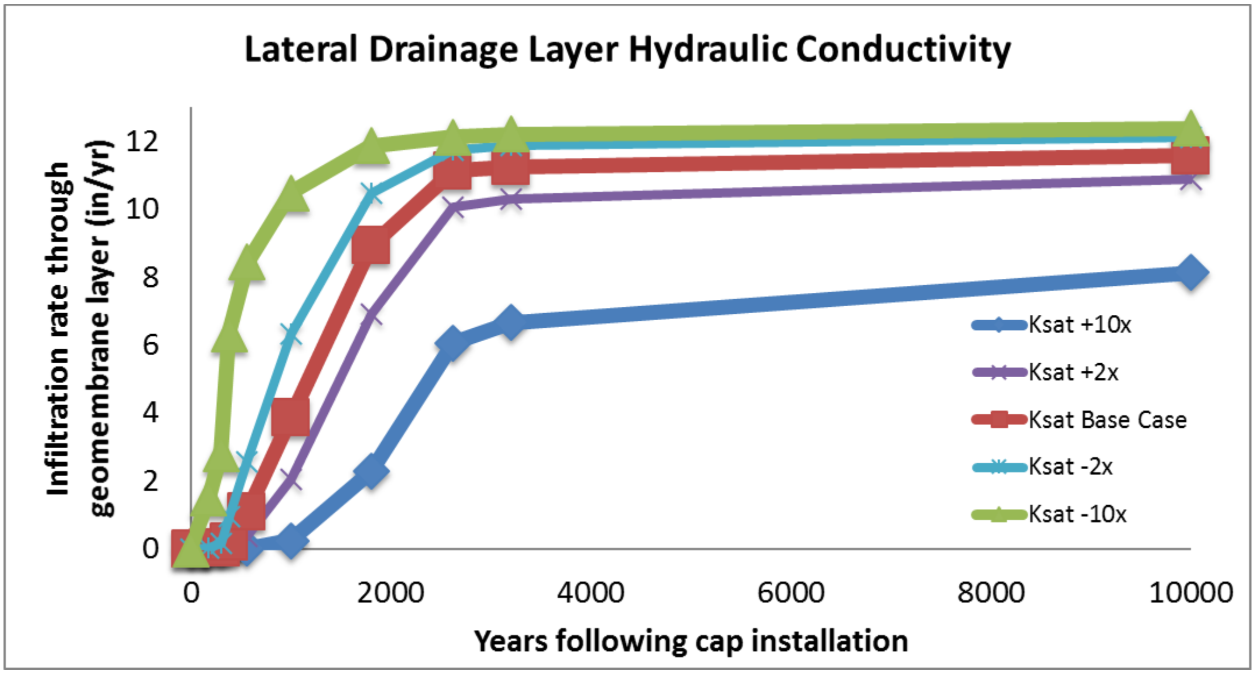


Figure 6-6. Impact of K_{sat} for LDL on Annual Avg. Infiltration Rate (0-10,000 Years)

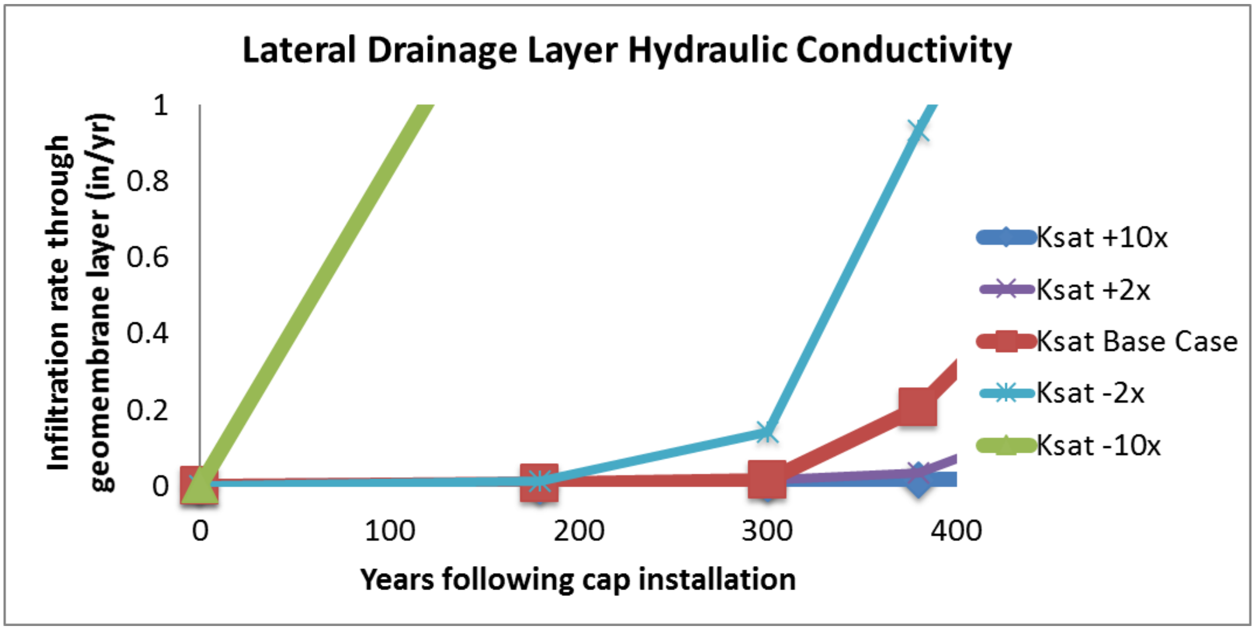


Figure 6-7. Impact of K_{sat} for LDL on Annual Avg. Infiltration Rate (0-400 Years)

Table 6-4. Change in Infiltration Rate with K_{sat} for LDL at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)									
Time (years)	LDL K_{sat} (Base Case)	LDL K_{sat} (-2X)	% Change (vs. base case)	LDL K_{sat} (-10X)	% Change (vs. base case)	LDL K_{sat} (+2X)	% Change (vs. base case)	LDL K_{sat} (+10X)	% Change (vs. base case)
0	0.000150	0.000530	250	0.00290	1800	0.0000600	-60	0.000	-100
180	0.00560	0.0137	140	1.51	27000	0.00471	-16	0.000670	-100
300	0.0146	0.142	880	2.79	19000	0.0144	-1.2	0.00513	-100
380	0.205	0.934	350	6.33	3000	0.0332	-84	0.0167	-100
560	1.10	2.54	130	8.43	670	0.369	-66	0.0211	-100
1000	3.85	6.32	64	10.5	170	2.05	-47	0.234	-98
1800	8.91	10.5	17	11.9	33	6.91	-22	2.28	-81
2623	11.1	11.7	5.5	12.1	9.0	10.1	-9.6	6.05	-50
3200	11.2	11.9	5.5	12.2	8.6	10.3	-8.5	6.66	-45
10000	11.6	12.1	4.7	12.4	7.0	10.9	-6.1	8.13	-34

6.4.2 Upper Foundation Layer

The saturated hydraulic conductivity of the upper foundation layer (UFL) was adjusted 2X and 10X above and below the base-case value at each time step (0 to 10,000 years). The UFL sits below the geomembrane/GCL layers and is identified in Figure 3-1 as the top lift-blended soil-bentonite layer. Figure 6-8 and Figure 6-9 indicate that K_{sat} has a strong positive correlation with annual average infiltration rate. Interestingly, if K_{sat} for the UFL drops 10X below the base-case value, the annual average infiltration rate never exceeds 1.3 inches per year; however, a +10X increase in K_{sat} increases the annual average infiltration rate substantially to a maximum of more than 15 inches per year. Table 6-5 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time.

Table C-2 in Appendix C reports K_{sat} values used in the base case and four sensitivity cases for the UFL.

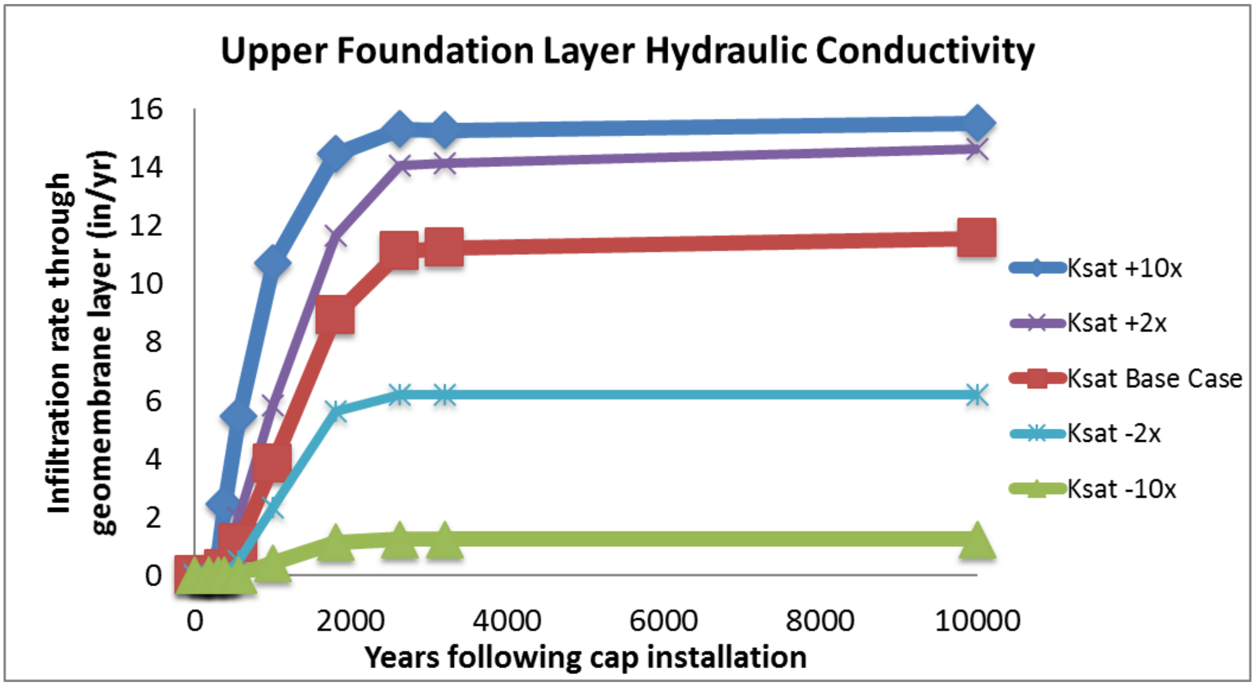


Figure 6-8. Impact of K_{sat} for UFL on Annual Avg. Infiltration Rate (0-10,000 Years)

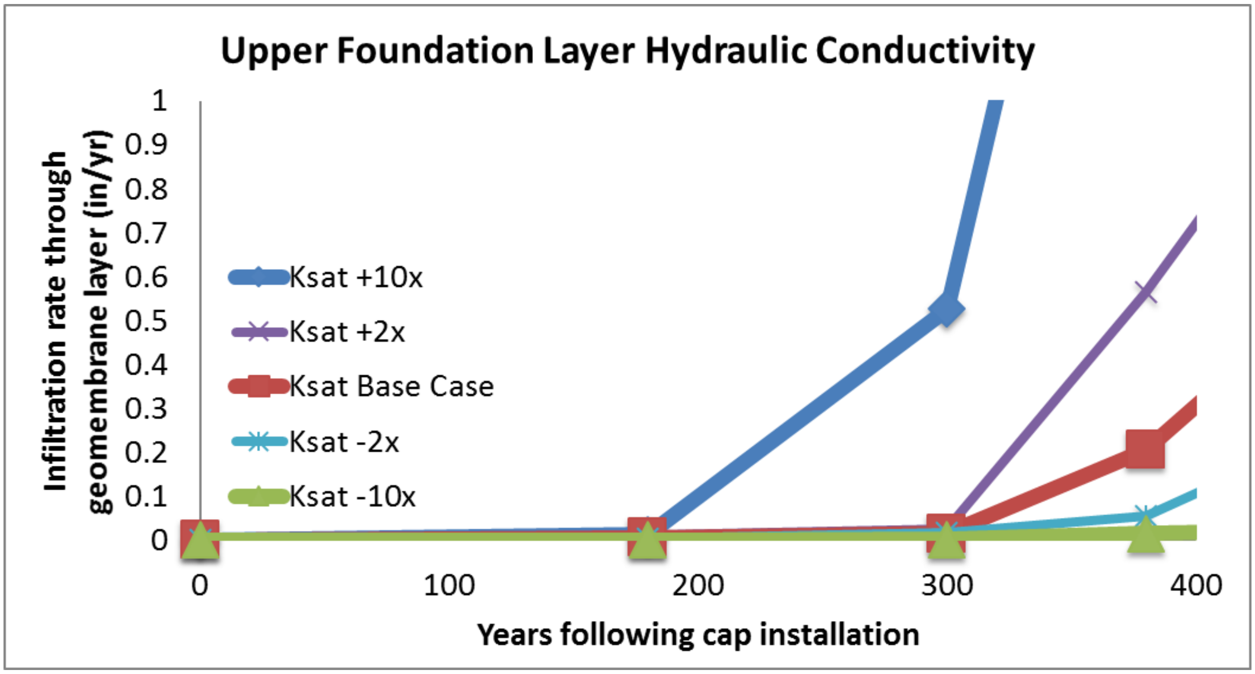


Figure 6-9. Impact of K_{sat} for UFL on Annual Avg. Infiltration Rate (0-400 Years)

6.5 Leaf Area Index

Leaf Area Index (LAI) is an input parameter tied to surface vegetation type and it influences the evapotranspiration rate. For bare ground, LAI is equal to zero; for ground covered with a good stand of grass, LAI is 3.5; for a coniferous forest, LAI has a value of 20. Figure 6-10 and Figure 6-11 show that infiltration rate is negatively correlated with LAI, although the effect on infiltration rate appears to be less significant when LAI > 3.5. A low value for LAI results in higher infiltration rates due to a decrease in the predicted evapotranspiration rates. Lower sensitivity of infiltration rate to LAI when LAI is greater than 3.5 is an artifact of the original HELP source code, which was developed for bare ground and grasses only (i.e., LAI values 0 to 5). The HELP v3.95D User's Manual states that the model underestimates evapotranspiration rates when LAI is greater than 5.0 (Berger 2012). Table 6-6 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time.

Table 6-5. Change in Infiltration Rate with K_{sat} for UFL at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)									
Time (years)	UFL K_{sat} (Base Case)	UFL K_{sat} (-2X)	% Change (vs. base case)	UFL K_{sat} (-10X)	% Change (vs. base case)	UFL K_{sat} (+2X)	% Change (vs. base case)	UFL K_{sat} (+10X)	% Change (vs. base case)
0	0.000150	0.000150	0.0	0.000150	0.0	0.000150	0.0	0.000150	0.0
180	0.00560	0.00233	-58	0.000150	-97	0.0107	91	0.0119	110
300	0.0146	0.0164	12	0.000870	-94	0.0260	79	0.527	3500
380	0.205	0.0544	-74	0.0148	-93	0.564	170	2.46	1100
560	1.10	0.520	-53	0.0306	-97	1.96	78	5.47	400
1000	3.85	2.32	-40	0.443	-89	5.82	51	10.7	180
1800	8.91	5.62	-37	1.15	-87	11.7	31	14.4	62
2623	11.1	6.21	-44	1.24	-89	14.1	27	15.3	38
3200	11.2	6.21	-45	1.24	-89	14.1	26	15.3	36
10000	11.6	6.21	-46	1.24	-89	14.6	27	15.5	34

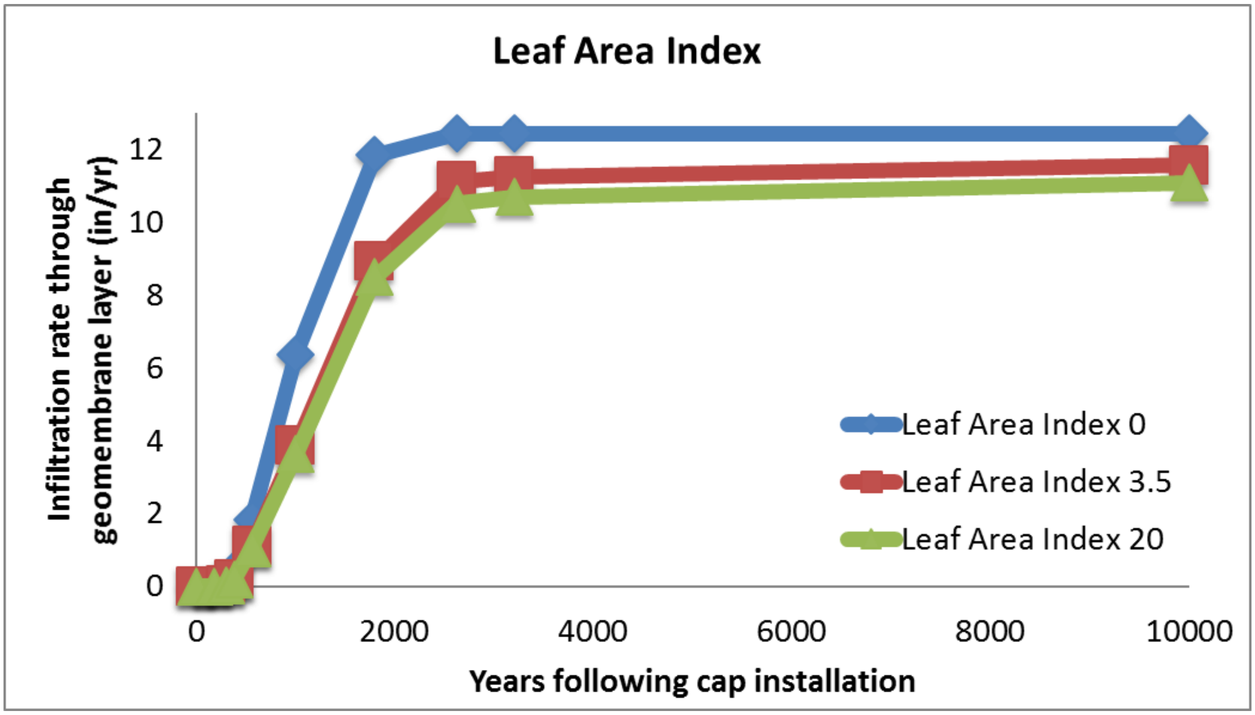


Figure 6-10. Impact of Leaf Area Index on Annual Avg. Infiltration Rate (0-10,000 Years)

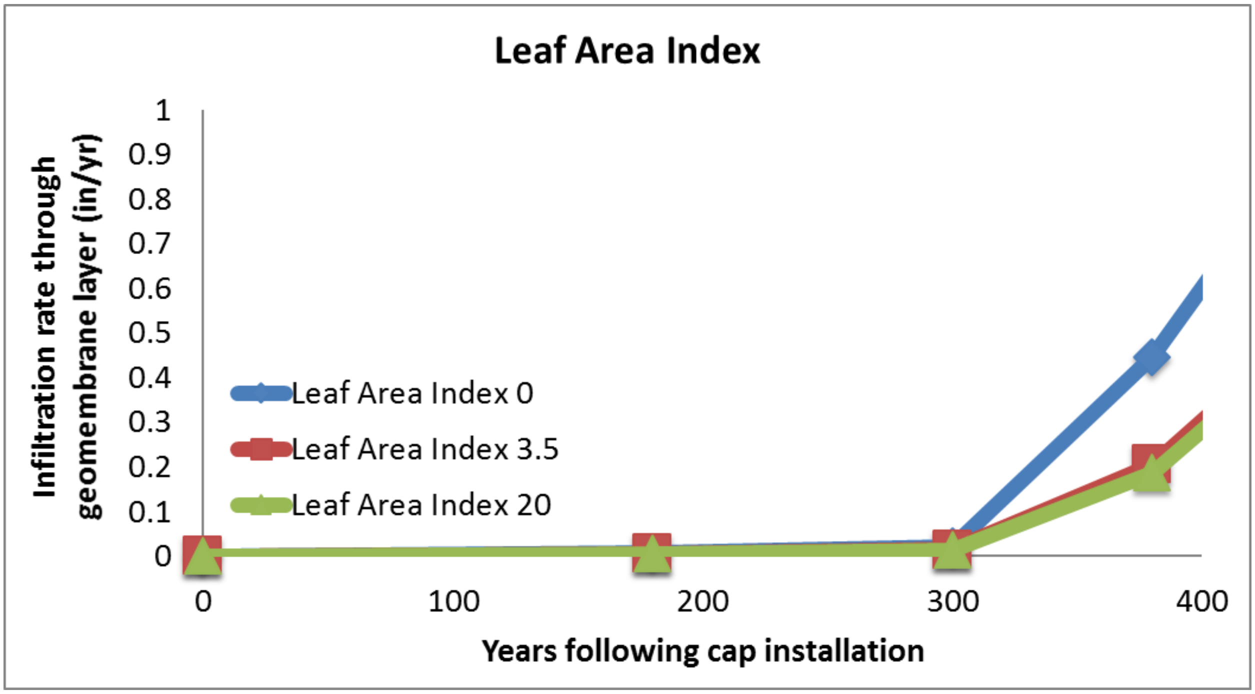


Figure 6-11. Impact of Leaf Area Index on Annual Avg. Infiltration Rate (0-400 Years)

Table 6-6. Change in Infiltration Rate with Leaf Area Index at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)					
Time (years)	LAI = 3.5 (Base Case)	LAI = 0	% Change (vs. base case)	LAI = 20	% Change (vs. base case)
0	0.000150	0.000230	53	0.000140	-6.7
180	0.00560	0.00842	50	0.00565	0.89
300	0.0146	0.0213	46	0.0144	-1.2
380	0.205	0.447	120	0.187	-8.8
560	1.10	1.84	68	1.05	-4.2
1000	3.85	6.37	65	3.63	-5.8
1800	8.91	11.8	33	8.49	-4.8
2623	11.1	12.4	12	10.5	-5.4
3200	11.2	12.4	11	10.7	-4.9
10000	11.6	12.4	7.4	11.1	-4.2

6.6 Slope Length

Slope Length is an input parameter related to the design of the engineered cover system. The length of the sloped cover is known to affect surface runoff and lateral drainage rates. Figure 6-12 and Figure 6-13 show a positive relationship between slope length and the annual average infiltration rate. At a fixed slope percentage (e.g., 3% for the base case), a longer slope length provides more time for the infiltrating precipitation to percolate vertically downward before draining horizontally to the edges of the cover system via surface runoff and lateral drainage. Table 6-7 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time.

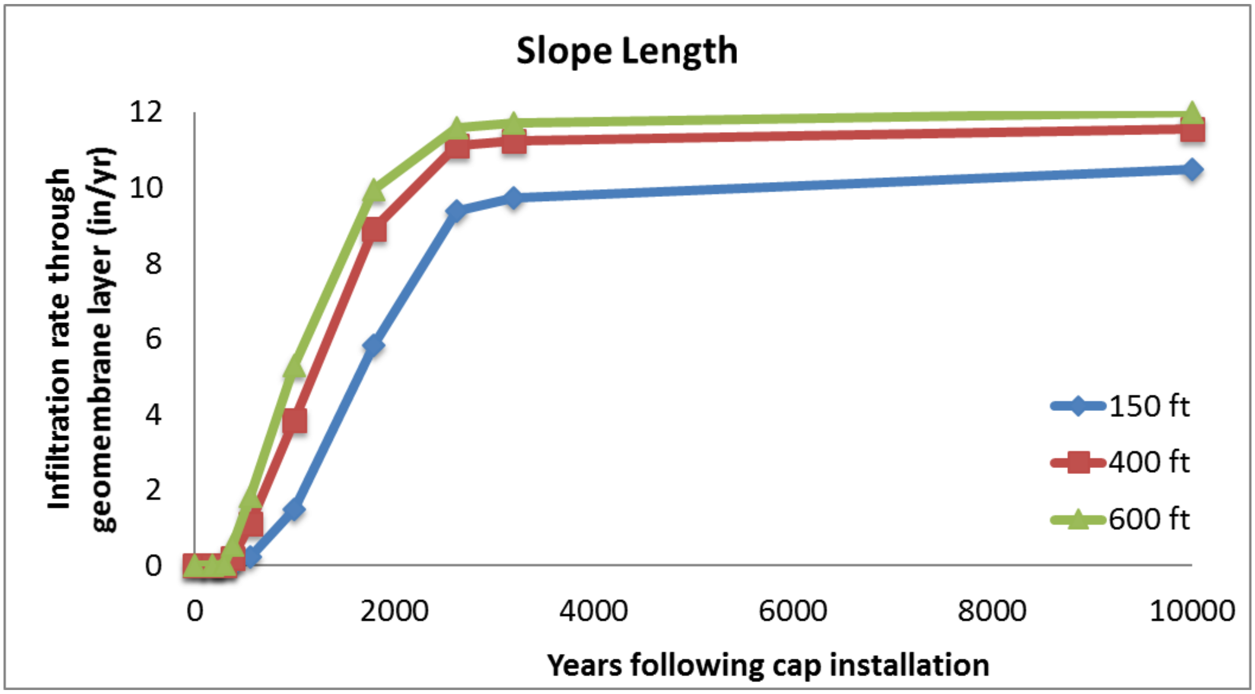


Figure 6-12. Impact of Slope Length on Annual Avg. Infiltration Rate (0-10,000 Years)

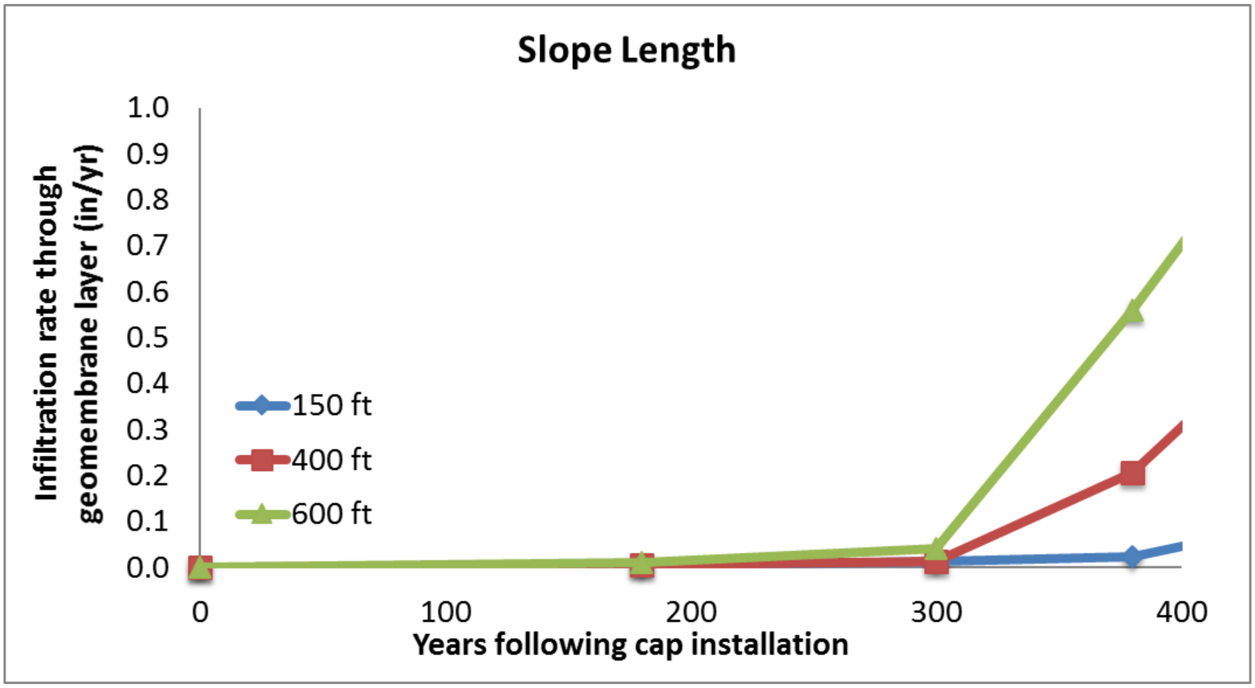


Figure 6-13. Impact of Slope Length on Annual Avg. Infiltration Rate (0-400 Years)

Table 6-7. Change in Infiltration Rate with Slope Length at 3% Slope

Annual Average Infiltration Rate (inches per year)					
Time (years)	400-Foot Slope (Base Case)	150-Foot Slope	% Change (vs. base case)	600-Foot Slope	% Change (vs. base case)
0	0.000150	0.0000415	-73	0.000300	93
180	0.00560	0.00345	-38	0.0108	92
300	0.0146	0.0134	-7.9	0.0409	180
380	0.205	0.0244	-88	0.558	170
560	1.10	0.227	-79	1.84	68
1000	3.85	1.49	-61	5.29	37
1800	8.91	5.84	-34	9.93	11
2623	11.1	9.37	-16	11.6	4.2
3200	11.2	9.72	-14	11.7	4.2
10000	11.6	10.5	-9.5	12.0	3.6

6.7 Precipitation Rate

Figure 6-14 and Figure 6-15 display the impact of total precipitation rate on the annual average infiltration rate through the proposed E-Area cover system. The graphs highlight that more precipitation leads to a greater infiltration rate through the geomembrane/GCL barrier layers. Conversely, less precipitation results in a lower annual average infiltration rate. For example, a decrease in total precipitation rate equivalent to -0.5σ shifts the annual average infiltration rate curve downward by more than 40% (11.2 inches per year to 6.4 inches per year at 10,000 years). The effect of precipitation rate on infiltration rate is more significant during the first 1000 years when the infiltration rates are very low and then increase sharply at 300 years due to barrier layer degradation. Table 6-8 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time.

Appendix C explains how the daily precipitation data were generated for the sensitivity cases. Table C-4 and Table C-5 summarize the mean monthly total precipitation data used by the HELP v3.95D synthetic weather generator to produce a 10-year data set of daily precipitation data for the base case and four sensitivity cases (-0.5σ, -1σ, +0.5σ, and +1σ).

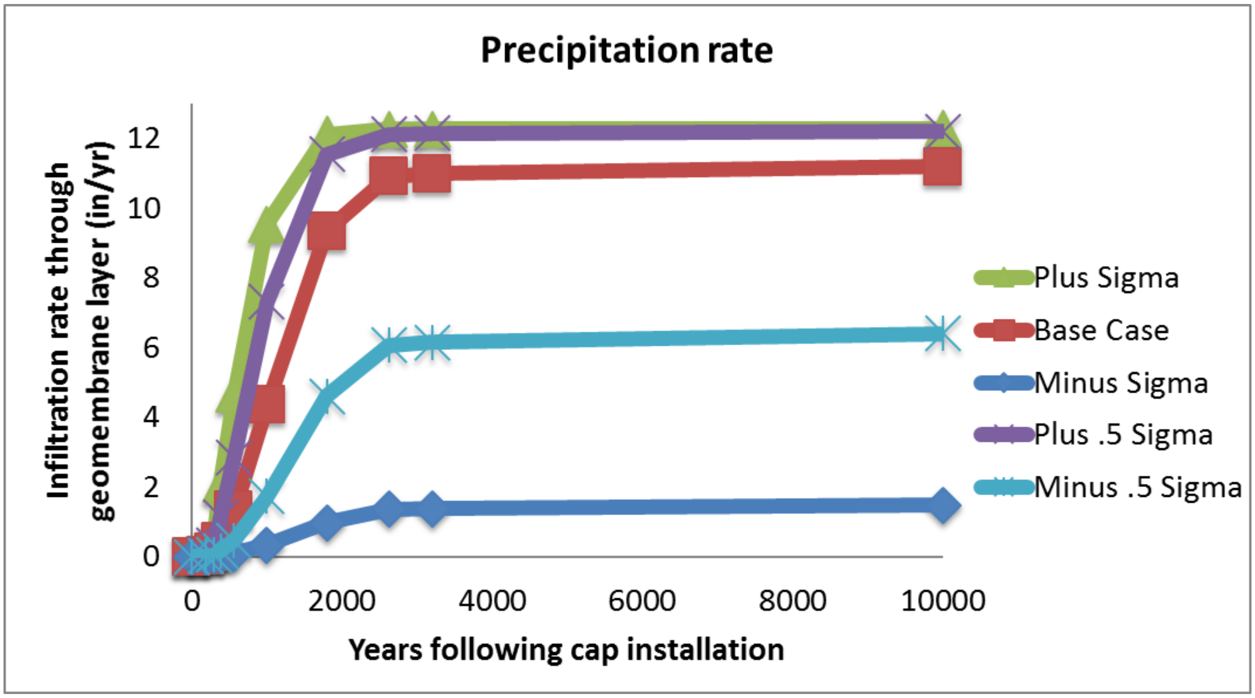


Figure 6-14. Impact of Precipitation Rate on Annual Avg. Infiltration Rate (0-10,000 Years)

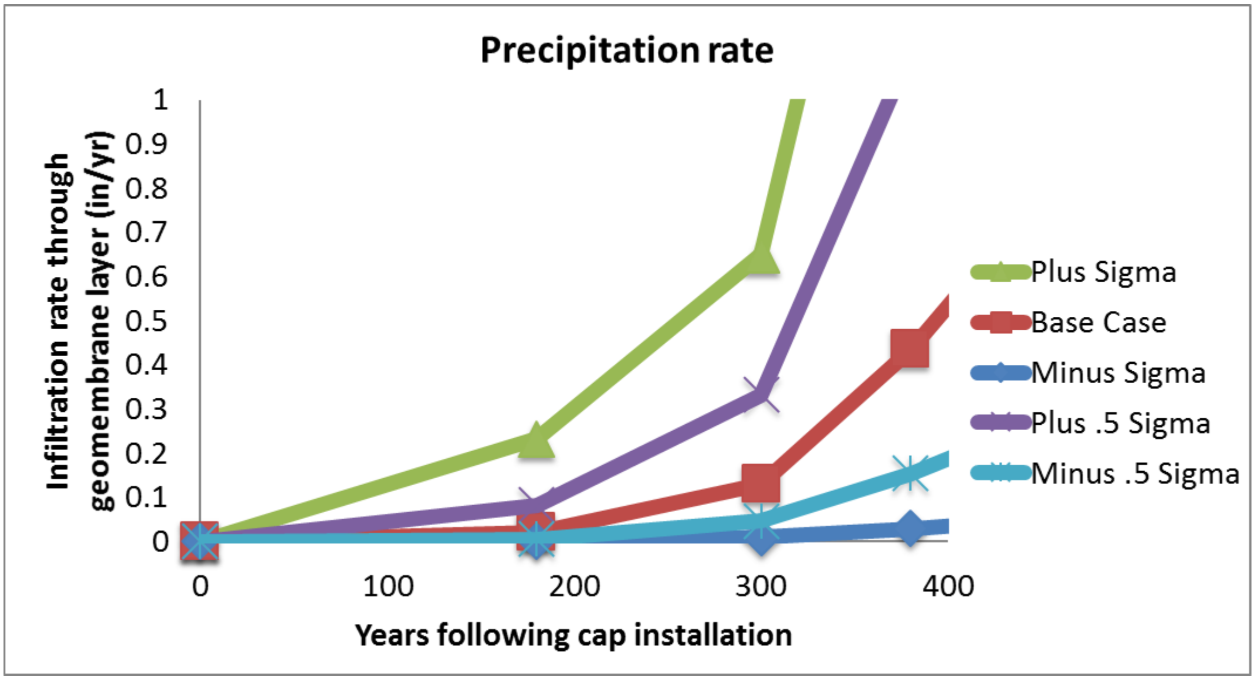


Figure 6-15. Impact of Precipitation Rate on Annual Avg. Infiltration Rate (0-400 Years)

Table 6-8. Change in Infiltration Rate with Precipitation Rate at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)									
Time (years)	Base Case	Minus 0.5σ	% Change (vs. base case)	Minus 1.0σ	% Change (vs. base case)	Plus 0.5σ	% change (from basis)	Plus 1.0σ	% Change (vs. base case)
0	0.000190	0.0000600	-68	0.0000100	-95	0.000490	160	0.00117	520
180	0.0217	0.00523	-76	0.000650	-97	0.0826	280	0.233	980
300	0.130	0.0471	-64	0.0105	-92	0.332	155	0.649	400
380	0.436	0.155	-64	0.0302	-93	1.11	155	2.08	380
560	1.33	0.461	-65	0.0866	-93	2.86	116	4.65	250
1000	4.35	1.72	-60	0.336	-92	7.31	68	9.53	120
1800	9.34	4.60	-51	0.968	-87	11.5	24	12.1	30
2623	10.9	6.07	-44	1.35	-88	12.1	11	12.3	13
3200	11.0	6.14	-44	1.37	-87	12.1	10	12.3	12
10000	11.2	6.40	-43	1.48	-87	12.2	8.9	12.3	9.8

6.8 Temperature

The sensitivity of annual average infiltration rate to temperature was also considered. Temperature will largely affect evapotranspiration rates. Figure 6-16 and Figure 6-17 show that decreasing/increasing the SRS mean monthly average temperatures obtained from the Atmospheric Technologies Center by minus/plus 1.0 sigma has only a small effect on the predicted annual average infiltration rate for the proposed E-Area cover system. Table 6-9 summarizes the percentage change in annual average infiltration rate relative to the base case as a function of time. The infiltration rate is much more sensitive to precipitation rate than temperature.

Appendix C explains how the daily temperature data were generated for the sensitivity cases. Table C-6 summarizes the mean monthly average temperature data used by the HELP v3.95D synthetic weather generator to produce a 10-year data set of daily temperature data for the base case and two sensitivity cases (-1σ and +1σ).

Table 6-9. Change in Infiltration Rate with Temperature at 400-Foot Slope Length

Annual Average Infiltration Rate (inches per year)					
Time (years)	Base Case	Minus 1.0σ	% Change (vs. base case)	Plus 1.0σ	% Change (vs. base case)
0	**0.000190**	0.000200	5.3	0.000170	-11
180	**0.0217**	0.0240	11	0.0190	-12
300	**0.130**	0.145	11	0.119	-8.4
380	**0.436**	0.491	13	0.398	-8.7
560	**1.33**	1.47	11	1.21	-8.7
1000	**4.35**	4.70	8.0	4.08	-6.3
1800	**9.34**	9.72	4.1	9.00	-3.6
2623	**10.9**	11.2	2.4	10.6	-2.3
3200	**11.0**	11.2	2.3	10.7	-2.3
10000	**11.2**	11.4	2.0	11.0	-2.0

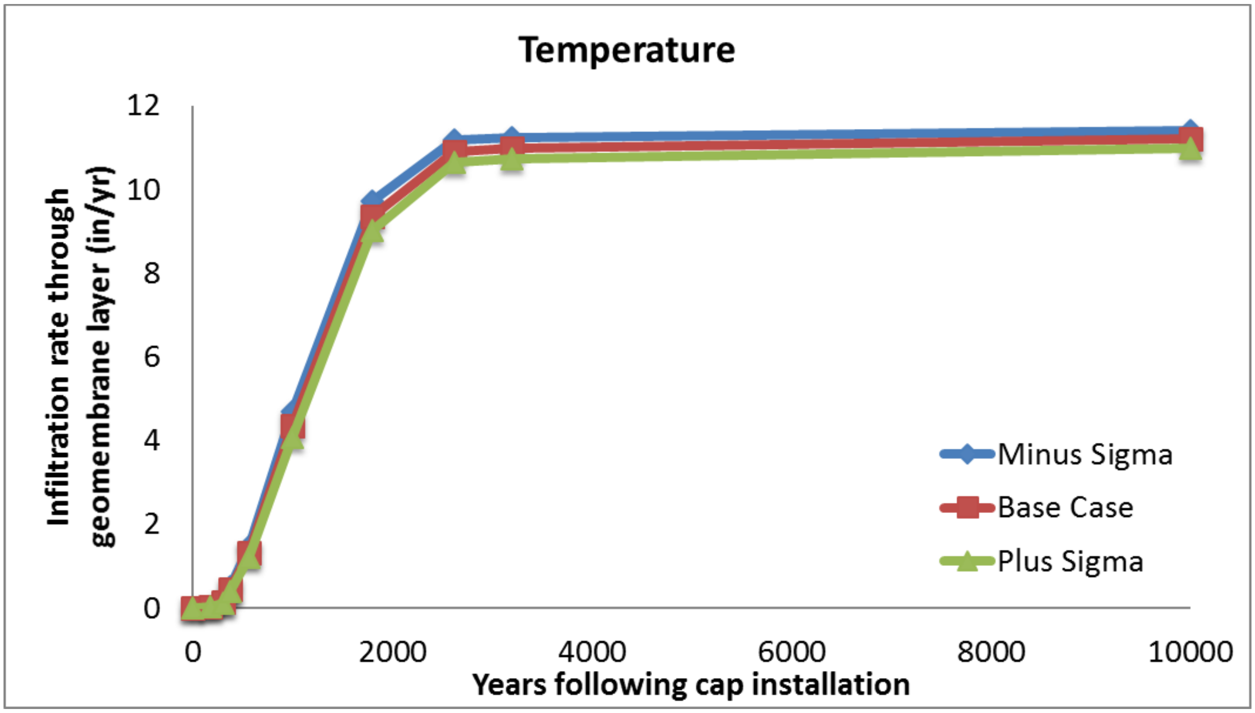


Figure 6-16. Impact of Temperature on Annual Avg. Infiltration Rate (0-10,000 Years)

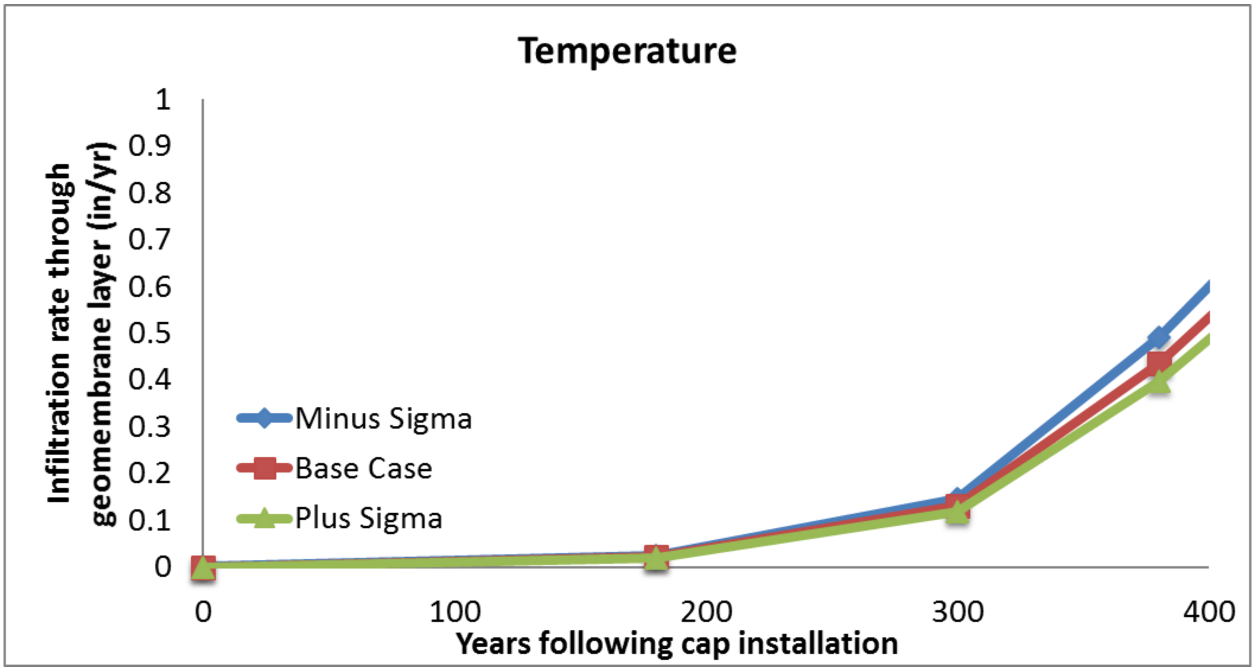


Figure 6-17. Impact of Temperature on Annual Avg. Infiltration Rate (0-400 Years)

7.0 Conclusions

Version 3.95D of the HELP model was used to complete a detailed sensitivity analysis of key design and degradation factors that will affect performance of the proposed E-Area LLWF cover system for a period of 10,000 years. The results of the sensitivity analysis highlight that precipitation rate, surface vegetation (as influenced in the model by leaf area index), saturated hydraulic conductivity of the lateral drainage and upper foundation layers, and geomembrane defect number will be dominant factors in influencing infiltration rate through the cover system into the waste zone. This work and its results provide a framework for quantifying uncertainty in the radionuclide transport and dose models for the 2018 E-Area Performance Assessment. Future work will focus on the development of a non-linear regression model for infiltration rate using Minitab 17® to facilitate execution of probabilistic simulations in the GoldSim® overall system model for E-Area.

8.0 References

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Schroeder, P. R., and Peyton, R. L. (1987) Verification of the Hydrologic Evaluation of Landfill Performance (HELP) Model Using Field Data. EPA/600/2-87/050. Environmental Protection Agency, Cincinnati, Ohio.

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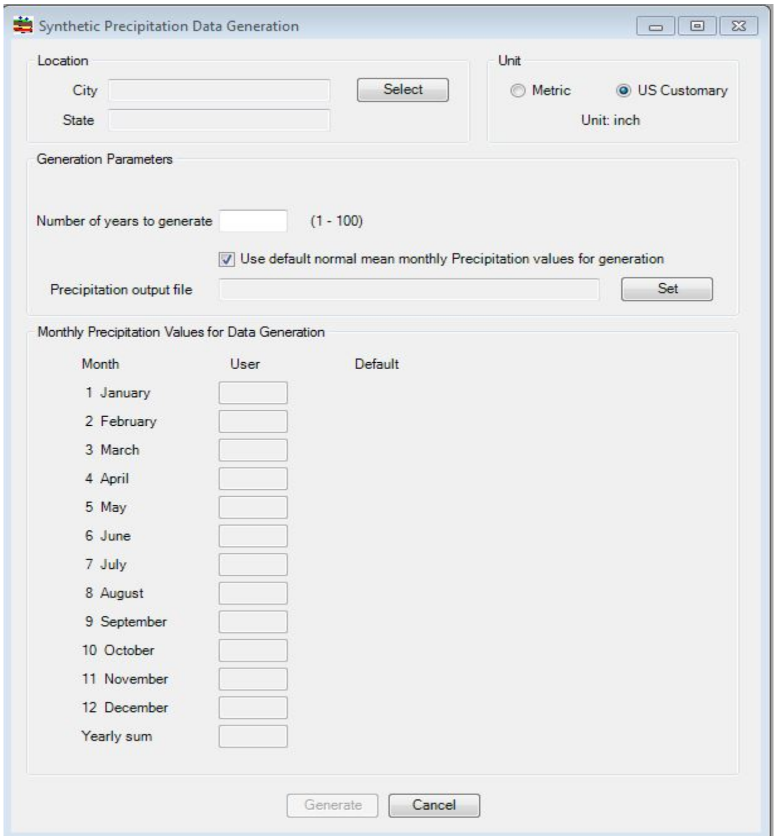
Appendix A. HELP v3.95D GUI for Input Parameters

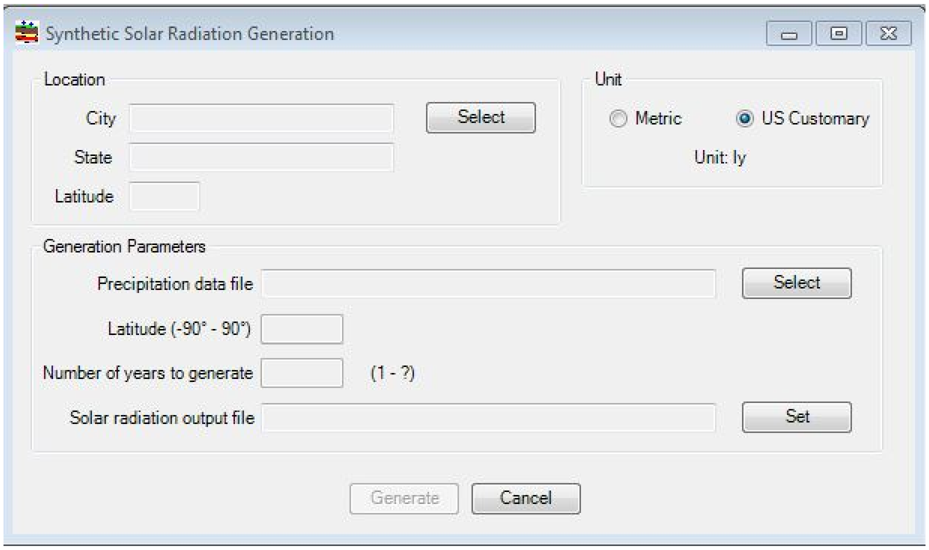


○ Metric ● US Customary

Unit: inch

☑ Use default normal mean monthly Precipitation values for generation

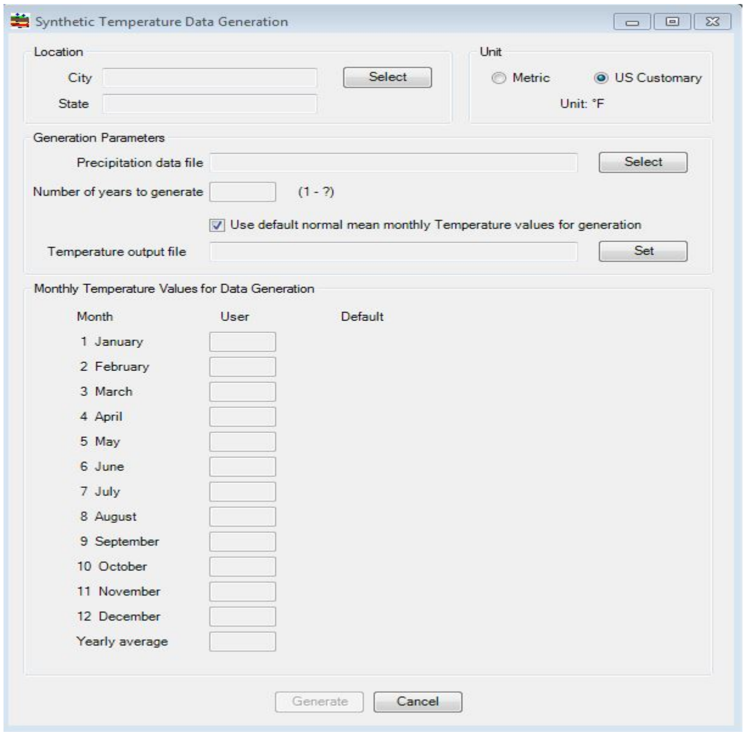
Figure A-1. GUI for Synthetic Precipitation Data Input



○ Metric ● US Customary

Unit: ly

Figure A-2. GUI for Synthetic Solar Radiation Data Input



Synthetic Temperature Data Generation

Location

City

State

Unit

○ Metric ● US Customary

Unit: °F

Generation Parameters

Precipitation data file

Number of years to generate (1 - ?)

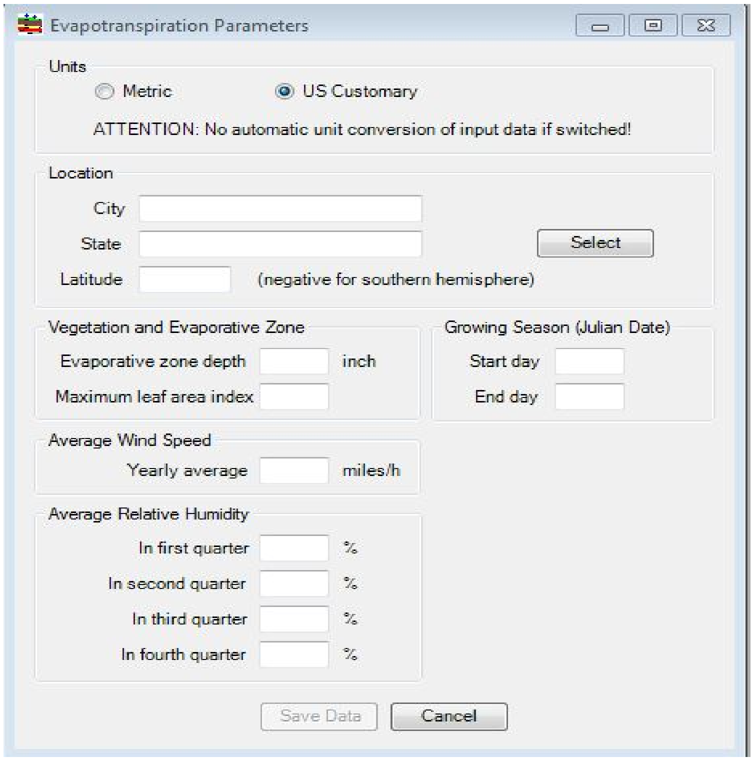
☑ Use default normal mean monthly Temperature values for generation

Temperature output file

Monthly Temperature Values for Data Generation

Month	User	Default
1 January		
2 February		
3 March		
4 April		
5 May		
6 June		
7 July		
8 August		
9 September		
10 October		
11 November		
12 December		
Yearly average		

Figure A-3. GUI for Synthetic Temperature Data Input



Evapotranspiration Parameters

Units

○ Metric ● US Customary

ATTENTION: No automatic unit conversion of input data if switched!

Location

City

State

Latitude (negative for southern hemisphere)

Vegetation and Evaporative Zone

Evaporative zone depth inch

Maximum leaf area index

Growing Season (Julian Date)

Start day

End day

Average Wind Speed

Yearly average miles/h

Average Relative Humidity

In first quarter %

In second quarter %

In third quarter %

In fourth quarter %

Figure A-4. GUI for Evapotranspiration Parameters

Appendix B. HELP v3.95D Model Input Parameters for Base Case Simulations

Table B-1. HELP Model Input Data for Year 0 (ST00.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane	6	4 (geomembrane liner)
GCL	7	3 (barrier soil liner)
Foundation Layer (1E-06)	8	1 (vertical percolation layer)
Foundation Layer (1E-03)	9	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	6		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.35	0.252	0.181	0.252
5	2	12		0.417	0.045	0.018	0.045
6	4	0.06					
7	3	0.2		0.75	0.747	0.4	0.747
8	1	12		0.35	0.252	0.181	0.252
9	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	4.1E-05					
5	2	5.0E-02	400	3			
6	4	2.0E-13					
7	3	5.0E-09					
8	1	1.0E-06					
9	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	4	2	

Table B-2. HELP Model Input Data for Year 180 (ST02.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane	6	4 (geomembrane liner)
GCL	7	3 (barrier soil liner)
Foundation Layer (1E-06)	8	1 (vertical percolation layer)
Foundation Layer (1E-03)	9	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.91		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.352	0.245	0.175	0.245
5	2	12		0.414	0.052	0.024	0.052
6	4	0.06					
7	3	0.2		0.75	0.747	0.4	0.75
8	1	12		0.35	0.252	0.181	0.252
9	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	5.22E-05					
5	2	3.91E-02	400	3			
6	4	2.0E-13					
7	3	5.0E-08					
8	1	1.0E-06					
9	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	90	2	

Table B-3. HELP Model Input Data for Year 300 (ST04.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	**CN Input Parameter Value**
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane & GCL	6	4 (geomembrane liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.84		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.353	0.24	0.172	0.24
5	2	12		0.413	0.057	0.027	0.057
6	4	0.26					
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	6.14E-05					
5	2	3.32E-02	400	3			
6	4	8.7E-13					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	170	2	

Table B-4. HELP Model Input Data for Year 380 (ST06.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches

CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane & GCL	6	4 (geomembrane liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture[2] (Vol/Vol)
1	1	5.80		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.354	0.237	0.169	0.237
5	2	12		0.412	0.06	0.03	0.06
6	4	0.26					
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	6.84E-05					
5	2	2.98E-02	400	3			
6	4	8.7E-13					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	479	2	

Table B-5. HELP Model Input Data for Year 560 (ST07.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane & GCL	6	4 (geomembrane liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.78		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.356	0.23	0.164	0.23
5	2	12		0.409	0.067	0.036	0.067
6	4	0.26					
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	8.71E-05					
5	2	2.33E-02	400	3			
6	4	8.7E-13					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	1115	2	

Table B-6. HELP Model Input Data for Year 1,000 (ST08.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane & GCL	6	4 (geomembrane liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture[2] (Vol/Vol)
1	1	5.72		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.361	0.212	0.15	0.212
5	2	12		0.403	0.084	0.049	0.084
6	4	0.26					
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	1.58E-04					
5	2	1.28E-02	400	3			
6	4	8.7E-13					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	2669	2	

Table B-7. HELP Model Input Data for Year 1,800 (ST09.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Middle Backfill	4	1 (vertical percolation layer)
Lateral Drainage Layer	5	2 (lateral drainage layer)
HDPE Geomembrane & GCL	6	4 (geomembrane liner)
Foundation Layer (1E-06)	7	1 (vertical percolation layer)
Foundation Layer (1E-03)	8	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.62		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	1	12		0.371	0.181	0.125	0.181
5	2	12		0.392	0.116	0.074	0.116
6	4	0.26					
7	1	12		0.35	0.252	0.181	0.252
8	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	1	4.62E-04					
5	2	4.3E-03	400	3			
6	4	8.7E-13					
7	1	1.0E-06					
8	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	5496	2	

Table B-8. HELP Model Input Data for Year 2,623 (ST10.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer (including Middle Backfill)	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.51		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	24		0.38	0.148	0.1	0.148
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	1.4E-03	400	3			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	8403	2	

Table B-9. HELP Model Input Data for Year 3,200 (ST11.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer (including Middle Backfill)	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	5.44		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	24		0.38	0.148	0.1	0.148
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	1.4E-03	400	3			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	10442	2	

Table B-10. HELP Model Input Data for Year 10,000 (ST13.D10)

Input Parameter (HELP Model Query)	Generic Input Parameter Value
Landfill area =	0.2686 acres
Percent of area where runoff is possible =	100%
Do you want to specify initial moisture storage? (Y/N)	Y
Amount of water or snow on surface =	0 inches
CN Input Parameter (HELP Model Query)	CN Input Parameter Value
Slope =	3 %
Slope length =	400 ft
Soil Texture =	4 (HELP model default soil texture)
Vegetation =	4 (i.e., a good stand of grass)
HELP Model Computed Curve Number = 50	

Layer	Layer Number	Layer Type
Topsoil	1	1 (vertical percolation layer)
Upper Backfill	2	1 (vertical percolation layer)
Erosion Barrier	3	1 (vertical percolation layer)
Lateral Drainage Layer (including Middle Backfill)	4	2 (lateral drainage layer)
HDPE Geomembrane & GCL	5	4 (geomembrane liner)
Foundation Layer (1E-06)	6	1 (vertical percolation layer)
Foundation Layer (1E-03)	7	1 (vertical percolation layer)

Layer #	Layer Type	Layer Thickness (in)	Soil Texture No.	Total Porosity (Vol/Vol)	Field Capacity (Vol/Vol)	Wilting Point (Vol/Vol)	Initial Moisture [2] (Vol/Vol)
1	1	4.55		0.396	0.109	0.047	0.109
2	1	30		0.35	0.252	0.181	0.252
3	1	12		0.15	0.1	0.07	0.1
4	2	24		0.38	0.148	0.1	0.148
5	4	0.26					
6	1	12		0.35	0.252	0.181	0.252
7	1	72		0.457	0.131	0.058	0.131

Layer #	Layer Type	Sat. Hyd. Conductivity (cm/sec)	Drainage Length (ft)	Drain Slope (%)	Leachate Recirc. (%)	Recirc. to Layer (#)	Subsurface Inflow (in/yr)
1	1	3.1E-03					
2	1	4.1E-05					
3	1	1.3E-04					
4	2	1.4E-03	400	3			
5	4	8.7E-13					
6	1	1.0E-06					
7	1	1.0E-03					

Layer #	Layer Type	Geomembrane Pinhole Density (#/acre)	Geomembrane Instal. Defects (#/acre)	Geomembrane Placement Quality	Geotextile Transmissivity (cm^2/sec)
6	4	1	34466	2	

Appendix C. Ranges of Uncertainty Considered for Input Parameters

The following tables display the values of HELP model input parameters used in the sensitivity analysis simulations.

Geomembrane Defects: Values for the geomembrane defect number used in the simulations of the base case (3% slope, 400-ft slope length) were held constant at 0 and 180 years. For time >/= 300 years, the defect numbers for the base case were regressed as a function of time to arrive at a linear equation for defect number versus time. The slope of the regression equation was halved and doubled to generate the defect numbers for the 0.5X and 2X sensitivity cases, respectively, as shown in Table C-1 below.

Table C-1. Geomembrane Defects vs. Time

Geomembrane Defect Number			
	Base Case	**.5X**	**2X**
Regression Eqn. for Defects	# = 3.5337t-868.86	# = 1.7669t-868.86	# = 7.0674t-868.86
Time (years)	**# Defects**	**# Defects**	**# Defects**
0	4	4	4
180	90	90	90
300	170	100	1251
380	479	110	1817
560	1115	121	3089
1000	2669	898	6199
1800	5496	2312	11852
2623	8403	3766	17669
3200	10442	4785	21747
10000	34466	16800	69805

Saturated Hydraulic Conductivity: Saturated hydraulic conductivity values for the Upper Foundation Layer (UFL) and Lateral Drainage Layer (LDL) were based on input values used for the 3% slope, 400-ft base case. Base-case values for K_{sat} were increased/decreased by +2X/-2X and +10X/-10X to arrive the four sensitivity cases summarized in Table C-2 for the UFL and Table C-3 for the LDL. For the UFL, K_{sat} does not vary with time.

Table C-2. Upper Foundation Layer Saturated Hydraulic Conductivity vs. Time

Upper Foundation Layer						
Time (years)	File name	Base K_{sat} (cm/sec)	+10X K_{sat} (cm/sec)	+2X K_{sat} (cm/sec)	-10X K_{sat} (cm/sec)	-2X K_{sat} (cm/sec)
0	ST00	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
180	ST02	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
300	ST04	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
380	ST06	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
560	ST07	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
1000	ST08	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
1800	ST09	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
2623	ST10	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
3200	ST11	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07
10000	ST13	1.0E-06	1.0E-05	2.0E-06	1.0E-07	5.0E-07

Table C-3. Lateral Drainage Layer Saturated Hydraulic Conductivity vs. Time

Lateral Drainage Layer						
Time (years)	File name	Base K_{sat} (cm/sec)	+10X K_{sat} (cm/sec)	+2X K_{sat} (cm/sec)	-10X K_{sat} (cm/sec)	-2X K_{sat} (cm/sec)
0	ST00	0.05	0.5	0.1	0.005	0.025
180	ST02	0.0391	0.391	0.0782	0.00391	0.01955
300	ST04	0.0332	0.332	0.0664	0.00332	0.0166
380	ST06	0.0298	0.298	0.0596	0.00298	0.0149
560	ST07	0.0233	0.233	0.0466	0.00233	0.01165
1000	ST08	0.0128	0.128	0.0256	0.00128	0.0064
1800	ST09	0.0043	0.043	0.0086	0.00043	0.00215
2623	ST10	0.0014	0.014	0.0028	0.00014	0.0007
3200	ST11	0.0014	0.014	0.0028	0.00014	0.0007
10000	ST13	0.0014	0.014	0.0028	0.00014	0.0007

Precipitation: SRS monthly total precipitation data for a 53-year period (January 1964 through December 2016) provided by the SRS Atmospheric Technology Group served as the basis for the daily synthetic weather data generated by the HELP v3.95D model and subsequently used in the base case and sensitivity analysis simulations. The SRS monthly total precipitation data for the 53-year period were analyzed to generate mean monthly precipitation rates and associated standard deviations. Sensitivity cases were developed based on plus and minus 0.5 and 1.0 standard deviations away from the monthly means, and are shown in Table C-4 in rows labeled -0.5σ, -1σ, +0.5σ, and +1σ. The 12 mean monthly precipitation values (January through December) for each sensitivity case were used in the HELP model weather generator to generate daily rainfall data for the 10-year simulation time period of interest. Table C-5 provides the corresponding annual average precipitation values for each sensitivity case.

Table C-4. Mean Monthly Precipitation Statistics for Jan. 1964 through Dec. 2016

January		**February**		**March**	
Mean	**4.103**	**Mean**	**4.015**	**Mean**	**4.629**
Median	**3.54**	**Median**	**3.875**	**Median**	**3.835**
Max	**9.54**	**Max**	**8.63**	**Max**	**11.32**
Min	**0.82**	**Min**	**0.79**	**Min**	**1.16**
STD	**2.177**	**STD**	**2.135**	**STD**	**2.559**
-0.5σ	**3.014**	**-0.5σ**	**2.947**	**-0.5σ**	**3.349**
-1σ	**1.926**	**-1σ**	**1.880**	**-1σ**	**2.070**
+0.5σ	**5.192**	**+0.5σ**	**5.083**	**+0.5σ**	**5.908**
+1σ	**6.280**	**+1σ**	**6.151**	**+1σ**	**7.188**
April		**May**		**June**	
Mean	**2.961**	**Mean**	**3.447**	**Mean**	**5.022**
Median	**2.445**	**Median**	**3.05**	**Median**	**4.495**
Max	**9.93**	**Max**	**10.91**	**Max**	**15.71**
Min	**0.59**	**Min**	**0.19**	**Min**	**0.26**
STD	**2.004**	**STD**	**2.374**	**STD**	**3.062**
-0.5σ	**1.959**	**-0.5σ**	**2.261**	**-0.5σ**	**3.491**
-1σ	**0.957**	**-1σ**	**1.074**	**-1σ**	**1.961**
+0.5σ	**3.963**	**+0.5σ**	**4.634**	**+0.5σ**	**6.553**
+1σ	**4.964**	**+1σ**	**5.821**	**+1σ**	**8.084**

Table C-4. Mean Monthly Precipitation Statistics for Jan. 1964 through Dec. 2016

July		**August**		**September**	
Mean	**5.228**	**Mean**	**4.626**	**Mean**	**4.005**
Median	**4.665**	**Median**	**4.055**	**Median**	**4.155**
Max	**11.18**	**Max**	**13.38**	**Max**	**9.47**
Min	**0.77**	**Min**	**1.78**	**Min**	**0**
STD	**2.684**	**STD**	**2.670**	**STD**	**2.268**
-0.5σ	**3.887**	**-0.5σ**	**3.291**	**-0.5σ**	**2.871**
-1σ	**2.545**	**-1σ**	**1.956**	**-1σ**	**1.736**
+0.5σ	**6.570**	**+0.5σ**	**5.961**	**+0.5σ**	**5.139**
+1σ	**7.912**	**+1σ**	**7.296**	**+1σ**	**6.273**
October		**November**		**December**	
Mean	**2.749**	**Mean**	**2.713**	**Mean**	**3.605**
Median	**2.53**	**Median**	**2.39**	**Median**	**3.668**
Max	**17.56**	**Max**	**7.73**	**Max**	**8.36**
Min	**0**	**Min**	**0.29**	**Min**	**1.15**
STD	**3.352**	**STD**	**1.783**	**STD**	**1.852**
-0.5σ	**1.073**	**-0.5σ**	**1.822**	**-0.5σ**	**2.679**
-1σ	**-0.603**	**-1σ**	**0.931**	**-1σ**	**1.753**
+0.5σ	**4.425**	**+0.5σ**	**3.605**	**+0.5σ**	**4.531**
+1σ	**6.102**	**+1σ**	**4.496**	**+1σ**	**5.458**

Table C-5. Annual Average Precipitation Values

Precipitation Case	Yearly Average Precipitation Value
+1σ	76.26 inches
+0.5σ	61.68 inches
Base Case	47.11 inches
-0.5σ	32.56 inches
-1σ	18.65 inches

Temperature: SRS monthly average temperature data for a 53-year period (January 1964 through December 2016) provided by the SRS Atmospheric Technology Group served as the basis for the daily synthetic weather data generated by the HELP v3.95D model and subsequently used in the base case and sensitivity analysis simulations. A monthly average temperature was calculated as follows: for each month for each of the 53 years, daily minimum and daily maximum temperatures were added and divided by two to obtain the daily average temperature; the daily average temperatures for each month of each year were then arithmetically averaged to obtain the 53 sets of monthly average temperature values provided by the SRS Atmospheric Technology Group. The monthly average temperature data for the 53-year period were further analyzed to generate mean monthly average temperatures and associated standard deviations. Sensitivity cases were developed based on plus and minus 1.0 standard deviations away from the monthly means, and are shown in Table C-6 in rows labeled -1σ and +1σ. The mean monthly average temperature data for each sensitivity case were processed through the HELP model weather generator to produce temperature data for the 10-year simulation time period of interest.

Table C-6. Mean Monthly Average Temperature Statistics for Jan. 1964 through Dec. 2016

January		**February**		**March**	
Mean	**46.4**	**Mean**	**49.4**	**Mean**	**57.2**
Median	**46.2**	**Median**	**49.3**	**Median**	**57.3**
Max	**59.6**	**Max**	**57.5**	**Max**	**66.1**
Min	**35.3**	**Min**	**41.3**	**Min**	**48.8**
STD	**5.0**	**STD**	**3.8**	**STD**	**4.0**
-1σ	**41.4**	**-1σ**	**45.6**	**-1σ**	**53.2**
+1σ	**51.4**	**+1σ**	**53.2**	**+1σ**	**61.2**
April		**May**		**June**	
Mean	**65.1**	**Mean**	**72.7**	**Mean**	**79.2**
Median	**65.0**	**Median**	**72.6**	**Median**	**79.3**
Max	**70.9**	**Max**	**77.9**	**Max**	**84**
Min	**58.9**	**Min**	**66.8**	**Min**	**72.9**
STD	**2.7**	**STD**	**2.6**	**STD**	**2.7**
-1σ	**62.5**	**-1σ**	**70.1**	**-1σ**	**76.5**
+1σ	**67.8**	**+1σ**	**75.4**	**+1σ**	**81.9**

Table C-6. Mean Monthly Average Temperature Statistics for Jan. 1964 through Dec. 2016

July		**August**		**September**	
Mean	**81.9**	**Mean**	**80.8**	**Mean**	**75.8**
Median	**81.7**	**Median**	**80.8**	**Median**	**75.7**
Max	**86.9**	**Max**	**85.8**	**Max**	**79.6**
Min	**78.1**	**Min**	**74.5**	**Min**	**70.5**
STD	**2.1**	**STD**	**2.3**	**STD**	**2.1**
-1σ	**79.9**	**-1σ**	**78.5**	**-1σ**	**73.6**
+1σ	**84.0**	**+1σ**	**83.1**	**+1σ**	**77.9**
October		**November**		**December**	
Mean	**65.7**	**Mean**	**56.4**	**Mean**	**49.5**
Median	**65.7**	**Median**	**56.5**	**Median**	**49.2**
Max	**73.4**	**Max**	**65.5**	**Max**	**61.2**
Min	**60.1**	**Min**	**48.7**	**Min**	**40.1**
STD	**3.1**	**STD**	**3.7**	**STD**	**4.7**
-1σ	**62.6**	**-1σ**	**52.7**	**-1σ**	**44.8**
+1σ	**68.7**	**+1σ**	**60.1**	**+1σ**	**54.2**

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Distribution List:

timothy.brown@srnl.doe.gov
michael.cercy@srnl.doe.gov
alex.cozzi@srnl.doe.gov
david.crowley@srnl.doe.gov
David.Dooley@srnl.doe.gov
a.fellinger@srnl.doe.gov
samuel.fink@srnl.doe.gov
jeff.griffin@srnl.doe.gov
nancy.halverson@srnl.doe.gov
erich.hansen@srnl.doe.gov
connie.herman@srnl.doe.gov
david.herman@srnl.doe.gov
Elizabeth.Hoffman@srnl.doe.gov
Kevin.Fox@srnl.doe.gov
john.mayer@srnl.doe.gov
daniel.mccabe@srnl.doe.gov
frank.pennebaker@srnl.doe.gov
William.Ramsey@SRNL.DOE.gov
luke.reid@srnl.doe.gov
geoffrey.smoland@srnl.doe.gov
michael.stone@srnl.doe.gov
Boyd.Wiedenman@srnl.doe.gov
bill.wilmarth@srnl.doe.gov
EM File, 773-42A – Rm. 243
(1 file copy and 1 electronic copy)
Records Administration (EDWS)

sebastian.aleman@srnl.doe.gov
tom.butcher@srnl.doe.gov
Thomas.Danielson@srnl.doe.gov
kenneth.dixon@srnl.doe.gov
James.Dyer@srnl.doe.gov
gregory.flach@srnl.doe.gov
luther.hamm@srnl.doe.gov
thong.hang@srnl.doe.gov
ralph.nichols@srnl.doe.gov
Roger.Seitz@srnl.doe.gov
Jennifer.Wohlwend@srnl.doe.gov
Tad.Whiteside@srnl.doe.gov